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WORKING GROUP WRITTEN PRESENTATION

TRAPPED RADIATION EFFECTS

A working group report prepared for the Space Environmental Effects on Materials Workshop–
A. L. Vampola and W. K. Stuckey, Chairmen; D. Coulter, E. J. Friebele, K. J. Hand,
D. A. Hardy, P. Higby, W. A. Kolasinski, R. T. Santoro, and S. S. Tompkins

ABSTRACT

This report presents the results of the Trapped Radiation Effects Panel for the Space Environmental Effects on Materials Workshop held at the NASA Langley Research Center in Hampton, Virginia in June, 1988. It lists the needs of the space community for new data regarding effects of the space environment on materials, including electronics, as perceived by the panel during their discussions. It addresses a series of questions asked of each of the panels at the workshop. It also suggests areas of research which should be pursued to satisfy the requirements for better knowledge of the environment and better understanding of the effects of the energetic charged particle environment on new materials and advanced electronics technology.

INTRODUCTION

The various panels at the Space Environmental Effects on Materials Workshop were asked to address a number of issues. In the case of the Trapped Radiation Effects Panel, the assessment was taken to include all direct effects on materials induced by the energetic particles, including dose effects, dose-rate effects, and Single Event Upset (SEU). The italicized introductions to each of the panel's responses below are quotations of the questions submitted to the panels for elucidation.

A. In your topic area: Which materials or classes of materials are most vulnerable? In what orbits? Why? And can you identify general or specific consequences on long term spacecraft or satellite performance?

Our current areas of highest concern are:

a) Microcircuits
b) Optics (glass, ceramics)
c) Organic materials

Reasons:

<u>Microcircuits</u>

i. Trend is toward smaller geometries and higher speeds, resulting in lower signal levels for circuit upset, thereby increasing the vulnerability to SEU.
ii. Difference between theory and practice for SEU is a factor of 2 to 5.

iii. No correlation between latchup/burnout and SEU.
iv. Significant lot-to-lot variations in total dose hardness.
v. Only empirical data available, no theory or prediction on dose and annealing effects.
vi. Basic physics parameters not readily available for calculation--e.g., proton inelastic interactions.

Optics and Organic Polymers

i. Serious effects in discoloration, embrittlement.
ii. Swelling, gas production.
iii. Changes in the coefficient of expansion, density changes, surface deformation.

Orbits of Concern

Basically, for all orbits above about 500 km the trapped particle population is of concern. The energetic proton environment is encountered in the region of the South Atlantic Anomaly on all orbits. These energetic protons (E_p > 100 MeV) which can't be shielded out of circuitry, can produce SEU in the most sensitive circuits. With a low probability, they also produce inelastic collisions ("star" events) which can upset even more resistant circuits. With the trend to smaller circuit element geometries, the probability of upset from this mechanism increases. For very long term missions, the integrated dose to optical and organic polymer elements may also be of concern. For orbits above 1000 km, the dose from the energetic protons and moderate energy electrons (50 keV to 1 MeV) also becomes a significant consideration. For orbits in the outer electron zone (altitudes greater than 10000 km), the radiation dose may be the controlling factor for mission lifetime. At geosynchronous orbit, the electron dose is still severe, although not as severe as in the 15000 to 25000 km orbits. At geosynchronous orbit, lightly shielded components can receive doses on the order of 50000 rads/year.

Consequences of Long-Term Spacecraft Operation

Electronic circuits:
a) SEU
b) Latchup
c) Burnout
d) Dose effects
e) Microelectronics degradation through attrition to parts

Long term radiation effects on solar panels are well known and the design of the power system includes the radiation degradation factors. Electronic circuitry is usually designed with size, speed, and power in mind and radiation resistance is either ignored or attempts are made to build it into the device almost as an afterthought, usually through processing methods. Once the circuits are built, radiation tolerance is partially achieved either through shielding (usually bulk methods even though chip shielding uses two orders of magnitude less mass), or operationally with powered-down redundancy, or signal processing. Some thought is being given to increasing the annealing rate in dose effects through heating circuitry up to increase the mobility of trapped charge carriers.

Glass optics:
a) Atomic displacements, ionization, dielectric breakdown
b) Optical degradation through discoloration and defocussing (figure-of-merit degradation)
c) Distortion (due to compaction)

Radiation effects are seen in glasses and glass-ceramics for optical components in the form of darkening and densification. For example, fused quartz compacts 20 ppm at 5 Mrads, its absorption coefficient in the 200-300 nm wavelength range has increased to ~5 cm^{-1}, and it has turned faintly purplish in color. These effects become more intense with dose. Darkening is especially detrimental in fiber optics due to the long path lengths involved (especially for the fiber gyroscope). Because of the competing darkening and recovery processes, irradiation at low dose rate results in lower incremental attenuation than at high dose rate. Typically, the loss induced in a fiber at 1.3 µm by a natural space background low dose rate irradiation (1-10 rads/day) is ~ 1 dB/km-krad if the fiber is maintained at 23 C°. The loss induced at 0.85 µm is approximately 5 times greater. Note, however, that dose rates of the order of 1 krad/hr have been observed in the outer electron zone behind nominal amounts of shielding (0.035 g/cm^2 Al), and of the order of 75 rads/day behind shielding an order of magnitude thicker. AR or HR dielectric coatings on optics tend to make an optic more sensitive to radiation.

Figure 1 shows quantitatively the effect of radiation on the deformation of optical materials. In the figure, the dose appears to be quite high. However, optical surfaces are apt to be exposed to the space environment where surface doses in excess of 1 rad per second can occur. Also, the deformation displayed is enormous compared to the distortions which would significantly degrade performance of a large space mirror (a quarter of a wavelength of light over the diameter of the mirror).

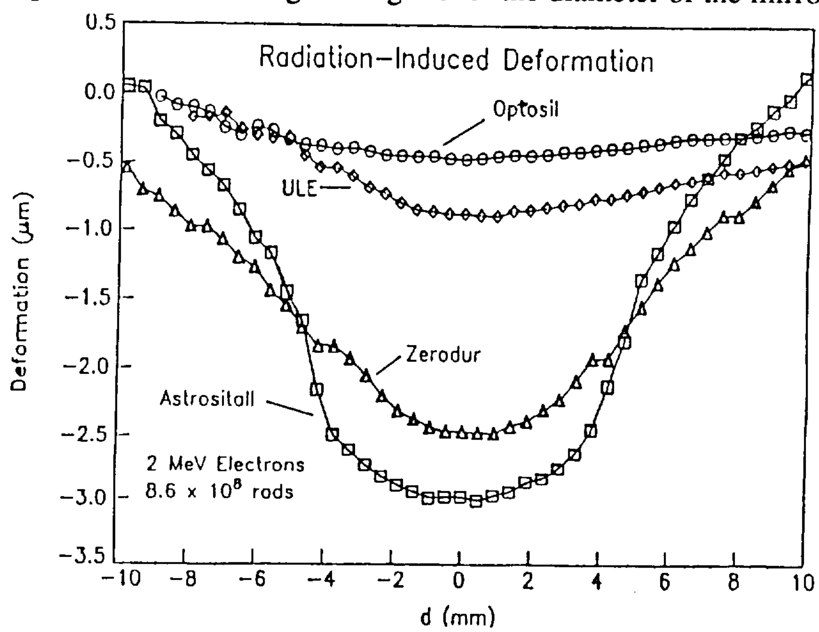

Figure 1. Radiation induced deformation of optical materials.

Organic Polymers:

a) Cross-linking, scission
b) Embrittlement
c) Modulus changes
d) Coefficient of expansion changes
e) Significant structural changes due to asymmetric changes in ceramic/glass/polymer structures

Doses in the range of the high 10^5 to 10^6 rads produce embrittlement, modulus changes, and discoloration of the binders. For light pipes, changes occur in the kilorad range--changes of coefficient of expansion, dislocations in various glasses; swelling and gas production. Data on the effects of energetic protons don't exist in the volumes that are needed. They haven't been done systematically. We need the response function of materials for electronics; we need ground testing and modeling, and we need cross-section data. Any long-term mission has a problem with proton-induced activation. We need an NDEF equivalent for proton interaction cross-sections to correlate the effects of P+>inelastic on spacecraft materials. We need a list of materials categorized by vulnerability in rads.

Many organic polymeric materials will be used in the space environment on future missions in the form of structural composites, adhesives, seals, coatings, optics, etc. In general, these materials are more sensitive to radiation than are inorganics and metallics. Cross-linking and chain scission, the two principal manifestations of radiation damage in polymers, cause significant degradation of a variety of properties including strength, color, modulus, and T_g. The reported thresholds for physical changes for most polymers are in the range of 1 to 100 megarads. These dose levels are not inconsistent with what could be experienced by long term missions in certain high orbits. Figure 2 displays graphically the radiation level at which significant deterioration of material properties occur.

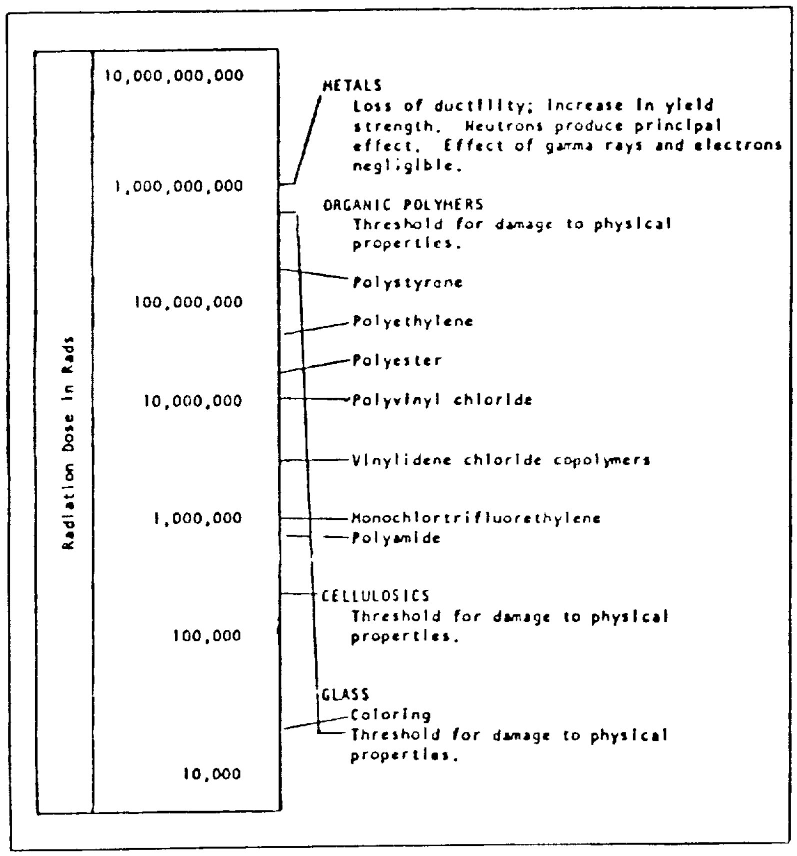

Figure 2. Relative sensitivity of materials to radiation.

Very little data exists on space radiation exposure for polymers. What does exist is poorly characterized as to dose and exposure conditions (temperature, UV, atomic oxygen, etc.). This is because few long term missions have flown and returned incorporating these materials. What is required is an exposure experiment in a known environment followed by analysis upon return of samples on selected materials from several basic classes of polymers (thermosets, thermoplastics, rubbers, etc.)

Areas of Concern

Basic physics data is not available to properly predict the SEU/materials effects:

a) P+ cross-sections/interactions have not been done systematically
b) P+ + Be > 2 α produces distortions in Be mirrors
c) Long-term missions will have an activation problem.

Comments:

a) Long-term missions will produce high integrated fluences which will have serious effects on optical elements/ceramics/glasses--misalignment of structures, defocussing, etc.
b) Flight tests of model structures to get experience on omnidirectional loading, complex spectral effects needed.
c) A well-organized ground test program is required.
d) What happened to all of the information gleaned from SREL activities in the 60's and the 70's?
e) More effort in the modeling area is required.
f) Recommendation for a bench-mark test site.

Is there any correlation between theory and lab experience (and space experience) so that long term performance can be predicted?

The difference between theory and practice for SEU in CMOS/SOS and CMOS/EPI is a factor of 2 to 5. There is no correlation between latchup/burnout and theory. The same is true for annealing/dose effects. We can't predict the effects, we can only test for them. Bulk properties not as well known as fiber optics, still in the "getting data" stage. Effects on materials/polymers is still basically in the empirical (qualitative) stage. Correlation between theory and practice to predict long-term performance: Space data base very sparse; new circuits and materials being introduced all need to be tested; Prediction (except for continued degradation in performance) not possible--at least not quantitatively.

Do we know enough, even if only empirically, to launch for 10 years (or 30 years) of service with confidence?

NO! Current practice shows that the 5-year+ spacecraft lifetime is the exception rather than the rule and that new technologies are less reliable because of the increased complexity. At this point, we can probably say that 10 years of service is improbable and 30 years is probably impossible.

Comments on the predictability of long-term performance:

a) Qualitative estimates only
b) Synergistic effects only guessed at
c) At this point, it is probably not possible to predict a given design will survive for 10 years in space with a high probability

B. In general, are terrestrial lab facilities available? Adequate?

Not really. They exist "in general" or "in principle", and that is precisely the problem, especially where proton accelerators with potential for simulating inner-zone and solar flare protons are concerned. These facilities are scattered all over the country, and no single accelerator can provide the complete range of energies, intensities, and spatial distributions needed to adequately simulate the effects of protons in space. Each group using a given facility has to perform its own studies of beam properties and develop special tuning techniques to obtain the desired beam. This results in much duplication of effort, unnecessary expense and waste of accelerator time, the availability of which is often very limited. Furthermore, most facilities are paid by each group for beam actually used and have no long term funding to develop generally applicable capabilities for conducting research on space radiation effects. As their usefulness to DOE nuclear physics programs declines, operation of the facilities is curtailed and eventually they become permanently shut down and dismantled. Under these circumstances, the availability of ground facilities to support space research is sporadic at best, and makes planning and development of long-term programs a high risk operation.

We need ground test facilities; should set up a committee with funding to oversee this area. (This could be either by discipline or by environmental effect). New technologies have made a more urgent requirement for ground testing than existed previously. The industry should have a national facility for space environmental effects testing.

Comments on lab facilities:

a) Availability
  - in general, yes
  - being closed down

b) Adequacy
  - in general, not adequate
  - problems with the beam characteristics
    - monoenergetic
    - unidirectional
    - intensity
    - species

c) We need data bases
  - systematic, p+
  - for test/development of theory

d) Need a committee to oversee facilities

Without being exhaustive, please identify major facilities and their strengths and weaknesses.

Some of the currently operating particle accelerators which are of potential use to the space program are

Radiation Facilities
(Partial List)

Heavy Ions:		
Brookhaven	Tandem Van de Graaff	20 MV
Oak Ridge	Holifield Heavy Ion Facility	20 MV
Law. Berkeley Lab	88-Inch Cyclotron	20 MeV/nuc
Law. Berkeley Lab	Bevelac	>1 GeV/nuc
Protons:		
Oak Ridge	Isochronous Cyclotron	70 MeV
Law. Berkeley Lab	88-Inch Cyclotron	50 MeV
Law. Berkeley Lab	Bevelac	>1 GeV
UC Davis	Cyclotron	45 MeV
UCLA	Cyclotron	45 MeV
Harvard	Cyclotron	150 MeV
Brookhaven	AGS	>350 MeV
Argonne	LINAC	50 MeV
Electrons:		
NRL	LINAC	10-60 MeV
NRL	FEBETRON	0.5 MeV
RADC	LINAC	2-20 MeV

ORELA		150 MeV
GSFC	Tandem Van de Graaff	2 MeV

Other Radiation Facilities:

NRL	Co60, 50-100 kV X-Rays, Excimer Laser
RADC	Co60, Van de Graaff, Dynamitron, Ion Beam
Savannah River	Hot Co60

C. Having heard a short tutorial on the major space environment factors: Is there likely to be interaction or synergism between your factor and one or more of the other factors?

Any discussion of synergism at the present time is speculative (except for temperature effects on SEU and latchup, and temperature/total dose effects on radiation-hardened RAMs, rad-soft circuits, and polymers). However, the suspected synergisms are

a) UV/particle radiation (in polymers, optics)

b) Temperature/UV/particle radiation (in thin materials, surfaces)

c) Temperature/trapped radiation (in electronic circuits, sensors, materials)

Has that interaction or synergism been tested and evaluated, or is it only speculative?

Some testing of the synergism between thermal effects and trapped radiation, particularly in the SEU effects area and total dose in MOS circuitry have been done. Some SEU and latchup radiation testing has been done as a function of temperature. Also, for some materials the synergism between trapped radiation and UV has been tested.

Do any lab facilities exist to test such interaction/synergism?

We know of no lab facilities, per se, that exist, although some synergisms can be tested in the lab--the general problem is that the energy spectrum and the angle of incidence for the particles cannot be properly simulated.

D. Are space experiments needed to assess the vulnerability of materials to long term exposure to your environmental factor? Why? (Possible reasons include validation or calibration of terrestrial experiments, identification of interactions or synergisms not possible to schedule on Earth, absence of equipment to duplicate an environment with real time and accelerated exposure capabilities, etc...)

Yes, additional space experiments are needed, but the need is for higher orbits and longer durations than Shuttle permits. There is a need to get samples back, not only for materials and optics, but also for microcircuits. In the case of malfunctioning circuits, there is a need for an "autopsy" in order to determine the cause and mechanism of failure. Ground measurements are also required. A recommendation: Boost a test vehicle up to the center of the inner zone (2000 km at low inclination), stay for a year, then deboost and retrieve the test vehicle with the Shuttle. There is also a need for tests intended to validate ground based experiment, theory, and models.

<u>Other Requirements:</u>

Analytic/Theoretical Capabilities: Development of computational capability for pre- and post-experiment analysis of trapped radiation (protons, electrons, and possibly weapons radiation pumped belts) effects on materials and electronics.

Data: Evaluated charged-particle cross section data to predict atomic displacements, gas production (p,p; p,α; α,p; α,α; etc.) and single event upset phenomena (SEU, latchup, burnout, etc.) Considerable data are required to predict bond breaking in organic materials, optical property effects, fiber optic response data, etc.

Facilities: Dedicated electron, proton, α-particle, and heavy ion accelerators for measurement of cross-section and damage data. Beam energies and intensities sufficient to replicate Van Allen belt proton and electron energy spectra.

Experiments: Carefully tailored and designed ground and space experiments to quantify radiation damage to materials and electronics.

Staffing: Multilaboratory, multidisciplinary committee to organize, design and classify needs and supporting experiments.

Modeling: Modeling capabilities to a) accurately model satellite and the environments; b) component representation (electronics); c) macro- and micro-material properties (?).

Computer Capabilities: Dedicated facilities a'la Livermore fusion computing center, etc. for the entire NASA/SDIO community.

E. Identify in priority order those experiments that must be conducted and can only be conducted in space. What duration(s) will be necessary? Is retrieval necessary? After what interval?

It is not possible to prioritize experiments at this time; that is probably best left to individual programs which recognize a need for basic data related to the operations of their specific missions. However, it is possible to indicate the generic types of experiments which should be conducted and their locations. The highest priority has to be given to CRRES, but since that already has a dedicated launch, emphasis can be placed on other high priority missions. Retrieval of LDEF is extremely important. A follow-up to LDEF, using information gleaned from LDEF and incorporating new materials not available when LDEF was designed. Although future work/advances in electronics and materials will be the driver in defining the space tests that must be done, we can identify orbit locations and durations for some experiments.

Tests of materials in which a varied angle-of-incidence of the particles produce special effects (stress in structures, deformations), tests in which a real cosmic ray spectrum is required (high-energy heavy ion production of SEUs, latchup, etc.) and long duration exposures to particles of varied energy at a low level (degradation of fiber optics, organic polymers) all need to be done in space with durations of a few months to a year. For glasses and polymers and possibly for other materials, we need to get megarads/year exposures. We could probably start with "quick and dirty" flights, then use a long-term program to follow up on what is initially learned.

F. Estimate, by order of magnitude, the volume, weight and complexity of each experiment and necessary auxiliary gear. Also identify platform characteristics essential to your experiment (orientation in the RAM direction or toward the sun, unmanned and adrift to prevent any disturbances, power for active experimentation, telemetry equipment to obviate retrieval, etc.)

The panel did not address this in much detail because specific experiments (other than CRRES, LDEF, LDEF-follow-on) were not identified. But it was the concensus that for valid testing of particulate radiation effects on materials, the orbit has to be at least 500 km; a boost-deboost mission is required; and environmental monitors should be installed on all flights, whether test or operational. For any space test, the energetic particle environment must be known because of synergistic effects of the energetic particles on the other environmental parameters being tested (which we did not address). For operational spacecraft, environmental monitors are needed to provide the data base which is required to determine the cause of a failure on the space system.

G. Does your technical community have any experiments planned/designed/built for early access to space? If so, please describe.

The technical community does have available experiments in this area. The CRRES mission, which is described elsewhere in this Proceedings, will make simultaneous measurements of the particle environment, the dose from that environment, and effects in circuits and materials from that dose. The effects that will be measured are the degradation of solar panels, microcircuit damage, SEUs, and electrostatic discharges due to the embedding of charge in cables and circuit boards. Other than CRRES, the only resource known to this panel is the reservoir of space instruments/experiments which exist in laboratories and museums which were at one time prototypes or backups for completed missions or flight units from cancelled missions.

Panel Recommendations

A. The panel recommends that a benchmark site for radiation effects on materials be established.

B. It is recommended that an interagency committee at the national level be formed to assess in depth the long term radiation effects testing requirements and act as a coordinator in the efficient utilization of the above and other facilities as the needs for their use rise.

C. A well-organized ground test program is required.

D. More effort in the modeling area is required.

E. Flight tests of model structures to get experience on omnidirectional loading, complex spectral effects needed.

F. All space vehicles should carry environmental monitors in order to assist in determining the cause of any degredation in performance or failures in orbit.