# COSMIC RADIATION EFFECTS ON AVIONICS, AN INCREASING HAZARD IN THE NEW MILLENNIUM?

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## Abstract

*With the increasing use of microelectronics of ever diminishing feature size, systems are becoming increasingly susceptible to single event effects arising from the highly ionising interactions of cosmic rays and solar particles. Such single event effects include soft errors, involving both single and multiple bits, and hard errors due to latch-up or burn-out. For space systems an increasing body of evidence has accumulated over the last twenty years, systems have been lost and expensive ground control procedures have had to be invoked. Although cosmic-ray effects are now a normal part of the specification, expensive mistakes are still made. While the earth's atmosphere shields out most of the primary cosmic rays, there is a build up of secondary neutrons which reach a maximum at around 60000 feet and are only a factor of three diminished at 30000 feet. By sea level there is a further factor 300 diminution. As a result of this mechanism the radiation hazard at aircraft altitudes is as severe as in certain low-earth orbits. During the past ten years there has been increasing evidence of single event effects on aircraft electronics as well as in sea- level systems. At the same time there is new legislation on the allied problem of the effects of these neutrons on aircrew and frequent flyers. The problem is expected to increase as more low power, small feature size electronics are deployed in More Electric aircraft. In addition, the current period of solar maximum activity following the turn of the millennium is likely to provide large solar particle events which can penetrate to aircraft altitudes. A Cosmic Radiation Effects Working Group has been established to pool research information on this problem. The work programme is described together with some initial results.*

## 1 Cosmic Rays

Cosmic rays were first discovered in 1912 in a Nobel prize-winning experiment when an Austrian called Hess flew a detector on a balloon and showed that ionisation increased with altitude. Many years of research and the ability to get above the atmosphere afforded by the space programme show that the earth's magnetosphere is bombarded by a nearly isotropic flux of energetic charged particles, primarily the nuclei of atoms stripped of all electrons. These comprise 85% protons (hydrogen nuclei), 14 % alpha particles or helium nuclei, and 1% heavier covering the full range of elements, some of the more abundant being, for example, carbon and iron nuclei. Most theories of their origin favour supernovae (cataclysmic stellar explosions occurring approximately once every hundred years in our galaxy) or the resulting pulsar (rapidly rotating neutron star).

They travel at close to the speed of light, have huge energies (>GeV) and appear to have been travelling through the galaxy for some ten million years before intersecting the earth. They are partly kept out by the earth's magnetic field and have easier access at the poles compared with the equator. An important quantity is the rigidity of a cosmic ray which measures its resistance to bending in a magnetic field and is defined as the momentum-to-charge ratio for which typical units are GV. The radius of curvature of the particle is then the ratio between its rigidity and the magnetic field. At each point on the earth it is possible to define a threshold rigidity or cut-off which a particle must exceed to be able to arrive there. Values vary from 0 at the poles to about 17 GV at the equator.

On the earth's surface in addition to geomagnetic shielding we are shielded by the atmosphere. The primary cosmic rays interact with air nuclei to generate a cascade of secondary particles comprising protons, neutrons, mesons and nuclear fragments The intensity of radiation builds up to a maximum at 60000 feet and then slowly drops off to sea level. At normal cruising altitudes the radiation is several hundred times the ground level intensity and at 60000 feet a factor three higher again.

The penetration of these galactic cosmic rays into the vicinity of the earth is influenced by conditions on the sun, which emits a continuous wind of ionised gas, or plasma, to form a bubble of gas extending beyond the solar system. This solar wind carries out magnetic field lines from the sun and the strength of the wind and geometry of the magnetic field influence the levels of cosmic rays. There is an eleven year cycle in solar activity and the last solar minimum was in late 1996 at which time cosmic rays had easier access and were at their most intense. For example, in a Shuttle mission which landed on 24 May 1997, close to solar minimum, our Cosmic Radiation Effects experiment showed levels at high latitude which were 2.5 times higher than during our first flight in September 1991, which was close to solar maximum. In the years around solar maximum the sun is an additional sporadic source of lower energy particles accelerated during certain solar flares. These particles are less penetrating and only a few events in each cycle can reach aircraft altitudes or ground level. Such events typically last for a few days.

## 2 Single Event Effects

### 2.1 Direct Ionisation

The primary particles are very energetic and are highly ionising, which means that they strip electrons from atoms in their path and hence generate charge. The rate of charge deposition per unit path length is proportional to the square of the atomic number of the cosmic ray and so the heavier species can deposit enough charge in a small volume of silicon to change the state of a memory cell, a one becoming a zero and vice versa. Thus memories can become corrupted and this could lead to erroneous commands. Such soft errors are referred to as *single event upsets* (SEU). Sometimes a single particle can upset more than one bit to give what are called multiple bit upsets (MBU). Certain devices could be triggered into a state of high current drain, leading to burn-out and hardware failure; such effects are termed *single event latch-up* or *single event burn-out*. In other devices localised dielectric breakdown and rupture can occur (*single event gate rupture* and *single event dielectric failure*). These deleterious interactions of individual particles are referred to as *single event effects* (SEE) to distinguish them from the cumulative effects of ionising radiation (total dose effects) or lattice displacements (damage effects). For avionics SEE are the main radiation concern but total dose can be of significance for aircrew (although the latter is in fact an accumulation of SEE in tissue).

The severity of an environment is usually expressed as an integral linear energy transfer spectrum which gives the flux (fluence rate) of particles depositing more than certain amount of energy (and hence charge) per unit pathlength of material. Energy deposited per unit pathlength is referred to as linear energy transfer (LET) and the common units employed for radiation effects in electronics are MeV per g $cm^{-2}$ or MeV per mg $cm^{-2}$ (the product of density and pathlength). These units are readily converted to those used in radiological protection (e.g. to convert from MeV per g $cm^{-2}$ to J $m^{-1}$ simply multiply by $1.602 \times 10^{-11}$ and by the density in g $cm^{-3}$ ). Devices are characterised in terms of a cross-section (effective area presented to the beam for a SEE to occur) which is a function of LET. For each device there is a threshold LET below which SEE does not occur. As device sizes shrink these thresholds are moving to lower LET and rates are increasing. An example of LET spectra resulting from high latitude cosmic rays at solar minimum is given in Figure 1 for various shielding depths.

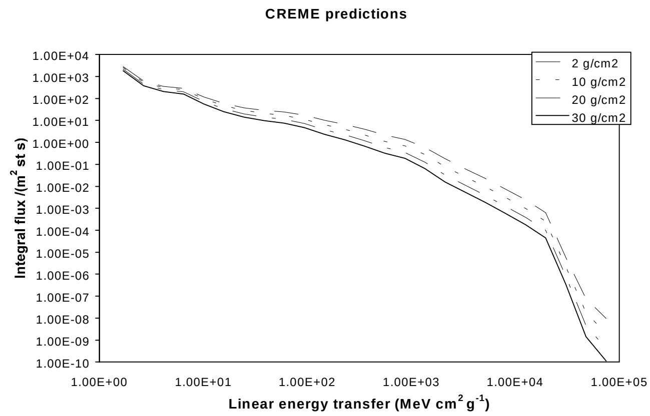


**FIGURE 1: Example integral LET spectra for interplanetary cosmic rays (no geomagnetic shielding) for various shielding depths in aluminium as predicted by the CREME code.**

Fortunately most primary cosmic rays are removed at normal aircraft altitudes and will have to be considered only for very high altitude situations. However the secondaries build-up and interact by the mechanism discussed below.

## 2.2 Nuclear Interactions

In addition to directly ionising interactions with electrons, particles may interact with atomic nuclei thus imparting a certain recoil energy and generating secondary particles. Both the recoiling nucleus and secondary charged particles are highly ionising so that if such a reaction occurs in, or adjacent to, a device depletion region a SEE may result. Collisions with nuclei are less probable than collisions with orbital electrons but when the fluxes of lightly ionising protons or indirectly ionising neutrons are intense this mechanism can dominate. This occurs in the earth's inner radiation belt where there are intense fluxes of energetic protons. It can also occur in the atmosphere where there is a build-up of significant fluxes of secondary neutrons. This mechanism is thought to be the dominant SEE hazard for current and near future avionics at most altitudes.

## 2.3 Radiobiological Effects

The same mechanisms that give large local energy depositions in device depletion regions also lead to localised ionisation in human cells where they can lead to DNA rupture. This is illustrated in Figure 2. If there are double-strand breaks which are not repaired, there is the possibility of producing cancers. Probabilities are related both to the ionising energy deposited per unit mass (ie dose in J/kg or grays) and to the density of ionisation as measured by LET. This is approximated by multiplying the dose by a *Quality Factor*, which is a function of LET, to give *the Dose Equivalent (in Sieverts)*. The Quality Factor is unity for lightly ionising particles, such as electrons and photons, but can be as large as 20 for heavy ions and fast neutrons.

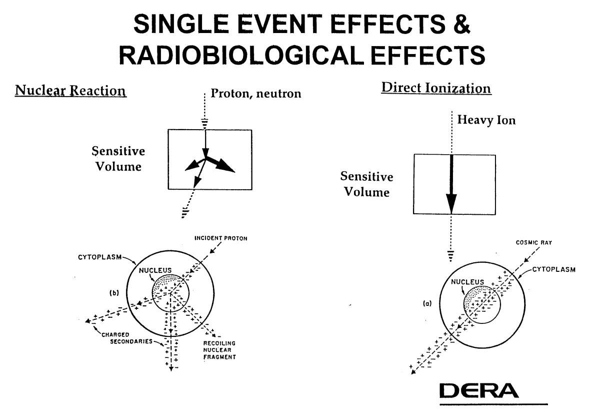


**FIGURE 2: Localised ionising events are common to single event effects in electronics and to cell damage.**

Increasing awareness of health risks has led to the European Union Council Directive 96/29/EURATOM, which took effect in May 2000. Article 42 demands that aircraft operators must take account of exposure of air crew who are liable to be exposed to more than 1 mSv (milliSievert) per year. Exposure must be assessed and reduced by rostering where appropriate and workers must be educated on the health risks. Pregnant women must not be exposed to more than 1mSv during pregnancy and crew exceeding 6 mSv per year must be carefully monitored and given health checks.

For aircraft flying above 49000 feet, where there is a significant probability of increased dose rates resulting from solar particle events, Air Navigation Orders demand that an active warning monitor should be carried.

There is clearly much commonality between health effects and electronic effects and both communities should share environment models and dosimetry calculations. Development of common monitors would also be sensible.

## 3 Experience Of The Space Industry

There is a strong body of evidence from the space business of errors, computer crashes and even hardware failure resulting from radiation. Such phenomena were first predicted in 1962 but computer technology did not become sensitive until 1975, since when increasing numbers of anomalies have been logged. Papers on such phenomena have formed an ever increasing part of the IEEE Nuclear and Space Radiation Effects Conference held every year in July with refereed papers published in the IEEE Transactions on Nuclear Science in December. In Europe the RADECS conference is held every two years and many papers on SEE are given. In recent years there have been an increasing number of papers on avionics and even ground-level systems at both these conferences.

A classic example of cosmic-ray induced upsets was experienced by the NASA/DoD Tracking and Data relay Satellite (TDRS-1) which incorporated sensitive RAM (Random Access Memory) chips in the Attitude Control System. Upset rates varied from one per day at quiet times to several hundred per day during solar particle events[1] and meant that expensive ground control procedures had to be employed on what was intended to be a largely autonomous spacecraft.

A classic example of hardware failure occurred in the PRARE (Precision Ranging Experiment) instrument carried on the ERS-1 (European Remote Sensing Spacecraft). A latch-up induced failure occurred in the heart of the South Atlantic Anomaly (a region of intense proton radiation for low earth orbits off the coast of Brazil) after five days and lead to loss of the instrument. Subsequent analysis and ground testing proved this diagnosis[2].

Commercial, unhardened systems are particularly vulnerable. For example IBM ThinkPad computers on the MIR Space Station have shown upsets every nine hours[3], while other laptop computers on Space Shuttle have shown upset rates of one per hour[4].

The extent of the problem for Space Systems has led to the development of software models of environment and interactions as well as to the flight of environment monitors and electronic upset experiments to validate the techniques. Steady improvements in prediction have been made but it is all too possible to be out by an order of magnitude, for example due to inadequate allowance for shielding or for device variation[5].

At DERA we have participated in a number of collaborative flight experiments using the Cosmic Radiation Effects and Activation Monitor (CREAM), which is returned to earth for analysis, and the Cosmic Radiation Effects and Dosimetry Experiment (CREDO) from which data are returned by telemetry. The CREAM detector comprises a 10-cm$^2$ array of pin diodes in which the charge deposition spectra are determined by pulse-height analysis, complemented by passive detectors, such as activation foils and neutron bubble detectors. CREAM has flown on eleven Shuttle flights since 1991 and has shown the time variability of the cosmic rays, movements in the South Atlantic Anomaly and the complex influence of spacecraft shielding (some aspects are made worse by secondary particle build-up, as occurs in the atmosphere). The CREDO version has flown in orbits ranging from low earth orbit (800 km on the University of Surrey microsatellite, UoSAT-3), to the heart of the inner belt (2500 km on the Advanced Photovoltaics and Electronics Experiment Spacecraft), and to geostationary altitudes (35000 km on the DERA microsatellite, Space Technology Research Vehicle). The later versions have comprised a telescope arrangement to define particle arrival directions and directly measure LET. Good correlation has been seen with rates of upsets and single event burn-outs (this was an experiment in which the burn-out was detected and prevented) and comparison with model predictions has enabled some improvements to be made. A review of data up until 1995 has been given by Dyer at al. [6].

## 4 Evidence For SEE In Aircraft

### 4.1 Environment Measurements

A version of the CREAM detector made regular flights on board Concorde G-BOAB between November 1988 and December 1992. Results from 512 flights have been analysed of which 412 follow high latitude transAtlantic routes between London and either New York or Washington DC [7]. Thus some 1000 hours of observations have been made at altitudes in excess of 50000 feet and at low cut-off rigidity of less than 2 GV (cut-off rigidity is the momentum-to-charge ratio of a particle which can just penetrate the earth's magnetic field to arrive at a particular point) and these span a significant portion of solar cycle 22. Figure 3 shows the count rate in CREAM channel 1 (charge depositions of 19fC to 46fC, equivalent to a particle of LET 6.1 to 14.8 MeV cm$^2$ g$^{-1}$ incident normally) plotted as monthly averages for the ranges 54-55 kfeet and 1-2 GV. The rates show a clear anticorrelation with the solar cycle and track well with the neutron monitor at Climax Colorado (altitude 3.4 km, cut-off rigidity 2.96 GV).

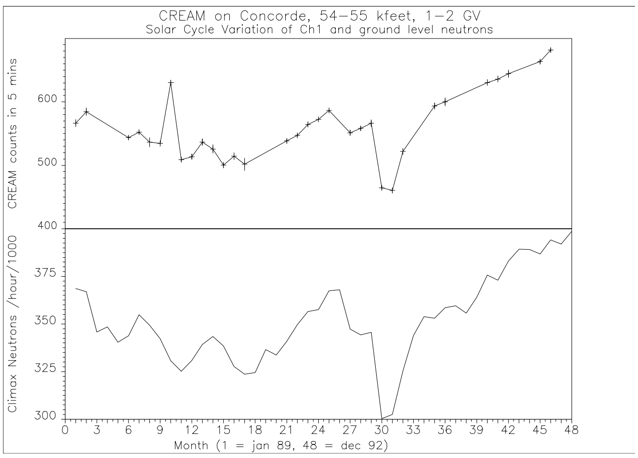


**FIGURE 3: Time variation of monthly averages of CREAM on Concorde at high latitude and high altitude showing solar modulation and solar particle enhancements during Sept-Oct 1989.**

The enhanced period during September and October 1989 comprised a number of energetic solar particle events observed by ground level, high latitude neutron monitors and the Concorde observations are summarised in Table 1 [8,9], which gives the enhancement factors compared with adjacent flights when only quiet-time cosmic rays were present.

**Table 1**
**Enhancement factors for CREAM on Concorde during solar particle events**

| Channel Number | 29-Sep 1406 - 1726 | 19-Oct 1420 - 1735 | 20-Oct 0859 - 1204 | 22-Oct 1814 - 2149 | 24-Oct 1805 - 2135 |
|---|---|---|---|---|---|
| 1 | 3.7 ± 0.02 | 1.6 ± 0.01 | 1.4 ± 0.01 | 1.5 ± 0.01 | 3.4 ± 0.01 |
| 2 | 4.9 ± 0.1 | 1.9 ± 0.04 | 1.6 ± 0.04 | 1.8 ± 0.04 | 4.5 ± 0.06 |
| 3 | 5.7 ± 0.1 | 2.1 ± 0.07 | 1.8 ± 0.07 | 1.9 ± 0.07 | 5.2 ± 0.1 |
| 4 | 5.9 ± 0.2 | 2.0 ± 0.1 | 1.8 ± 0.1 | 2.0 ± 0.1 | 5.7 ± 0.2 |
| 5 | 5.6 ± 0.6 | 2.0 ± 0.3 | 2.0 ± 0.4 | 2.1 ± 0.3 | 4.9 ± 0.4 |
| 6 | 6.1 ± 1.5 | 3.0 ± 0.7 | 1.1 ± 0.8 | 1.0 ± 0.6 | 4.3 ± 1.1 |
| 7 | (17.4 ± 17.4) | - | (30.4 ± 30.4) | - | - |
| 8 | - | - | - | - | - |
| 9 | - | - | - | - | - |

More recently the CREAM detector has been operated on a Scandinavian Airlines Boeing 767 flying between Copenhagen and Seattle via Greenland, a route for which the cut-off rigidity is predominately less than 2 GV. Approximately 540 hours of data accumulated between May and August 1993 have been analysed and these are combined with Concorde data from late 1992 to give the altitude profiles of counts for channels 1 and 5 in Figures 4 and 5 respectively. Channel 5 corresponds to charge depositions of 0.61 to 1.45 pC (LET from 191 to 456 MeV cm$^2$ g$^{-1}$). A variety of radiation transport codes have been applied to determine the contributions of various components and interaction processes.

The AIRPROP code of Tsao et al[10] predicts the contribution of cosmic-ray heavy ions and the energetic secondary ions into which they fragment by collisions with air nuclei. It can be seen from Figures 4 and 5 that these directly ionising species are not the major contribution. Figure 5 includes predictions from the Integrated Radiation Transport Suite (IRTS) operated at DERA in which the nuclear reactions of atmospheric secondary neutrons in the silicon diodes are modelled (curve labelled LHI + IMDC; the light heavy ion code[11] models nuclear interactions and recoils using intranuclear cascade and evaporation codes, while the ion microdosimetry code models the local charge deposition of the products of the reaction). This neutron contribution dominates the channel 5 rate for altitudes of 30-40 kfeet but cosmic ray ions start to contribute at supersonic altitudes.

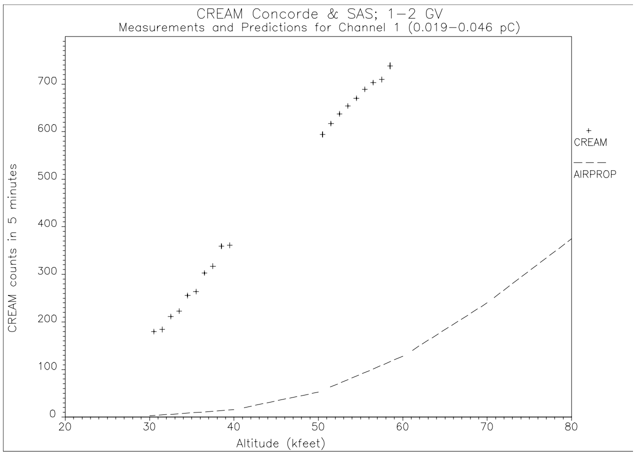


**FIGURE 4: CREAM channel 1 counts vs altitude from high latitude flights on SAS (30-40 kfeet) and Concorde (50-58 kfeet). AIRPROP calculation shows cosmic ray ions are a minor contribution.**

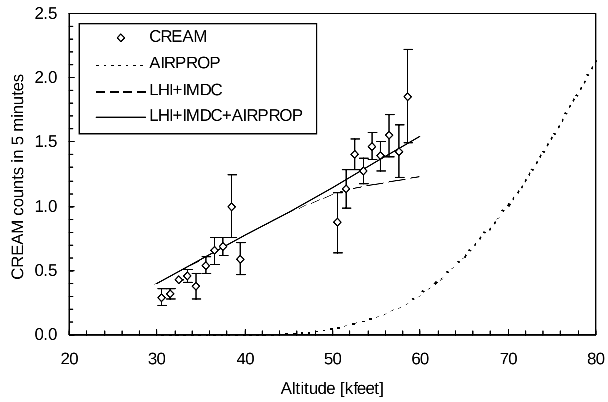


**FIGURE 5: As for Figure 4 but for channel 5 and with the addition of the predicted contribution from neutron interactions made using radiation transport & microdosimetry codes (LHI+IMDC). Neutrons dominate at 30-40kfeet but cosmic ray ions start to contribute at supersonic altitudes.**

The spectrum of charge depositions at 30 to 31 kfeet is given in Figure 6, together with predictions of various contributions. The burst generation rate (BGR) method [12] models nuclear recoils from both elastic and inelastic neutron interactions while LHI alone models recoils from inelastic interactions. It can be seen that full treatment of reaction products using IMDC is required to give a good fit at the high end. Neutron interactions are clearly a major contribution except at low charge depositions where direct ionisation by atmospheric secondary electrons and muons contribute. The work of Normand et al [13] scales results from a ground irradiation of diodes using a spallation neutron source to show the importance of neutron interactions. These results clearly show that there exists an atmospheric environment which can produce SEE and that models can give a good description of the charge depositions as long as all the particles and interaction processes are taken into account.

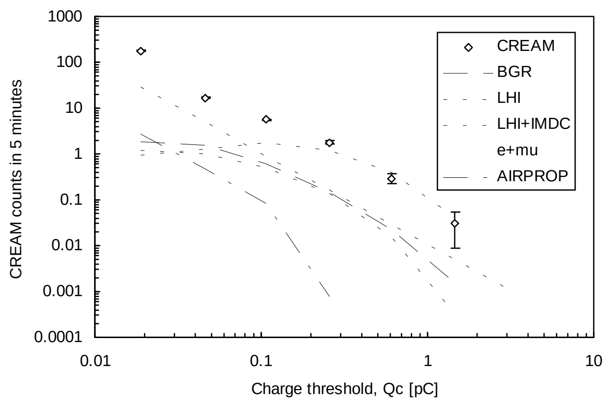


**FIGURE 6: The spectrum of charge depositions from CREAM at 30-31 kfeet compared with predictions. It can be concluded that neutrons dominate at high values while electrons & muons contribute at the low end.**

## 4.2 Published Instances of Upsets

There are published instances in refereed journals where hardware has shown unexpected error rates and where subsequent analysis and use of ground irradiation testing has confirmed cosmic rays to be the source of the problem. Some investigators have specifically flown large solid-state memories and recorded the error rates. In addition there are many anecdotal stories of upsets and non-repeatable errors. More of these require follow-up analysis. There are no published instances of burn-out but these have been observed in space systems.

In an unintentional experiment, reported by Olsen et al [14], a commercial computer used to calculate aircraft take-off performance was temporarily withdrawn from service when bit-errors were found to accumulate in 256 Kbit CMOS SRAMs (Complementary Metal Oxide Silicon Static RAMs of part number D43256 A6U-15LL). Following ground irradiations by neutrons, the observed upset rate of $4.8\times10^{-8}$ upsets per bit-day at conventional altitudes (35000 feet) was found to be explicable in terms of SEUs induced by atmospheric neutrons.

In an intentional investigation of single event upsets in avionics, Taber and Normand [15] have flown a large quantity of CMOS SRAM devices at conventional altitudes on a Boeing E-3/AWACS aircraft and at high altitudes (65000 feet) on a NASA ER-2 aircraft. Upset rates in the IMS1601 64Kx1 SRAM varied between $1.2\times10^{-7}$ per bit-day at 30000 feet and 40$^{o}$ latitude to $5.4\times10^{-7}$ at high altitudes and latitudes. Reasonable agreement was obtained with predictions based on neutron fluxes.

## 4.3 Ground Level Events

The importance of soft error production by the radioactive contaminants, uranium and thorium, in chip packaging was recognised by May and Woods[16] in 1975. Despite action to remove this source of contamination, soft errors still occur at a rate of about $10^{-12}$ per bit-hour in modern RAMs at sea level. Data have been obtained from major computer installations and from biomedical devices such as implantable cardiac defibrillators. Recently released information from IBM[17] and a review by Normand [18] have shown these rates to be consistent with the levels of secondary neutrons at sea level. Recently ground-level, neutron-induced burn-outs in high power electronics have been identified.

## 4.4 Ground Testing and Extrapolation

It is possible to use ground spallation neutron sources which closely mimic the atmospheric neutron spectrum to test devices and then scale rates to flight levels [13]. Attempts to extrapolate technology trends and memory usage in US military avionics have been made by Kerness and Taber [19] and results suggest that by the year 2000, 100MB SRAM systems will be in use and experiencing upsets every 2 hours at 40000 feet, while for the anticipated 1GB DRAM (Dynamic RAM) systems the rate could be one every 3 to 14 hours. Other unpublished studies have shown that hard failures from single events could dominate reliability estimates.

## 5 Mitigation Strategies

For future systems there is likely to be increasing reliance on faster, “better” computers and large solid-state memories using smaller devices operated at lower voltages. This trend is likely to be accompanied by the use of higher flight altitudes so that SEE are likely to become increasingly significant. The influence of cosmic rays will have to be properly considered in the assessment of reliability and cost-effective mitigating strategies adopted.

In considering hardening possibilities it must be borne in mind that physical shielding is useless as the particles are so energetic. In fact it usually leads to local increases in radiation. In addition radiation-hardened components are becoming less available due to the decreasing influence of the defence industry in the global market.

For hard failures, devices will have to be screened against the possibility of latch-up and burn-out resulting from radiation, while for soft errors increasing use will have to be made of error detection and correction codes; e.g. using an overhead of 4 bits to protect 8 bits. However adequate account must be taken of multiple-bit upsets where physically adjacent bits can be upset by the same particle. For safety critical features there must be adequate use of redundancy and back-up units. For example the majority voting of three or more computers can be used; five are in fact used on the Space Shuttle.

## 6 Research Programme

There is a need for an ongoing research programme to implement these techniques in a cost-effective, whilst safe manner. A Cosmic Radiation Effects Working Group has been formed as a subgroup of the European Aircraft EMC Research Group. This includes the authors’ organisations amongst others and has the aim of feeding twenty years of space experience into the avionics industry. A research programme has been commenced and is benefiting from military, civil and international collaboration, as well as collaboration with the air crew dosimetry community. Key elements are as follows:

- Development of models of the atmospheric radiation environment and its interaction with devices to enable accurate prediction of SEE rates;

- Development of cost-effective ground-testing and screening techniques using irradiation facilities and laboratory techniques such as lasers;

- Validation and improvement of models by comparison with flight data from environment monitors and SEE experiments obtained over a wide range of latitudes and altitudes;

- Investigation of cost-effective monitoring equipment for both SEE and air crew dosimetry;

- Creation of a database of observed anomalies with follow-up analyses pursued wherever possible to ascertain whether radiation is the cause.

Some progress is being made in certain of these areas. Neutron irradiation facilities at University Catholique, Louvain-la-Neuve, Belgium and at the Theodore Svedberg Laboratory, Uppsala, Sweden have been used to characterise upsets in Hitachi, Toshiba and Samsung 4Mbit SRAMs. Comparative testing has also been performed on ion beams and a laser test facility at Matra BAe Dynamics, Filton. Measurements of neutron susceptiblity (cross-sections) as a function of energy are given Figure 7. It can be seen that there can be order of magnitude differences in susceptibility between different versions and manufacturers.

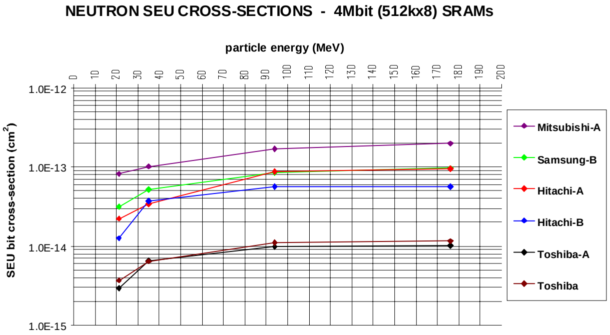


**FIGURE 7: Measured upset cross-sections as a function of neutron energy for a number of 4- Mbit SRAMs. Order of decreasing susceptibility is same as the order in the legend box.**

Upset rates per second at normal cruising altitudes (35000 feet) are approximately equal to the plateau cross-section values. Further details are available in references [20, 21]. Relating these results requires calculations of particle energy depositions and to this end a microdosimetry code has been developed. This is extensively discussed in reference [22] together with applications to a range of devices. Considerable success has been achieved in fitting results on both single and multiple-bit upsets in devices ranging from 10 µm to sub micron.

It is hoped that through this research programme the experience gained in the space industry can be used to avoid future problems in avionics as device technology rapidly evolves.

## Acknowledgements

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