SECTION 23. RECOMMENDATIONS AND FUTURE DEVELOPMENTS

23.1. GENERAL

In the use of this document, one is made aware of the presence of gaps in the techniques necessary to improve the radiation tolerance of a spacecraft system. Further R&D work is needed before a coherent discipline for radiation tolerance engineering is available to European Design groups. Some of the fields needing more work are listed below:

System level engineering

- Orbital radiation analysis,
- Trade-offs for mission orbit selection,
- Orbit/weight/life/cost trade-offs,
- Written equipment procurement specifications, including improved environment specifications and radiation-effect control procedures,
- Detailed comparison of radiation transport and shielding computer programs.

Layout

- Radiation protection analysis of whole spacecraft,
- Computer-aided design of local spacecraft protection,
- Testing procedures for the integrity of protection after assembly,
- Written design rules for layout of:
  (a) Spacecraft,
  (b) Electronic boxes.

Electrical effects

- Scheme for predicting degradation of:
  (a) Bipolar,
  (b) MOS and
  (c) Optoelectronic devices,
- Scheme for predicting orbital upset rates from SEU,
- In-flight monitoring:
  - Telemetry of selected circuit points,
  - Distributed Radiation Monitoring Units (RMU),
  - Design rules for radiation tolerance of circuits.

Radiation test techniques

- Low-cost bench-top tests,
- Test guidelines (see MIL standards and ESA/SCC procedures),
- Standard methods of test interpretation,
- Dosimetry standardisation,
- Device Response Data Bank,

- Research into radiation effects on new devices.

Worthy of comment in the "lost opportunities" department are:

- The present lack of unambiguous monitoring of spacecraft circuits for signs of radiation-induced degradation and single-event upsets,
- The probability that, from time to time, unnecessary shield weight has been launched owing to imperfect knowledge of the existing built-in protection given by spacecraft structure and
- Lack of routine radiation environment monitoring.

Indeed, the relative cost-effectiveness of alternative methods of hardening has never been rationalised.

23.2. FUTURE DEVELOPMENTS IN RADIATION HARDNESS ENGINEERING

Changes in electronic and aerospace technology can affect the approach adopted to radiation-hardening of both manned and unmanned space vehicles. Although we recommend that "Radiation Hardness Engineering" should become a distinct and recognized part of space systems engineering and configuration control, it is not yet a discipline. Some of the influences causing change in spacecraft design are:-

A. In aerospace technology

- Lighter spacecraft structures can be assembled and launched from earth-orbiting bases,
- Satellites are now being serviced in orbit,
- Increased use of modular designs requires increased standardisation of all spacecraft equipment, but especially of MOS devices, shielding and dosimetry,
- Jupiter fly-by's incur high radiation environments,
- Use of space nuclear power systems (RTGs and reactors) will increase, especially if Lunar and Martian bases are developed,
- Spiral transfer to geosynchronous altitude from low earth orbit will be used; prolonged transit through the radiation belts imposes serious constraints on electronic and optical designs and
- Increasing popularity of eliptical orbits for science and communications.

B. In electronic technology

- New MOS fabrication methods (e.g. use of Si gate implantation, e-beams, dry plasma etching) will make control of hole-trapping in semiconductor/insulator structures more challenging,
- The expected scaling-down of MOS device geometry (including thinning of the gate oxide), although reducing the effectiveness

of charge build-up in the thinner oxides used, also confers added chances of new "electrical noise" phenomena, including single-event upsets, high-field electron avalanche effects and trapping.

The increasing use of optoelectronic devices will increase the impact of radiation-induced coloration in optical materials, of radiation-induced "optical noise" in optical signal-processing and of bulk-damage to CCD's.

To summarise the trends in aerospace technology: on the bad side, it appears that - in general - environments will become more severe and devices more sensitive to radiation; on the good side, it is likely that space vehicle degradation problems will be slightly relieved by the falling cost of launches, allowing replacement of modules in orbit and sometimes extra shielding. Radiation hardness engineering will still be needed in order to supply the rationale for choice between these two alleviating measures in payloads of ever-increasing complexity. It should not be assumed that the coming of the shuttle era will remove the need to limit the quantity of shielding.

For electronic technology, the good news is that empirical methods for controlling hole-trap densities in oxides are now offered commercially in some "radiation-hardened" device series. Moreover, now that oxides are more likely to be exposed to various avalanche injection processes, including hole injection, because of reduced device dimensions, more attention is paid to oxide-charging. The bad news is that the increasing use of dry technology for processing and the constraints of VLSI densities make the control of MOS device-charging more difficult, the use of small dimensions has already brought in two new effects: single-event upsets and electron-trapping.

In brief, it is not likely that the need for radiation hardness engineering will disappear and it is likely that research and development in this field will be required for some time, especially in the areas of device physics, testing, shielding and instrumentation.

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SECTION 24. CONCLUSIONS

The effects of space radiation on electronic devices, especially those on LSI devices and optics, provide the engineer with a complex problem. This document is a manual which specifically addresses the engineering problem and some of its management aspects. Summary graphs, tables and calculation methods are presented which are intended to help spacecraft designers to gauge the significance of the space radiation problem from their particular point of view and then to communicate this problem to management.

Descriptions of the environment, effects and possible solutions have been couched, as far as possible, in simple language. Much of the graphical material is original to ESA and gives comparisons of data from several publications or unpublished data. In all areas, improvements in analytical methods have been sought. Some difficult questions of transmission of electrons and protons into electronic boxes have been clarified and approximate methods for calculating dose-depth curves are given. The method is useful for preliminary investigations, but computer approaches are recommended for detailed equipment design.

"Dose-depth" curves for orbits of importance ("reference missions") are compared. A simple example of a geometrical sector analysis for one mission is given. In view of the importance of its use in telecommunications, the geostationary Earth orbit (GEO), is given special attention. Because of the development of manned space stations, low Earth orbits (LEO) are also of increasing interest.

The problem of predicting the responses of advanced electronic devices to radiation is a challenging one because the device physics involved is complex and the field is in continual development. During the preparation of this handbook, existing methods have been reviewed and new ones developed, e.g. the Simple Engineering Model for MOS devices. The designer must have the design tools that allow him the choice of circuit alteration, added shielding or the premium cost on hardened devices. By force of circumstances, designers will have to use many devices that are probably only available in "unhardened form". Thus, the sections on procurement, radiation test procedures and project aspects will be useful to system engineers and management.

Looking forward, a more formal interaction with projects is sought. Considering the rapid developments in aerospace and semiconductor technology, ESA is encouraging forward-looking research in this field.

New trends in space include the use of space stations, increased use of on-board data processing and sensors and the great increase in complexity of integrated circuits. It is hoped that by outlining the present state of radiation effects analysis techniques and the provision of guidelines, this handbook will lead to enhancement of the efficiency of European and international space project systems.