TECHNICAL SPECIFICATION

IEC TS 62396-1

First edition
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Process management for avionics – Atmospheric radiation effects –

Part 1:
Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

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CONTENTS

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PROCESS MANAGEMENT FOR AVIONICS –
ATMOSPHERIC RADIATION EFFECTS –

Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

FOREWORD

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- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 62396-1, which is a technical specification, has been prepared by IEC technical committee 107: Process management for avionics.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
107/41/DTS	107/46/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

IEC 62396, as currently conceived, consists of the following parts, under the general title *Process management for avionics – Atmospheric radiation effects:*

Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

Part 2: Guidelines for single event effects testing for avionics systems[1]

Part 3: Guidelines to optimize avionics system design to reduce single event effects rates[1]

Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects[1]

Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems[1]

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

[1] Under consideration.

INTRODUCTION

This industry-wide technical specification informs avionics systems designers, electronic equipment, component manufacturers and their customers of the kind of ionising radiation environment that their devices will be subjected to in aircraft, the potential effects this radiation environment can have on those devices, and some general approaches for dealing with these effects.

The same atmospheric radiation (neutrons) that is responsible for the radiation exposure that crew and passengers acquire while flying is also responsible for causing the Single Event Effects (SEE) in the avionics electronic equipment. There has been much work carried out over the last few years related to the radiation exposure of aircraft passengers and crew. A standardised industry approach on the effect of the atmospheric neutrons on electronics should be viewed as consistent with and an extension of the on-going activities related to the radiation exposure of aircraft passengers and crew.

Atmospheric radiation effects are one factor that could contribute to equipment hard and soft fault rates. From a system safety perspective, using derived fault rate values, the existing methodology described in ARP4754 (accommodation of hard and soft fault rates in general) will also accommodate atmospheric radiation effect rates.

In addition, this technical specification is related to the JEDEC Standard JESD89, which relates to soft errors in electronics by atmospheric radiation at ground level (at altitudes less than 10 000 feet (3 040 m)).

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

1 Scope and object

This Technical Specification is intended to provide guidance on Atmospheric Radiation effects on Avionics electronics used in aircraft operating at altitudes up to 60 000 feet (18,3 km). It defines the radiation environment, the effects of that environment on electronics and provides design considerations for the accommodation of those effects within avionics systems.

This Technical Specification is intended to help aerospace equipment manufacturers and designers to standardise their approach to Single Event Effects in Avionics by providing guidance, leading to a standard methodology.

Details of the radiation environment are provided together with identification of potential problems caused as a result of the atmospheric radiation received. Appropriate methods are given for quantifying Single Event Effect (SEE) rates in electronic components. The overall system safety methodology should be expanded to accommodate the Single Event Effects rates and to demonstrate the suitability of the electronics for the application at the component and system level.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62239, *Process management for avionics – Preparation of an electronic components management plan*

3 Terms and definitions

For the purpose of this document, the following terms and definitions apply.

NOTE Users of this technical specification may use alternative definitions consistent with convention within their companies.

3.1
aerospace recommended practice
these documents relating to avionics are published by the Society of Automotive Engineers Inc

3.2
avionics equipment environment
is, for aeronautical equipment, the applicable environmental conditions (as described per the equipment specification) that the equipment shall be able to withstand without loss or degradation in equipment performance during all of its manufacturing cycle and maintenance life (the length of which is defined by the equipment manufacturer in conjunction with customers)

3.3
capable
term used to indicate that a component can be used successfully in the intended application

3.4
certified
indicates assessment and compliance to an applicable third party standard and maintenance of a certificate and registration (i.e. JAN, IECQ- CECC)

3.5
characterisation
process of testing a sample of components to determine the key electrical parameter values that can be expected of all produced components of the type tested

3.6
component application
process that assures that the component meets the design requirements of the equipment in which it is used

3.7
component manufacturer
organisation responsible for the component specification and its production

3.8
critical charge
smallest charge that will cause a SEE if injected or deposited in the sensitive volume

NOTE Units: picoCoulomb (pC). For many devices, this is now measured in femtoCoulombs (fC) rather than pC.

3.9
cross section (σ)
in radiation terms for proton and neutron interactions, this is combination of sensitive area and probability of an interaction depositing the critical charge for a SEE.

The cross section may be calculated using the following formula:

$$\sigma = number\ of\ errors/particle\ fluence$$

NOTE The units for cross section are cm^2 per device or per bit.

3.10
electron
elementary particle having a mass of approximately 1/1 840 atomic mass units, and negative charge of $1{,}602 \times 10^{-19}$ C

3.11
Electronic Components Management Plan
ECMP
equipment manufacturer's document that defines the processes and practices for applying components to an equipment or range of equipment. Generally, it addresses all relevant aspects of controlling components during system design, development, production, and post-production support

3.12
electronic components
electrical or electronic devices that are not subject to disassembly without destruction or impairment of design use. They are sometimes called electronic parts, or piece parts

NOTE Examples are resistors, capacitors, diodes, integrated circuits, hybrids, application specific integrated circuits, wound components and relays

3.13
electronic equipment
item produced by the equipment manufacturer, which incorporates electronic components

NOTE Examples are end items, sub-assemblies, line-replaceable units and shop-replaceable units.

3.14
Electronic Flight Instrumentation System
EFIS
example of an avionics electronic system requiring system development assurance level A type II and for which the pilot will be within the loop through pilot/system information exchange

3.15
expert
has demonstrated competence to apply knowledge and skill to the specific subject

3.16
firm fault
term used at the aircraft function level. It is a failure that cannot be reset other than by rebooting the system or by cycling the power to the relevant functional element. Such a fault could impact the value for the MTBF of the LRU and provide no fault found during subsequent test

3.17
Fly By Wire
FBW
example of avionics electronic system requiring system development assurance level A type I and for which the pilot will not be within the aircraft stability control loop

3.18
Functional Hazard Analysis
FHA
assessment of all hazards against a set of defined hazard classes

3.19
GeV
radiation particle energy giga electron volts (thousand million electron Volts)

NOTE The SI equivalent energy is 160,2 picoJoule.

3.20
gray
Gy
SI unit of ionising radiation dose and is the energy deposited as ionisation and excitation (J) per unit mass (kg)

NOTE Related units centigray (cGy) and rad. 1 cGy is equal to 1 rad.

3.21
hard error
permanent or semi-permanent damage of a cell by atmospheric radiation that is not recoverable even by cycling the power off and on

3.22
hard fault
term used at the aircraft function level. It refers to the permanent failure of a component within an LRU. A hard fault results in the removal of the LRU affected and the replacement of the permanently damaged component before a system/system architecture can be restored to full functionality. Such a fault could impact the value for the MTBF of the LRU repaired

3.23
heavy ions
positively charged nuclei of the elements other than hydrogen

3.24
in-the-loop
test methodology where an LRU is placed within a radiation beam that provides a simulation of the atmospheric neutron environment and where the inputs to the LRU would be from an electronic fixture external to the beam to enable a closed loop system

NOTE The electronic fixture would contain a host computer for the aircraft simulation model. The electronic fixture would also contain appropriate signal conditioning for compatibility with the LRU. In the case of an automatic control function, the outputs from the LRU could be, in turn, sent to an actuation means or directly to the host computer. The host computer would automatically close a stability loop (as in the case of a fly-by-wire control system). In the case of a navigation function, the outputs from the LRU could be sent to a display system where the pilot could then close the navigation loop.

3.25
Integrated Modular Avionics
IMA
implement aircraft functions in a multitask computing environment where the computations for each specific system implementing a particular function are confined to a partition that is executed by a common computing resource (a single digital electronic circuit)

3.26
latch-up
triggering of a parasitic pnpn circuit in bulk CMOS, resulting in a state where the parasitic latched current exceeds the holding current, this state is maintained while power is applied

3.27
Linear Energy Transfer
LET
energy deposited per unit path length in a semiconductor along the path of the radiation

NOTE Units: MeV cm^2/mg.

3.28
Linear Energy Transfer threshold
LETth
for a given component is the minimum LET to cause an effect at a particle fluence of 1×10^7 ions/cm^2

3.29
Line Replaceable Unit
LRU
piece of avionics electronic equipment that may be replaced during the maintenance cycle of the system

3.30
may
indicates a course of action that is permissible within the limits of this document

3.31
MeV
radiation particle energy Mega electron volts (million electron Volts)

NOTE The SI equivalent energy is 160,2 femtojoule.

3.32
Mean Time Between Failure
MTBF
is a measure of reliability requirements and is the mean time between failure of equipment or a system in service

3.33
Mean Time Between Unscheduled Removals
MTBUR
is a measure of reliability requirements and is the mean time between unscheduled removal of equipment or a system in service

3.34
Multiple Bit Upset
MBU
occurs when the energy deposited in the silicon of an electronic component by a single ionising particle causes upset to more than one bit

3.35
neutron
elementary particle with atomic mass number of one and carries no charge. It is a constituent of every atomic nucleus except hydrogen

3.36
particle fluence
is for a unidirectional beam of particles the number crossing unit surface at right angles to beam. For isotropic flux, this is number entering sphere of unit cross-sectional area

NOTE Units: particles/cm^2.

3.37
particle flux
fluence rate per unit time

NOTE Units: particles/cm^2 s.

3.38
pion or pi-meson
sub atomic particle. The charge possibilities are (+1, –1, 0) and they are produced by energetic nuclear interactions

3.39
Preliminary System Safety Assessment
PSSA
evaluation of the planned architecture to determine the reasonableness of the architecture to meet the system safety requirements

3.40
proton
elementary particle with atomic mass number of one and positive electric charge. It is a constituent of all atomic nuclei

3.41
risk
measure of the potential inability to achieve overall program objectives within defined cost, schedule, and technical constraints

3.42
Single Event Burn Out
SEB
occurs when a powered electronic component or part thereof is burnt out as a result of the energy absorption triggered by an individual radiation event

3.43
Single Event Effect
SEE
response of a component caused by the impact of a single particle (for example galactic cosmic rays, solar energetic particles, energetic neutrons and protons)

NOTE The range of responses can include both non-destructive (for example upset) and destructive (for example latch-up or gate rupture) phenomena.

3.44
Single Event Functional Interrupt
SEFI
upset in a usually complex device, for example, a microprocessor, such that a control path is corrupted, leading the part to cease to function properly

NOTE This effect has sometimes been referred to as lockup, indicating that sometimes the part can be put into a "frozen" state (see 6.2.6).

3.45
Single Event Gate Rupture
SEGR
occurs in the gate of a powered insulated gate component when the radiation charge absorbed by the device is sufficient to cause gate rupture, which is destructive

3.46
Single Event Latch Up
SEL
occurs in a four layer semiconductor device when the radiation absorbed by the device is sufficient to cause a node within the powered semiconductor device to be held in a fixed state whatever input is applied until the device is de-powered, such latch up may be destructive or non-destructive

3.47
Single Event Transient
SET
spurious signal or voltage, induced by the deposition of charge by a single particle that can propagate through the circuit path during one clock cycle (see 6.2.4)

3.48
Single Event Upset
SEU
occurs in a semiconductor device when the radiation absorbed by the device is sufficient to change a cell's logic state

NOTE After a new write cycle, the original state can be recovered.

3.49
Single Hard Error
SHE
single event induced hard error
occurs when in a single event the radiation absorbed by the device is sufficient to cause permanent stuck-bit in the device, and a hard error within the equipment

3.50
Single word Multiple-bit Upset
SMU
occurs when the energy deposited in the silicon by a single ionising particle causes upset to more than one bit in a single memory word

3.51
soft error
also known as a single event upset and is the change of state of a latched logic state from one to zero or vice-versa, it is non-destructive and can be rewritten or reset

3.52
soft fault
is a term used at the aircraft function level that refers to the characteristic of invalid digital logic cell(s) state changes within digital hardware electronic circuitry

NOTE It is a fault that does not involve replacement of a permanently damaged component within an LRU but it does involve restoring the logic cells to valid states before a system/system architecture can be restored to full functionality. Such a fault condition has been suspected in the "no fault found" syndrome for functions implemented with digital technology and it would probably impact the value for the MTBUR of the involved LRU. If a soft fault results in the mistaken replacement of a component within the LRU, the replacement could impact the value for the MTBF of the LRU repaired.

3.53
Solar Energetic Particle (SEP) events
during these periods there is enhancement of solar particles (protons, ions and some neutrons) caused by solar flare activity or coronal mass ejections

NOTE The enhancement can last from a few hours to several days. A small fraction has sufficiently energetic spectra to produce significantly enhanced secondary neutron fluxes in the atmosphere.

3.54
substitute component
component used as a replacement in equipment after the equipment design has been approved

NOTE In some contexts, the term “alternate component” is used to describe a substitute component that is “equal to or better than” the original component.

3.55
System Safety Assessment
SSA
performed to verify compliance with the safety requirements

3.56
system
collection of hardware and software elements that implement a specific aircraft function or set of aircraft functions

3.57
Total Ionising Dose
TID
cumulative radiation dose that goes into ionisation that is received by a device during a specified period of time

3.58
validation
method of confirmation of component radiation tolerance by the equipment manufacturer, when there is no in-service data from prior use or radiation data from a test laboratory

3.59
will
expresses a declaration of intent when used in the context of being compliant to this document

4 Abbreviations used in the document

AC	Advisory Circular
AIR	Atmospheric Ionizing Radiation
ARP	Aerospace Recommended Practices
ASIC	Application Specific Integrated Circuit
BIT	Built-In Test
BPSG	Borophosphosilicate glass
CECC	CENELEC Electronic Components Committee
CMOS	Complimentary Metal Oxide Semiconductor
COTS	Commercial Off The Shelf
D-D	Deuterium-Deuterium
DOE	Department Of Energy (USA)
DRAM	Dynamic Random Access Memory
DSP	Digital Signal Processor
D-T	Deuterium-Tritium
DTS	Draft Technical Specification
E	Energy
ECMP	Electronic Components Management Plan
EDAC	Error Detection And Correction
EFIS	Electronic Flight Instrumentation System
ESA	European Space Agency
eV	electron Volt
FBW	Fly-By-Wire
FHA	Functional Hazard Analysis
FPGA	Field Programmable Gate Array
GCR	Galactic Cosmic Rays
GeV	Giga electron Volt
GLE	Ground Level Event
GV	Giga Volt (Rigidity unit)
HW	Hardware
IBM	International Business Machines
ICE	Irradiation of Chip and Electronics
IECQ	IEC Quality Assessment System for Electronic Components
IEEE Trans. Nucl. Sci.	IEEE Transactions on Nuclear Science
IGBT	Insulated Gate Bipolar Transistor
IMA	Integrated Modular Avionics
IUCF	Indiana University Cyclotron Facility (USA)
JAN	Joint Army Navy (USA Department of Defence)
JEDEC	JEDEC Solid State Technology Association
JESD	JEDEC Standard
JPL	Jet Propulsion Laboratory
LET	Linear Energy Transfer
LETth	Linear Energy Transfer threshold
LRU	Line Replaceable Unit

MBU	Multiple Bit Upset
MeV	Mega electron Volt
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MTBF	Mean Time Between Failure
MTBUR	Mean Time Between Unscheduled Removals
NASA	National Aeronautical and Space Agency
PCN	Product Change Notification
PSI	Paul Scherrer Institute (Switzerland)
PSSA	Preliminary System Safety Assessment
PWM	Pulse Width Modulator
RADECS	RADiations, Effets sur les Composants et Systèmes.
RAM	Random Access Memory
RVC	Result of Voting (IEC)
SAFETI	Systems and Airframe Failure Emulation Testing and Integration
SC	Stacked Capacitance
SDRAM	Synchronous Dynamic Random Access Memory
SEB	Single Event Burn-out
SECDED	Single Event Correction Double Event Detection
SEDR	Single Event Dielectric Rupture
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEGR	Single Event gate Rupture
SEL	Single Event Latch
SEP	Solar Energetic Particles
SER	Soft Error Rate
SET	Single Event Transient
SEU	Single Event Upset
SHE	Single event induced Hard Error
SMU	Single word Multiple-bit Upset
SRAM	Static Random Access Memory
SSA	System Safety Assessment
SSEEM	Segmented Secondary Electron Emission Monitor
SW	Software
TIC	Trench Internal Capacitance
TID	Total Ionizing Dose
TRIUMF	Tri-University Meson Facility (Canada)
TSL	Theodor Svedberg Laboratoriet (Sweden)
WNR	Weapons Nuclear Research (Los Alamos USA)

5 Radiation environment of the atmosphere

5.1 Radiation generation

The atmosphere is penetrated by a flux of various charged and neutral particles that in combination create a complex ionising radiation environment. These particles are created by the interaction of the continuous stream of primary cosmic ray particles with the atoms in the atmosphere (mainly nitrogen and oxygen), and so are called secondary cosmic rays. The primary cosmic rays are usually referred to as the galactic cosmic rays (GCR), indicating that their origins are beyond that of the solar system.

The galactic cosmic radiation is composed of atomic nuclei that have been completely ionised (fully stripped of their electrons) and subsequently accelerated to very high energies. Galactic cosmic rays consist of about 83 % protons, 16 % alpha particles and <2 % heavy ions (particles with atomic number Z > 2). As the primary cosmic rays, mainly very high-energy protons, bombard the atmosphere, they create a cascade of secondary, tertiary, etc. particles from their interactions with the atoms of the atmosphere. Thus, for each primary cosmic ray entering, many more secondary particles are created. At a very approximate level, the flux of incoming primary cosmic rays at the top of the atmosphere is 3 particle/cm^2·s, and at aircraft altitudes, the flux of all secondary particles is about 10 particle/cm^2·s. The density of the lowest portion of atmosphere is so high, that most of the flux of particles is absorbed, so that at sea level the nominal flux of secondary particles is less than 0,1 particle/cm^2·s.

The flux of secondary particles is not uniform around the earth due to the effect of the earth's magnetic field that is at right angles to the particle direction at the equator. Particles cross field lines at right angles at the equator and are bent away while at the poles they travel parallel to the field and are not deflected. As a result the primary cosmic rays are able to penetrate into the atmosphere more readily near the magnetic poles and they interact with the atoms in the atmosphere creating larger numbers of cascade particles.

5.2 Effect of secondary particles on avionics

Some of the secondary particles can interact with microelectronic devices within aircraft avionics systems and cause single event effects (SEE) in the devices. These secondary particles deposit enough charge through the recoils they create within a sensitive portion of a device to result in a malfunction of the device. It has been found that neutrons, protons and pions are the main particles that can cause these effects.

5.3 Atmospheric neutrons

5.3.1 General

Neutrons are the secondary cosmic ray particles that have been shown to be mainly responsible for causing single event upsets (SEUs) in memories and other devices on aircraft since the early 1990s. This identification of the neutrons as the main cause of the SEUs was based on several different kinds of correlations:

1) the variations of the upset rates against altitude and geographic latitude followed the variation of the neutron flux with altitude and latitude,

2) neutron induced SEU rates calculated using SEU cross sections measured in a laboratory and integrated with the neutron flux in the atmosphere agreed with measured in-flight SEU rates and

3) upset rates at ground level, due to secondary neutrons are proportional to rates at aircraft altitudes. For the neutrons, as well as all of the secondary particles within the atmosphere, the variation of the particle flux with three parameters is most important, (energy, altitude and latitude), for understanding the variation of the SEU rate.

5.3.2 Energy spectrum of atmospheric neutrons

The energy variation of the atmospheric neutrons is usually presented by plotting the differential flux (flux per unit energy interval) as a function of energy, which is often called the spectrum, see Figure 1. Monte Carlo generated spectra have produced the following fractions <1 MeV 0,53; 1 to 10 MeV 0,2; >10 MeV 0,27. The fits quoted below may give slightly different values. Measurements of the energy spectrum of the cosmic ray neutrons have been made since the 1950s using a variety of techniques. In Figure 1 we plot four neutron spectra at an altitude of approximately 40 000 feet (12,2 km). These include the original measurements made by Hess in 1959 (Ref. 1)[2], a calculation by Armstrong in 1973 (Ref. 2), a fit to measurements by Hewitt et al at NASA in 1977 (Ref. 3) and the recent DOE measurements by a fit to measurement by Goldhagen in an ER-2 aircraft during 1997 (Ref 4).

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2 This refers to the bibliography.

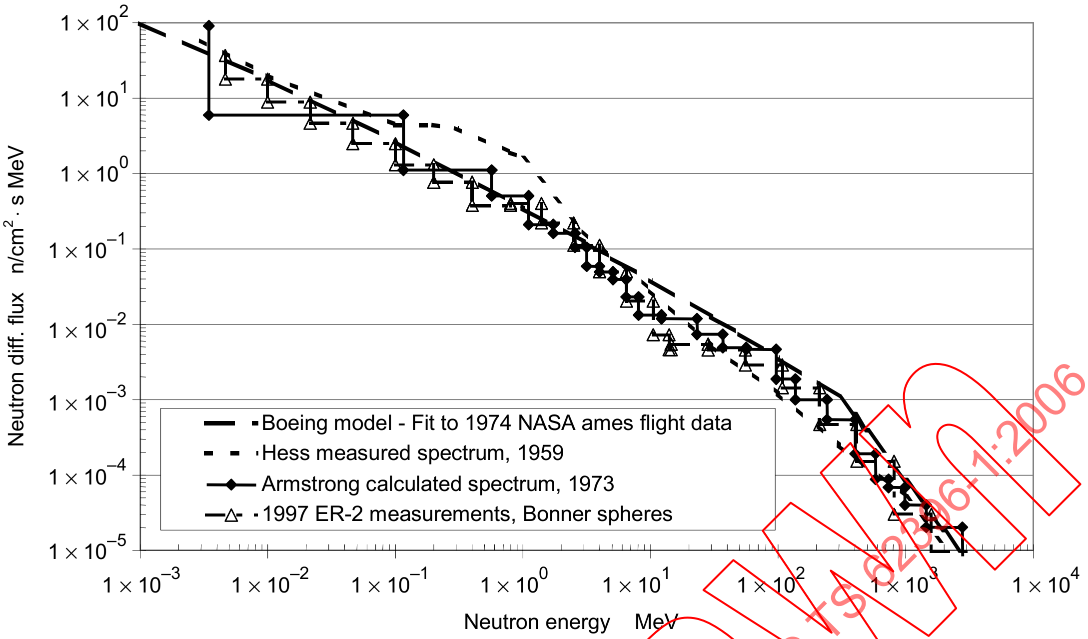

Figure 1 – Energy spectrum of atmospheric neutrons at 40 000 Feet (12 160 m), latitude 45 degrees

A fit to the NASA Ames data (Energy (E) up to 300 MeV), that had been used in the past has been modified for Energy > 300 MeV using the more recent measurements. The modified spectrum is given, with Energy in MeV, as

$$dN/dE = \begin{cases} 0{,}346E^{-0{,}922} \times \exp(-0{,}0152(\ln E)^2) & E < 300 \text{ MeV} \\ 340E^{-2{,}2} & E > 300 \text{ MeV} \end{cases} \quad \text{n/cm}^2\cdot\text{s}\cdot\text{MeV} \qquad (1)$$

It should be noted that when this differential flux is integrated for Energy > 10 MeV, the integrated neutron flux is ~5 600 n/cm^2 per hour, which can be rounded up to 6 000 n/cm^2 per hour. This nominal high energy neutron flux 6 000 n/cm^2 per hour at 40 000 feet (12,2 km) and geographic latitude 45° may be treated as a typical in flight envelope and scaled for different avionics applications (for example, for altitude variation per 5.3.3 and for latitude variation per 5.3.4). This flux of 6 000 n/cm^2 per hour is conservative by a factor of approximately 2 compared to the ER-2 measurements. At ground level the flux is approximately a factor of 300 lower than at 40 000 feet (12,2 km), thus on the ground, the flux for Energy > 10 MeV is 20 n/cm^2 per hour, (Ref 5) and this agrees with an independently derived calculation for New York City (Ref 6).

5.3.3 Altitude variation of atmospheric neutrons

The altitude variation of the atmospheric neutron derives from the competition between the various production and removal processes that affect how the neutrons and the initiating cosmic rays interact with the atmosphere. The result is a maximum in the flux at about 60 000 feet (18,3 km), called the Pfotzer maximum that can be seen in Figure 2. The Figure compares the altitude variation of the 1 to 10 MeV neutron flux as given by two models as a function of altitude. Of the two models, the simplified Boeing model was developed utilising two sets of 1 to 10 MeV neutron flux measurements from balloons, and is based on a latitude of 45°. (Refs. 7, 8). A much more rigorous approach was taken by NASA-Langley in developing a model that is currently called AIR (Ref. 9). It utilised measurements made on aircraft during the 1960s and 70s, and developed a model that gives the 1 to 10 MeV neutron flux as a function of three parameters, the atmospheric depth (g/cm^2), vertical rigidity cut off (GV) and solar weather conditions.

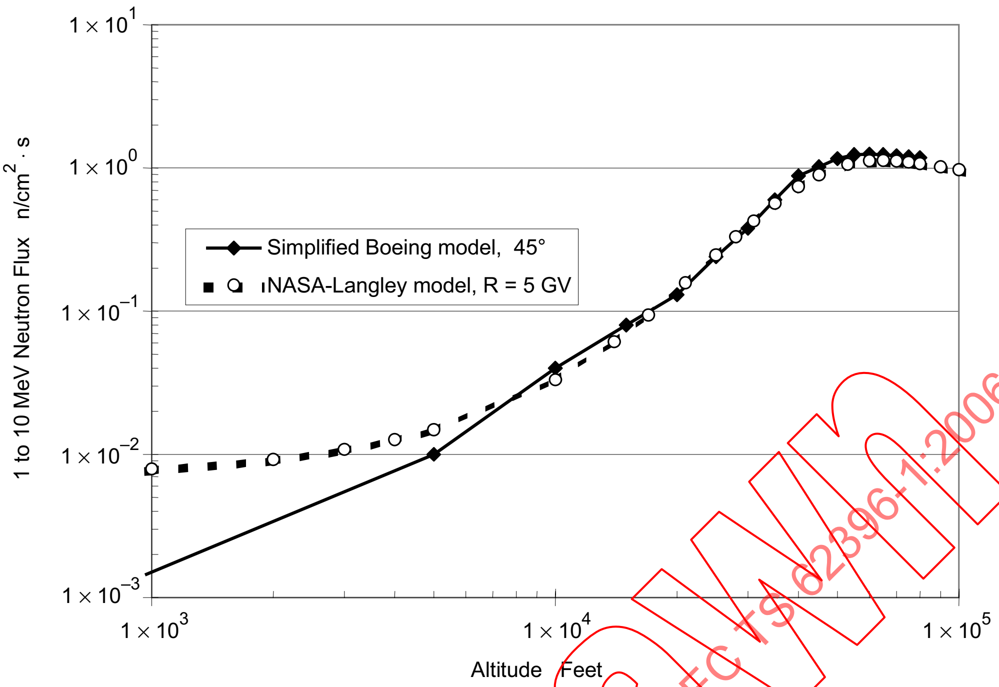

Figure 2 – Variation of the atmospheric neutron flux with altitude (see Annex D)

A tabular description of the variation of atmospheric neutron flux with altitude and also with latitude as given by the Boeing model is provided in Annex D to enable calculation of neutron flux at various flight locations.

5.3.4 Latitude variation of atmospheric neutrons

The latitude variation is expressed in terms of the vertical rigidity cut off, R, in units of GV. The rigidity cut offs indicate the required rigidity (essentially the particle momentum divided by its charge) of primary cosmic ray particles needed to penetrate to a given location above the atmosphere. At the equator, where the magnetic field is at right angles to particle direction, it requires particles with the highest rigidity, R ~ 15 GV, to penetrate to this region, and where it is parallel to the particle direction, near the poles, particles with R <1 GV can reach. The geographical distribution of the vertical rigidity cut offs around the world at an altitude of 20 km (Ref. 10) is shown in Figure 3.

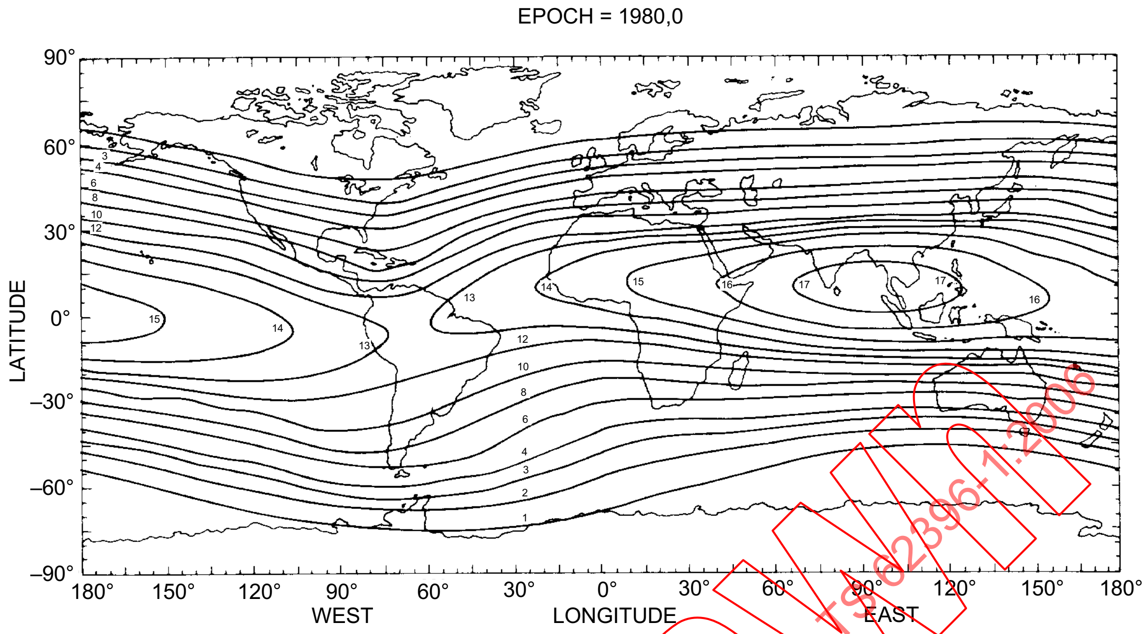

Figure 3 – Distribution of vertical rigidity cut offs around the world

Two models are also available for the variation of the 1 to 10 MeV neutron flux as a function of latitude, a simplified Boeing model and the NASA-Langley AIR model. The simplified Boeing model is based on measurements made in aircraft during the 1960s, in particular pole-pole latitude surveys aboard a Boeing 707 aircraft (Ref. 11). The initial data was given as the neutron flux as a function of the vertical rigidity cut off. Based on the observation in Figure 3 that the rigidity cut offs exhibit their main variation with latitude, the vertical cut offs were averaged over geographical longitude for each 5° in geographical latitude. These contours are evolving with time due to the Earth's changing geomagnetic field. This allowed the measured 1 to 10 MeV neutron flux, originally given as a function of rigidity cut off, to be converted to a curve of the 1 to 10 MeV neutron flux as a function of latitude. This is shown in Figure 4, along with a curve from the more rigorous NASA-Langley model, which was also converted to latitude variation through use of the curve of averaged vertical rigidity cut off as a function of geographical latitude.

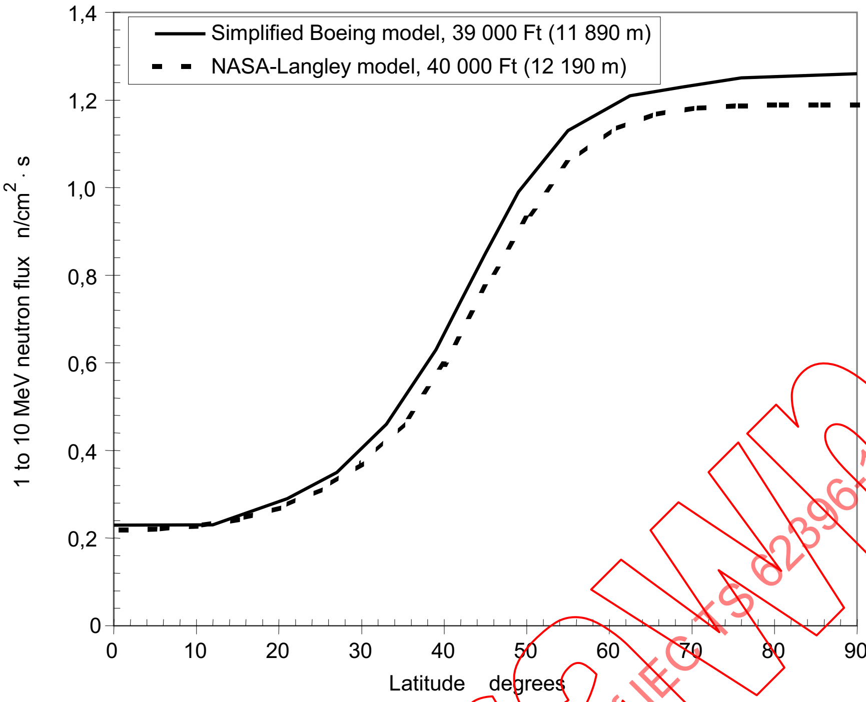

Figure 4 – Variation of the 1 to 10 MeV atmospheric neutron flux with latitude

The variation of the neutron flux with altitude shown in Figure 2 for energies 1 to 10 MeV has also been shown to apply for neutrons with higher energies (ref. 8). Therefore Figures 2 and 4 can be used to scale the greater than 10 MeV neutron flux of 6 000 n/cm^2 per hour which applies at 40 000 feet (12,2 km) and 45° latitude to other altitudes and latitudes.

5.3.5 Thermal neutrons within aircraft

Thermal neutrons are low energy neutrons that have scattered sufficiently to be in thermal equilibrium with their surroundings. At room temperatures this leads to an average energy of 0,025 eV. The majority of the thermal neutrons inside the aircraft are created by the interaction of the aircraft structure and all of its contents with the higher energy neutrons within the atmosphere. Thermal neutrons can be significant because they have a very high probability of interacting with certain isotopes, such as boron 10 (B10), and boron is present in microelectronics in two main areas, as a p dopant, and in some forms of the glassivation layer, for example borophosphosilicate glass. Thus, a 0,025 eV neutron interacting with a B10 atom leads to two charged particles in a device with a combined 2,3 MeV of energy; if this energy is deposited within the sensitive volume of a microelectronic device, it can lead to a single event upset (SEU).

To date, only one study has attempted to calculate the thermal neutron flux within an aeroplane (Ref. 12). The hydrogenous materials within an aeroplane, the fuel, the passengers and crew and the baggage, all serve to thermalise the higher energy neutrons. An entire large commercial airliner was modelled in terms of 20 sub-volumes, some extremely large. Even with this crude model the calculations were very useful, showing that at the several locations within the aeroplane that were reported upon, the thermal neutron flux was about a factor of 10 higher than it is just outside the aeroplane. Based on the few measurements and calculations available a nominal flux of 1 cm^{-2} s^{-1} for Energy < 1 eV appears to be suitable for calculations of the SEU rate due to thermal neutrons. The number of measurements of SEU cross sections in devices induced by thermal neutrons is very limited see 8.3.3.

5.4 Secondary protons

Charged particles have also been measured in the atmosphere, most of which are, like the neutrons, cosmic ray secondaries, from the interaction of the primary cosmic rays with the oxygen (O) and nitrogen (N) nuclei in the air. The secondary protons can cause single event effects in electronics in a manner very similar to that of the neutrons. The distribution of secondary protons is similar to that of neutrons, especially with respect to energy and altitude. The energy spectrum of the atmospheric protons is similar to that of the neutrons, as seen in Figure 5, which contains proton measurements at two mountain tops (US and Russia, Refs. 13 and 14) and from one balloon experiment (Ref. 14). The mountain-top data indicate a peaking in the differential proton flux at about 200 to 300 MeV. Figure 5 shows that for energies up to about 500 MeV, the secondary protons in the atmosphere are about 20 to 30 % of the flux of the neutrons, but at higher energies the proton and neutron fluxes are comparable. Measurements have shown that for secondary protons in the energy range (100 < Energy < 750 MeV), the variation with altitude is very similar to that of the neutrons (Ref. 15), i.e., there is a maximum at ~80 g/cm^2 (55 000 feet (16,8 km)), the Pfotzer maximum. With respect to the latitude variation there is a slight decrease in the total atmospheric proton flux of about a factor of 2 in traversing from the polar to equatorial regions, which is less pronounced than the latitude variation with neutrons. Therefore, for purposes of calculating SEE rates in the atmosphere, since the neutron flux dominates and the suggested flux of 6 000 n/cm^2 per hour (Energy > 10 MeV) is conservative, the contribution of the protons to the SEE rate can be considered as being included within the neutron-induced SEE rate.

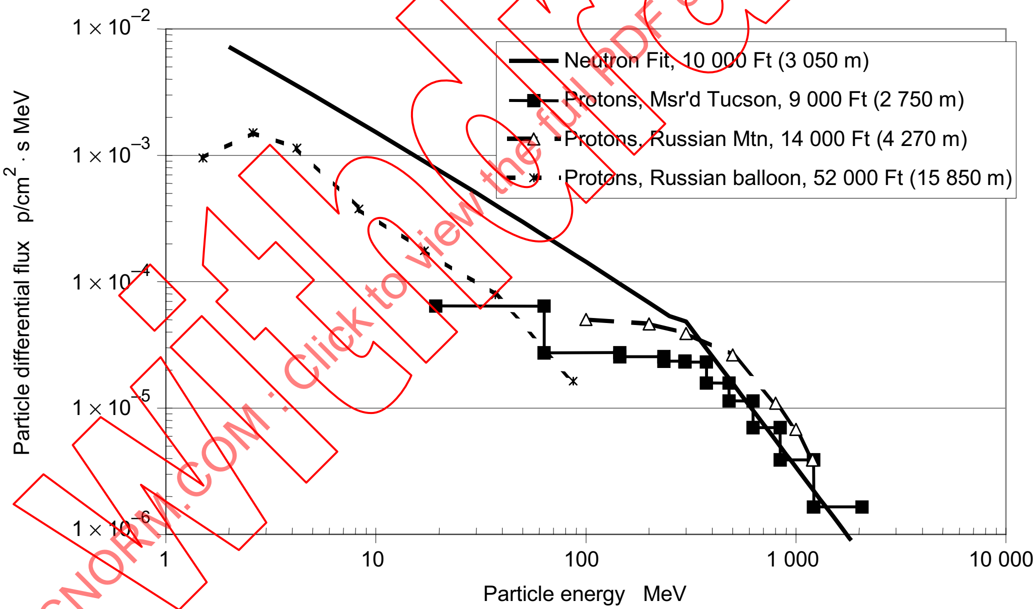

Figure 5 – Energy spectrum of protons within the atmosphere

5.5 Other particles

The other charged particle secondary cosmic ray within the atmosphere that can induce single event effects in electronics is the pion (there are both positively and negatively charged pions). However, in the atmosphere at aircraft altitudes, the pion flux is only a small fraction of the neutron and proton flux. For energies ≤1 GeV, the pion/proton (π/p) ratio is estimated to be ~0,1, and it applies at both aircraft altitudes, 500 g/cm^2 (20 000 feet (6,1 km)), as well as ground level (Ref. 16). At 40 000 feet (12,2 km) and at an energy of 1 GeV, the differential pion flux has been calculated to be ~1/30 that of the neutrons and protons (the differential neutron and proton fluxes are about equal), and at 100 MeV, the differential pion flux is ~1/100 that of the neutron flux (Ref. 17). Thus, the flux of pions in the atmosphere is so small (<1 %) compared to that of the neutrons, that they can be ignored for purposes of effects on electronics.

Electrons and gamma rays are also produced as secondary cosmic radiation in the atmosphere. Although these particles do not have a high enough dE/dx (energy deposition per path length) in silicon to cause single event effects in electronics, they do deposit ionising dose in the electronics. In general terms, the fluxes of high energy electrons and gamma rays are roughly comparable to those of the atmospheric neutrons.

There are also a very small percentage of heavy ions, i.e., primary cosmic rays and their secondary fragments, in the atmosphere that survive the passage through the hundreds of g/cm^2 of atmosphere. However their flux is very low. Therefore, heavy ions in the atmosphere can be generally ignored as a potential threat to electronics, although for the case of very high altitudes it is possible that some heavy ions may be encountered. Only for altitudes greater than 60 000 feet (18,3 km), may additional consideration need to be given for the effects of heavy ions (Refs. 18, 19), for the effects from primary cosmic rays and their secondary fragments.

5.6 Solar enhancements

Solar activity follows an approximately 11 year cycle, during which time there are periods of heightened activity (approximately the middle 6 years) and lessened activity (approximately the first 2,5 years and last 2,5 years). During the entire period there is a finite probability of eruptions on the sun, such as solar flares or coronal mass ejections that result in energetic particles being emitted.

In general, these solar energetic particles have less energy than the galactic cosmic rays. The first particles reach the Earth in a matter of minutes but the enhancements last for several hours to days. They interact with the atmosphere to create secondary particles in a similar way to galactic cosmic rays but their lower energy means that they produce much steeper altitude and latitude profiles. For a few events the particle energies are sufficiently high to give enhanced secondary fluxes at aircraft altitudes and on the ground (so called ground level events or GLEs).

The enhanced secondary cosmic rays during solar flares have been measured on the ground by the worldwide network of cosmic ray neutron detectors (continually tracking the variation of the cosmic ray environment) and occasionally by instruments aboard aircraft (Refs. 20 and 21). The SEP enhancement in the atmospheric neutron flux, relative to the background flux (>10 MeV) of 6 000 n/cm^2 per hour, in 5.3.2, has been calculated for a number of worst-case scenarios. These scenarios are dependent on the particle spectra from specific solar flare events, the altitude and the rigidity cut-off. For the September 1989 flare, the enhancement factors at 39 000 feet (12 km) are 50 and 33 for rigidities of 0,1 and 5 GV respectively, and at an altitude of 56 000 feet (17 km) the factors increase by a factor of 2,5. With the February 1956 flare, for which the incoming particle spectrum is less well characterized, the enhancement factors are about a factor of 6 larger. Thus extreme SEE rates could occur in the high latitude regions (R $\leq$ 1 GV) during worst case flares that could be as high as 300 at 39 000 feet (12 km).

This sudden increase in neutron flux leads to a SEE rate enhancement, which lasts for short periods (4 to 12 h), and is most pronounced at high latitudes.

6 Effects of atmospheric radiation on avionics

6.1 Types of radiation effects

The ionising radiation environment in the atmosphere, and therefore within an aircraft, can cause a variety of effects on the electronics used in avionics. Three basic types of radiation effects on electronics are dealt with in this clause, single event effects, total ionising dose and displacement damage. It is shown that some single event effects have an impact on the avionics but that total ionising dose and displacement damage are not of concern. Thus, the main focus is on single event effects in avionics. Single Event Effects is a generic term and encompasses all of the potential effects on the electronics caused by the interaction of a single element of radiation, in the case of Atmospheric Radiation this is secondary neutron.

Out of the many types of particles resulting from cosmic rays cascading through the earth's atmosphere reaching sea level, neutrons are the most significant in causing electronic circuit problems.

6.2 Single event effects

6.2.1 General

All single event effects (SEE) are caused by the deposition of energy within a microelectronic device by a single particle that interacts with the device. The energy deposition, which occurs either directly or indirectly, leads to charge being collected. When the incoming particle is charged (for example, cosmic ray heavy ion), the ionisation proceeds directly as the particle deposits its energy by ionising the surrounding silicon atoms. The greater the ability of the particle to release its energy, the greater the energy deposited by the particle (expressed as the LET, Linear Energy Transfer, energy/path length), the more likely that the charge released is sufficient to cause an effect. When the single particle is neutral, such as a neutron, the particle first has to have a nuclear interaction with an atom within or near the active area of the device. This creates recoiling atoms, called recoils, which possess energy that is deposited (indirectly) into the surrounding silicon atoms.

A proton is charged but it has a low enough LET in silicon that it has not yet been shown to cause SEE by direct ionisation. However, at high energies (>5 MeV), it also has nuclear reactions with silicon in a manner similar to how a neutron of the same energy would interact. Thus to date, protons cause single event effects in devices only through nuclear reactions. Based on actual measurements, we assume that for energies >100 MeV, protons and neutrons have the same ability to induce a single event upset (SEU), a flip in the logic state, in electronic devices. This is called the SEU cross section, and hence, atmospheric neutrons are assumed to have the same SEU cross section as high energy protons.

In avionics, single event effects have been observed in electronic devices used in aircraft since the early 1990s (Refs. 5, 7, 22, 23, 24). In the existing literature it has been Single Event Upsets (SEUs) in memory devices that have been recorded. Most if not all of the upsets have been attributed to the atmospheric neutrons. As the size of the total number of bits in an aircraft that are susceptible to SEU has increased geometrically over the last decade (more bits/device, greater functionality led to the need for more memory), the number of SEUs being induced has similarly increased. However, there is not a great deal of documented evidence of these in-flight SEUs for a variety of reasons:

a) the use of error detection and correction schemes is routinely used in avionics, but since the errors are corrected, there is little interest in recording the errors that are detected and corrected,

b) the occurrence of these errors is considered proprietary information, hence it is rarely collected, and even less often analysed and

c) most error correction schemes look for errors only in memory that is being utilised, hence bit flips in unused memory will always be ignored.

6.2.2 Single Event Upset (SEU)

Single event upset (SEU) is the most common type of a single event effect. SEU is caused by the deposition of charge in a device by a single particle that is sufficient to change the logic state of a single bit from one binary state to the other. Single bit upsets are sometimes called soft errors because they are readily corrected by reinitialising the bits. Devices susceptible to SEUs generally have been memory bits, register bits or latches. Random access memories are generally the most susceptible devices to SEU because they contain the largest number of memory bits. However due to the large number of volatile memory bits contained within microprocessor cached memories and registers, microcontrollers, ASICs and field programmable gate arrays (FPGAs) are also vulnerable. SEU susceptibility increases as the applied supply voltage decreases.

More recently the potential for SEU due to thermal neutrons has been observed in high density complex devices that have very small feature size and a low critical charge for upset. Thermal neutrons are produced when the high energy secondary neutrons interact with the aircraft structure, in particular the hydrogenous materials for example baggage, passengers and fuel. The thermal neutron flux within the aircraft may be about 2 times that of the high energy neutrons at some locations. A thermal neutron SEU cross-section comparable to that of the high energy secondary neutrons was observed during the SEU testing of SRAMs by several different groups, reference 8.3.3. These devices have a thermal neutron cross-section because they contain boron 10. The comparatively high thermal neutron flux associated with the aircraft environment means that for devices that contain boron 10 in any percentage, consideration shall be given to the thermal neutron flux, for further details refer to Annex A.

6.2.3 Multiple Bit Upset (MBU)

Some memory devices are also susceptible to Multiple Bit Upset, MBU, in which more than one bit is upset. In general, multiple bit upsets involve more than a single logic word. However, with MBU, energetic particles may also upset two or more bits in a single word, depending on the physical arrangement and size and distribution of the memory cells within a device. This type of event can have a large system impact because it is not easily correctable. Generally, the MBU rate is at most 1 to 2 % of the SEU rate, but some devices are much more susceptible to MBU than others, even if they have similar SEU rates. The MBU fraction increases with incident particle energy and has been observed to be 7 % for 63 MeV protons on 16 Mega bit DRAMs. Multiplicities up to 4 have been observed for protons and nineteen for ions (Refs. 25 and 26).

6.2.4 Single Effect Transients (SET)

An SEU-related event in some devices that leads to the generation of a single event transient (SET) which a device may interpret as a new bit of information. These transients are spurious signals or voltages, induced by the deposition of charge by a single particle that propagates through the circuit path during one clock cycle. These signals may be harmful by propagating to a latch and becoming fixed, or striking an internal node and causing an unwanted response, or they can be effectively removed by the legitimate synchronous signals of the circuit. Initially, such transients were observed in linear analogue devices such as comparators and operational amplifiers, but they have also been recorded in digital devices. Most SET tests have been performed using beams of heavy ions, but SET has also been induced in linear devices with high-energy proton beams (Refs. 27, 28), hence the atmospheric neutrons also cause this kind of effect.

6.2.5 Single Event Latch-up (SEL)

Single event latch-up (SEL) is a regenerative current flow condition in which a parasitic n-p-n-p pathway in a silicon device is turned on by the deposition of charge from a single particle. SEL has generally been a concern in bulk CMOS devices, but it has also been seen in CMOS devices with relatively thick (>10 µm) epitaxial layers. The regenerative circuit provides a path for large current flow and can often lead to destructive breakdown. Even if the breakdown does not occur, the latched path will persist until power is removed from the device, so power shall be recycled to restore normal operation. Beginning in 1992, a small number of CMOS devices have been shown to be susceptible to proton and neutron-induced latch-up (Refs. 29, 30). SEL susceptibility decreases as the applied voltage decreases, and increases as the device temperature increases. In addition, on very rare occasions, other single event induced mechanisms have been observed which can lead to a high current condition in a device that could lead to its destruction. One such example is a driver contention mechanism in one type of FPGA (Ref. 31) and other specialized mechanisms have been observed to impact bipolar devices (Refs. 32, 33).

6.2.6 Single Event Functional Interrupt (SEFI)

Single event functional interrupt (SEFI) refers to a SEU in a device, usually a complex device, for example, a microprocessor, such that a control path is corrupted, leading the part to cease to function properly. This effect has sometimes been referred to as lockup, indicating that the part has been put into a “frozen” state. Generally, SEFI is brought about by a SEU in a critical bit, such as a bit that controls important downstream operations. Examples of such bits are program counters, special function registers, control, timing and mode registers in DRAMs and even built-in test (BIT) bits utilised by the device vendor only for pre-screen testing. In some devices such as DRAMs (Ref. 34) and FPGAs (Ref. 35), a SEFI can lead to an increase in the supply current which is similar to the effect of a single event latch-up, but proceeds via a different mechanism.

6.2.7 Single Event Burnout (SEB)

Devices such as N-channel power MOSFETs, Insulated Gate Bipolar Transistors (IGBTs) and bipolar power transistors and diodes, which have large applied voltage biases and high internal electric fields, are susceptible to single event induced burnout (SEB). The penetration of the source-body-drain region by the charge deposited by a heavy ion can forward bias the thin body region under the source. If the terminal bias applied to the drain exceeds the local breakdown voltage of the parasitic bipolar, the single event induced pulse initiates avalanching in the drain depletion region that eventually leads to destructive burnout. In commercial N-channel power MOSFETs, this effect can occur at values of the drain voltage, V_{ds}, lower than the rated voltage of the device. Based on the results from radiation testing in a heavy ion beam, a threshold V_{ds} is defined as the highest V_{ds} at which the MOSFET can be operated with no probability of SEB being induced by that heavy ion. Energetic neutrons and protons are also able to induce SEB in N-channel power MOSFETs (Ref. 36). In all cases, the threshold V_{ds} for neutrons and protons is higher than it is for heavy ions. SEB is precluded by operating the MOSFET below the V_{ds} threshold for neutrons and protons as determined by radiation testing. For high voltage devices, those with a rated V_{ds} of ≥400 V, tests at ground level (V_{ds} at >90 % of rated voltage) have experienced destructive failures that are consistent with rates due to SEB by the atmospheric neutrons (Ref. 37). Since the atmospheric neutron flux level at aircraft altitudes is more than 100 times greater than at ground level, the potential for SEB in high voltage devices in avionics is a potential concern.

6.2.8 Single Event Gate Rupture (SEGR)

Both N-channel and P-channel power MOSFETs are subject to single event gate rupture (SEGR). This effect is explained via the transient plasma filament created by a heavy ion track when it strikes the MOSFET through the thin gate oxide region. As a result of this ion track filament, there is a localised increase in the oxide field which can cause oxide breakdown leading first to gate leakage and finally to gate rupture. With MOSFETs, ground level testing of high voltage devices (Ref. 37) has shown that in some of the devices the failure was due to SEGR, rather than SEB. Thus the high energy atmospheric neutrons are able to induce SEGR in some high voltage MOSFETs.

A related effect that has been seen in devices such as field programmable gate arrays (FPGA) is single event dielectric rupture (SEDR) in which a thin dielectric is ruptured by heavy ions with very high LET. Testing to date has shown that the dielectrics are ruptured only by heavy ions with very high LETs, and not by energetic neutrons or protons.

6.2.9 Single event induced Hard Error (SHE)

It has long been known that heavy ions are able to cause "stuck bits" in SRAMs. These events are sometimes referred to as single hard errors (SHE). These hard errors are due to very localised total dose effects, caused by a few ions impinging on the gate oxide of sensitive transistors. Stuck bits are significant because they can invalidate the most common form of error detection and correction, EDAC, called SECDED, single error correct, double error detect. Stuck bits are not corrected by EDAC so they persist. If a word contains a stuck bit, a single SEU in another bit in that word at any time in produces an observable error.

In the early occurrences of these hard errors, they were caused only by heavy ions with high LET. More recently the first occurrence of SHE by protons in a laboratory test was published, indicating that in newer devices (in this case a 64 Mbit DRAM, Ref. 38), protons, and hence atmospheric neutrons, are capable of inducing stuck bits.

6.3 Total Ionising Dose (TID)

Total Ionising Dose (TID) effects refer to the cumulative effect of ionisation (charge build-up) in an IC device leading to a gradual degradation of electrical parameters. When a MOS (metal oxide-semiconductor) device is exposed to ionising radiation, electron-hole pairs are created throughout the oxide that induce the build-up of charge which leads to device degradation. The main mechanisms are the build-up of positive oxide trap charge in the oxide, and of interface-trap charge in the interface between the silicon and the silicon dioxide. Large concentrations of oxide-trap charge cause increased leakage current in a device. Large concentrations of interface-trap charge increase the threshold voltage of transistors, degrading the timing parameters of a device. Similar effects are also caused in bipolar devices.

Based on previous total dose testing experience of microelectronics devices over the past 20 years, involving probably thousands of different devices, an effective lower bound on the minimum TID level that can cause a device to operate out of spec is 1 000 cGy(Si). For the vast majority of devices, including almost all commercial off the shelf (COTS) devices, the TID threshold level is much higher than 1 000 cGy. Nevertheless, using 1 000 cGy as the minimum threshold, and even including a factor of 2 for margin, this means that a worst case minimum total dose level that aircraft avionics would have to absorb is 500 cGy before TID effects could possibly be an issue of concern in the avionics.

Ionising dose is contributed by all of the major particles that constitute the radiation environment within the atmosphere, i.e., neutrons, protons, electrons, photons, etc. Based on measurements made in a commercial airliner (Ref. 39), the maximum dose rate from all of the particles is ~70 nGy per minute (~0,4 millirad per hour or ~4 microgray per hour). For a nominal 100 000 flight hours, this results in ~40 cGy of dose over that lifetime, which is an order of magnitude lower than the worst case TID threshold of 500 cGy. For aircraft at higher altitudes for example 55 000 feet (16,8 km) the dose rate doubles to 8 microgray per hour with a maximum dose over 100 000 flight hours of 80 cGy well below the TID threshold. However the total ionising dose is cumulative and any dose from other sources should also be considered for example mechanical X-ray testing.

An upper bound estimate on the maximum dose that an electronics device might receive from an x-ray inspection is 1 milligray. This is extrapolated from the maximum dose that objects may receive from x-ray machines used to inspect luggage (10 microgray, and is also consistent with the approximate range of doses known to be received from commercial x-ray inspection systems (200 to 500 microgray). Thus, TID effects are not generally an issue for avionics.

Mechanical X-ray and gamma ray inspection is carried out on certain parts of the airframe to demonstrate structural integrity. The radiation doses delivered by this type of inspection may be higher than that from the luggage inspection machines. Where such inspections are carried out if the cumulative dose received by any localised avionics electronic equipment over its lifetime in service potentially exceeds 50 cGy then consideration shall be given to removing the electronic equipment before the radiation inspection is carried out. Examples of such equipment include wing and engine mounted electronics.

6.4 Displacement damage

Still another kind of effect that ionising radiation can induce in microelectronic devices is displacement damage. This is also a cumulative effect, but in this case it refers to atoms that are displaced out of their lattice. When a sufficient number of atoms are displaced, the device no longer functions normally. This effect is primarily due to the heavier particles, neutrons and protons, since lighter particles, such as electrons and gamma rays, are much less effective in knocking atoms out of their lattice.

Based on previous experience of testing dozens of parts for displacement damage, an effective lower bound on the minimum neutron fluence that causes a device to operate out of spec is 1×10^{10} n/cm^2. The 1×10^{10} n/cm^2 value is based on displacement damage in sensitive optocouplers (Ref. 40). For microelectronic devices, the neutron fluence threshold for damage is higher. The basis for this testing was a fluence of 1 MeV equivalent neutrons. A large fraction of the neutrons at aircraft altitudes are at higher energies than 1 MeV, and their potential for causing displacement damage in devices is greater than that of 1 MeV neutrons. The NIEL (non-ionising energy loss) function has been calculated for semiconductor materials such as silicon and GaAs as a function of energy, and the NIEL is accepted as the best measure for the potential of a material to undergo displacement damage. Based on the NIEL for silicon by neutrons as a function of energy, it is conservative to assume that the higher energy neutrons have at the most a factor of 3 greater effectiveness in causing displacement damage compared to 1 MeV neutrons.

At aircraft altitudes, a useful estimate of the flux of high-energy neutrons (1 to 1 000 MeV) is 8×10^3 n/cm^2 per hour. Thus assuming the electronics are exposed for 1×10^5 flight hours, this results in a neutron fluence of 8×10^8 n/cm^2. Using the factor of 3 as an upper bound equivalence between the higher energy neutrons and the 1 MeV neutrons for purposes of displacement damage, this fluence converts to a 1 MeV equivalent neutron fluence of $2{,}4\times10^9$ n/cm^2. This upper bound 1 MeV neutron equivalent fluence for avionics is still a factor of 4 below the minimum level to cause displacement damage to the most sensitive devices. Hence displacement damage is not a problem for avionics devices, based on a minimum 1 MeV neutron fluence of 1×10^{10} n/cm^2.

7 Guidance for system designs

7.1 Overview

Methodology and practices associated with safety aspects of system design can result in the accommodation of component and equipment soft and hard fault rates. If avionics electronic components that can experience atmospheric radiation induced upset and failure effects which have the potential to adversely affect aircraft safety are identified, the method of assessing the safety impact of such effects is identical to that used to assess other potential hazards associated with an electronic avionics product. Figure 6 contains a flow chart showing this process at a high level. The flowchart is consistent with the aerospace recommended practices contained in ARP4754 (Certification Considerations for Highly-Integrated or Complex Aircraft Systems) and ARP4761 (Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment). In addition to the ARPs, quantitative requirements for the availability of aircraft functions are provided in AC23.1309-1C and AC25.1309-1A.

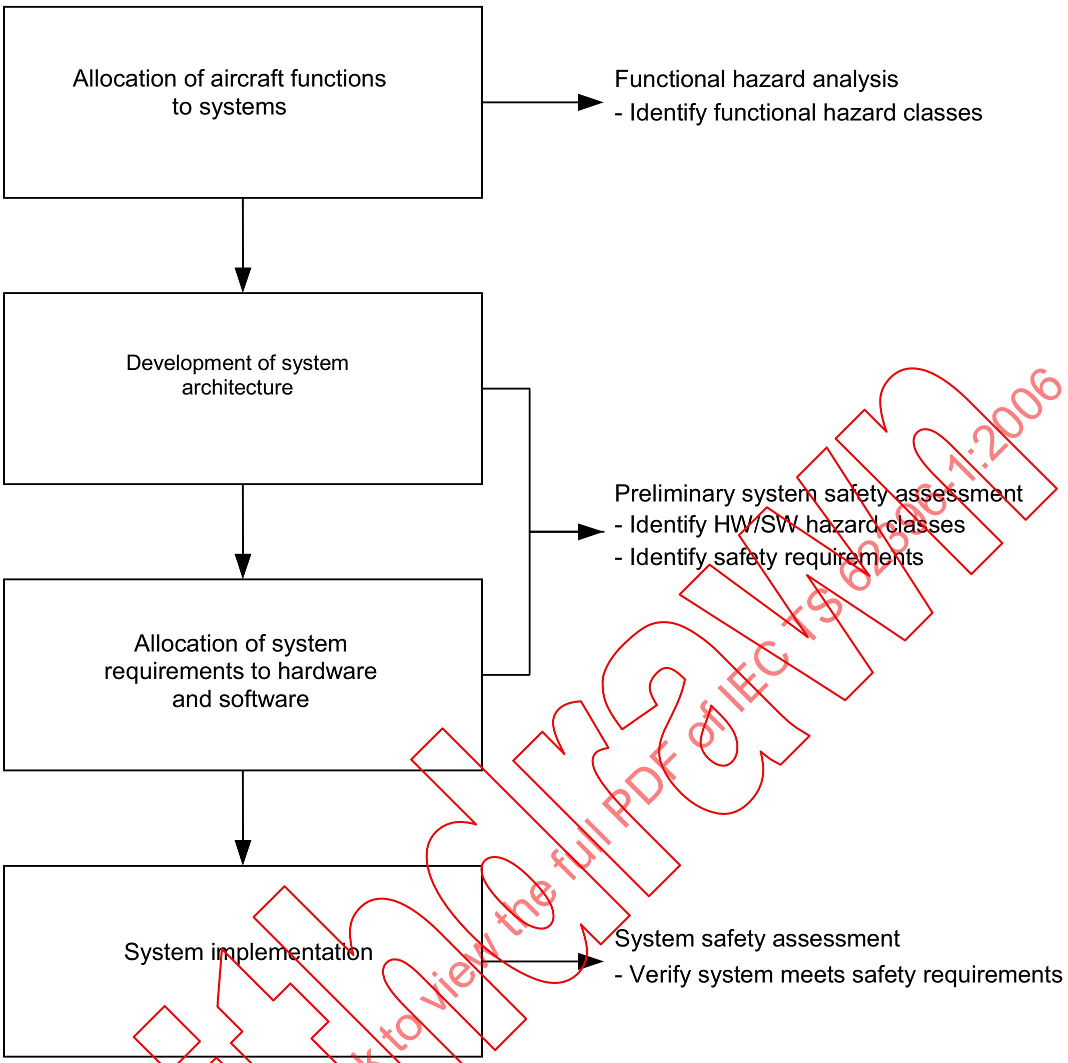

Figure 6 – System safety assessment process

The first step in the development process is to allocate the aircraft level functions to systems which will implement these functions. As part of this development phase, each of the systems is assessed relative to potential hazards, which could impact aircraft safety, by use of a Functional Hazard Analysis (FHA). The FHA assesses all hazards against a set of hazard classes similar to the classes shown in Table 1. In addition to identification of top-level system hazards the FHA identifies required hazard classifications for each function. This classification is set equal to the highest criticality hazards associated with each function. SEE does not generally cause unique function level failure effects as other hardware failure modes can cause the same effects. As a result SEE does not need to be included as a separate hazard within the FHA.

System development assurance levels refer to processes used during system development (design, implementation, verification/certification, production, etc.). It was deemed necessary to focus on the development processes for systems based upon 'highly-integrated' or 'complex' (whose safety cannot be shown solely by test and whose logic is difficult to comprehend without the aid of analytical tools) elements (primarily digital electronic components and software).

Development assurance activities support system development processes. Systems and items are assigned "development assurance levels" based on failure condition classifications associated with aircraft-level functions implemented in the systems and items. The rigor and discipline needed in performing the activities supporting development processes will vary corresponding to the assigned development assurance level and should be tailored accordingly.

Systems that implement aircraft functions are classified by the failure effects of the functions they implement. Table 1 provides a cross-reference between functional failure effects and the classification of systems that implement the corresponding function.

Table 1 – Nomenclature cross reference

Functional failure condition classification (AC 23.1309-1C, AC 25.1309-1A and ARP4754)	System development assurance level (ARP4754)
Catastrophic	Level A
Severe major/hazardous	Level B
Major	Level C
Minor	Level D
No Effect	Level E

During the development of the system architecture and allocation of system requirements to hardware and software, a Preliminary System Safety Assessment (PSSA) is performed. The purpose of the PSSA is to evaluate the planned architecture to determine the reasonableness of the architecture to meet the system safety requirements. Unlike the FHA, the PSSA considers the intended system architecture and identifies failure modes, which individually or in combination, can lead to the top-level hazardous events identified in the FHA. Since SEE would not introduce new failure modes, the failure modes considered in the PSSA would include SEE. Depending on the effects of SEE the PSSA will consider those that cause soft versus hard faults separately. The impact of phase of flight typically will need to be considered since the probability of SEE is higher during cruise than during take-off and landing. Since PSSA results will drive architecture mitigation measures, it will identify any architectural mitigation that is required.

During the system implementation phase the design is completed and verified. The System Safety Assessment (SSA) is performed to verify and document that the system, as designed and built, complies with the safety requirements. Thus, all applicable SEE rates will be included in the SSA.

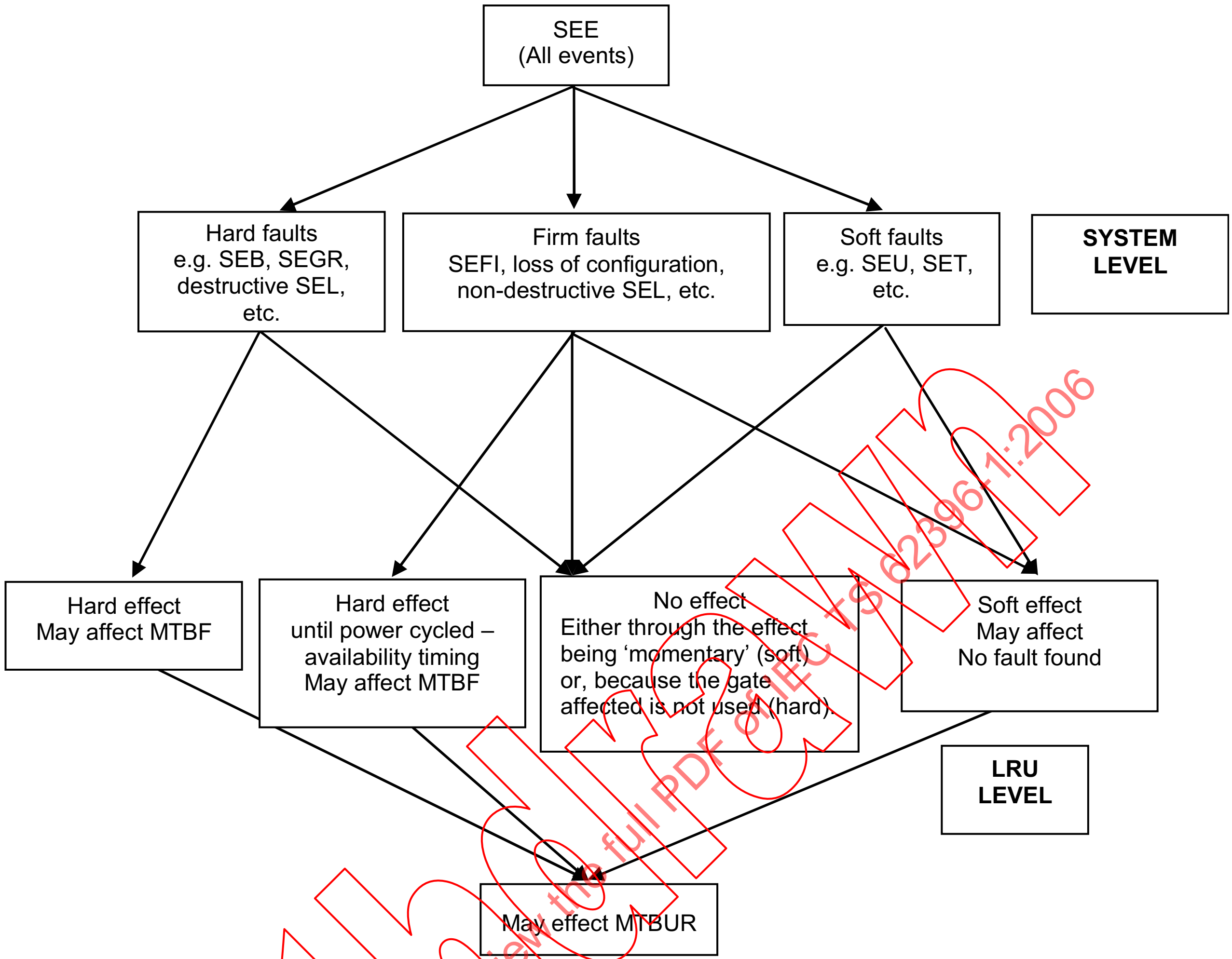

Figure 7 – SEE in relation to system and LRU effect

7.2 System design

Because failure effects may include both malfunction and loss of function, the implementation of some aircraft functions usually require system architectures with some degree of equipment monitoring and redundancy. The degree of redundancy is dictated by equipment component failure rates and would include SEE failure/fault rates an indication of the impact of SEE is given in Figure 7. Since the neutron interaction events that result in SEE are stochastic and relatively rare, potentially adverse safety effects would be confined to Level A, B or C systems. For Level D and E systems, the impact of SEE would primarily affect economics and customer satisfaction and need not be considered in system safety assessments.

For Level A, B and C systems the SEE rates shall include single event effects that result in both soft errors and hard errors. Soft errors are defined as those that are easily recovered from, usually by a rebooting of the system, or even recycling power. The non-destructive SEE effects that comprise soft errors include SEU, MBU, SET and SEFI (most of the time). Hard errors are those that cannot easily be recovered from by a rebooting of the system. They can be brought about by destructive damage to a device or by a soft error being propagated within a system that results in the standard boot-up not being available. The destructive SEE effects that constitute hard errors include SEL, SHE, SEB, SEGR and on occasion SEFI. In those few devices that are susceptible to destructive SEE effects by high-energy neutrons, such as SHE and SEL, the SEE rates in avionics (see 8.2.3 and 8.2.4) will be much larger than the rates of hard failures in those devices due to mechanical mechanisms, which are generally in the range of 100 to 1000 FITs (1×10^{-6} to 1×10^{-7} Failure/device·hour, Ref. 41) for avionics.

The SEU rates for individual devices may be obtained from a variety of data sources, and the two main approaches that can be utilized for these are discussed in Clause B.3 and Clause B.4. The approach described in Clause B.2, exposing an LRU or circuit board to a proton or neutron beam, provides more information as to how potential SEEs in devices affect the subsystem, but few such tests have been carried out. Very few devices have been documented to be susceptible to destructive SEE effects, primarily SEL, by high-energy neutrons or protons, but only a limited number of devices have been tested in such beams in the first place. However, actual in-flight experience of devices used in avionics boxes could be utilized to demonstrate the lack of susceptibility to destructive SEE mechanisms, although this has not been done formally to date.

Equipment redundancy along with other mitigating architecture measures would in turn translate to requirements for acceptable SEE rates. For a single system implementation of a particular aircraft function, objectives should revolve around acceptable equipment failure rates that include SEE rates. Architectural considerations, equipment design or component selection mitigates the impact of failure rates (including SEE rates) on a product. The discipline and rigor required in the system design for and verification of mitigation of fault effects is dependent on the system development assurance level.

Separate error rates are required for soft errors and hard errors (faults) depending on the overall equipment impact of these errors/faults. For example, soft errors may not constitute an equipment fault if an automatic or crew initiated reset is able to return the equipment to full operation. The discipline and rigor associated with SEE rate determination could range from characterisation of the actual SEE rate for a specific device to a determination of similarity to a class of devices with a known SEE rate. A device SEE rate impacting a Level A (function failure effect of Catastrophic) system should be quantified with greater rigor (see 7.4.2) than that impacting a Level B (function failure effect of Severe Major/Hazardous) system. In like manner, a SEE rate impacting a Level B system should be quantified with greater rigor (see 7.4.3) than those impacting Level C (Major) systems (see 7.4.4) or Level D (Minor) and Level E (No Effect) systems (see 7.4.5).

For the purpose of this document soft errors result in error or loss of function but recoverable for example by reset or power cycle. Hard errors result in equipment failure that is permanent and only recoverable by repair activity.

7.3 Hardware considerations

SEU rates are a particular issue with digital electronic hardware. Such effects refer to the characteristic of invalid state changes; for example, those that occur in latch circuits (memories, registers, etc) that are fundamental building blocks of digital hardware.

Extreme solar flare events produce additional neutrons within the atmosphere that increase the overall atmospheric neutron flux without direct warning. Therefore for Levels A, B and C systems a scaling factor for solar enhancement of the high-energy neutron flux should be applied (see 5.6).

Using the safety assessment process and given a failure/fault rate, for each type of SEE, the system architectures can be provided to achieve robust operation in a potentially fault producing environment. System architectural features, such as redundancy, monitoring, error correction, or partitioning, can be useful in mitigating the effects of an equipment fault on the system operation and reducing the probability of a system hazard. Redundancy is a technique for providing multiple implementations of a function – either as multiple items, or multiple lanes within an item. It assumes that a hard error/fault (SEE induced, etc) impacting one element of the system implementing a function is independent of such a fault impacting the redundant system element. Monitoring for and accommodation of an equipment fault effect is a useful technique to minimise the impact of any such effects.

If various functions are provided by Integrated Modular Avionics (IMA) technology, the determination of the development assurance level shall include the effects of the simultaneous loss and/or malfunction of all of the functions that the IMA system provides. The rigor and discipline associated with the highest system development assurance level would typically be applied to the hardware associated with the IMA computing platform.

7.4 Parts characterisation and control

7.4.1 Rigour and discipline

The rigour and discipline needed in characterising parts SEE rates and in parts control will vary according to the development assurance level and should be tailored accordingly.

7.4.2 Level A systems

7.4.2.1 Characterisation

Level A systems are categorised into two groups. One group involves functions for which the pilot will not be part of the operational loop. These are classified as Level A Type I systems, for example, FBW, etc.

The second group involves functions for which the pilot will be within the loop through pilot/system information exchange. These are defined as Level A Type II systems, for example, EFIS, etc.

NOTE Level A Type I system failures and malfunctions can more directly and abruptly contribute to a catastrophic event than Level A Type II system failures and malfunctions. It is, therefore, appropriate to require a more rigorous compliance method for Type I systems than for Type II systems.

7.4.2.2 Level A Type I

This assurance level will require the most rigorous/disciplined (testing/analysis) approach (including SEE rate characterisation) for showing compliance to requirements for acceptable function performance in the radiation environment. One of the following methods should be employed:

- SEE rates in electronic components may be derived from neutron testing on the specific parts used in the design by exposure to a suitable simulation facility. An example of a high fidelity atmospheric neutron environment simulation is the Los Alamos WNR see 8.3.3 and Annex C. Accuracy of this method is approximately a factor of 2 on the event rate.
- SEE rates in electronic components may also be derived from proton testing on the specific parts used in the design by exposure to high energy (greater than 100 MeV) proton beams (see 8.3.3, Clause B.2 and Annex C). Accuracy of this method is approximately a factor of 3 on the event rate.
- At system level “in-the-loop” type of SEE testing of avionics equipment or systems may be used as described in Clause B.1. Accuracy of this method is approximately a factor of 2 to 3 on the event rate dependent on particle beam used.
- Where such data is not available or testing is impractical then the methods of 7.4.2.3 may be used to derive event rates, however a suitable minimum factor in event rates over values calculated by these methods shall be applied.

These types of systems require the most robust parts performance and device technology controls. Technology controls shall be in place to monitor device supplier changes that could impact SEE failure/fault rates.

7.4.2.3 Level A Type II

SEE rates should be based on either:

a) Level A Type I rigour/discipline or

b) less rigorous/disciplined approach using one of the following methods:

   – The use of proprietary information and data applicable to SEE for example silicon on insulator and established thin radiation tolerant epitaxial layer to prevent latch up, and non contiguous memory to avoid MBU (Accuracy approximately factor of 2 on event rate).

   – Irradiation of individual avionics equipment items containing a variety of potentially susceptible parts as described in Clause B.2.

   – Any of the following SEE engineering tools that shall be applied by SEE radiation effects experts:

   1) Use of heavy ion SEE data processed using an analytical approach to obtain neutron SEE data (see Clause B.3). Accuracy is approximately a factor of 10 on the event rate.

   2) Use of neutron/proton SEE data on specific part types (see Clause B.3). Accuracy is approximately a factor of 10 on event rate.

   3) Use of generic SEE data based on component basic technology and type (for example CMOS SRAM); (see Clause B.4) it is used where there is no relevant SEE data for the parts. Accuracy is approximately a factor of 10 on the event rate because this is an inherently conservative method.

   4) Use of component SEE testing by laser simulation using a laser that has been calibrated using a reference device of the same functional type (for example SRAM) and similar technology and feature size. (see Clause B.5). Accuracy using calibration devices is approximately a factor of 10 on the event rate.

These types of systems require the most robust parts performance and device technology controls. Technology controls shall be in place to monitor device supplier changes that could impact SEE failure/fault rates.

7.4.3 Level B

SEE rates should be based on either:

a) Level A rigour/discipline or

b) SEE failure/fault rates traceable to SEE tests on similar parts using test results from non-neutron testing facilities see Clauses B.3, B.4 and B.5.

These types of systems require moderate parts and technology control with periodic assurances that no supplier changes could impact SEE failure/fault rates.

7.4.4 Level C

SEE rates should be based on either:

a) Level B rigour/discipline or

b) SEE failure/fault rates traceable to testing results via a SEE failure/fault rate model (use of an average SEE error rate for all potentially sensitive components – in these instances, the SEE error rate may be high for some components and low for others but the overall equipment error rate can be expected to be acceptable – see Clause B.4).

These types of systems use normal parts control and change notification practices. Changes shall be reviewed for potential impact on SEE failure/fault rates. The impact of a part change will be tracked by product (identify trends indicating major increases in failure/fault rates).

7.4.5 Levels D and E

These types of systems use of normal parts control and change notification practices. No additional screening for the effects of atmospheric radiation is required unless specifically requested by the customer.

8 Determination of avionics single event effects rates

8.1 Main single event effects

Many microelectronic devices are susceptible to single event effects in avionics at aircraft altitudes, and there are many different ways of dealing with the phenomena. First, it shall be recognised that even though Clause 6 lists many different kinds of single event effects, in almost all cases for devices available at the beginning of the 21st century, the three main effects that need to be dealt with are SEU, MBU and SEFI. This may not hold true in the future as fabrication methods and output requirements of newer electronic devices are further advanced through developments in device technology. The event rate for the other single event effects are generally low enough that they can be ignored in most cases. However, SEL presents a difficulty because while the vast majority of CMOS parts are not susceptible to SEL due to the atmospheric neutrons, a few parts are susceptible, and the atmospheric neutron SEL rate for some of these may not be considered small enough to ignore.

The key to being able to deal with single event effects in avionics is to quantify the SEE rate of an LRU, which usually is taken as the combined SEE rate of all of the devices that are used in the LRU. The SEE rate per device-hour is calculated by the following equation:

SEE rate = atmospheric neutron flux (n/cm^2 per hour) × SEE cross section (cm^2 per device)

A number of different approaches can be used for this, from testing an LRU or the electronic boards within it while exposed to a beam of neutrons or protons (dynamic test), to calculating rates based on data for the static SEE response of individual parts.

The SEE response of a device to a beam of particles is characterised as the SEE cross section, which is the number of events divided by the fluence of particles (p/cm^2; the particle flux integrated over the exposure time) to which the device was exposed. Thus the cross section is given in units of cm^2/device or cm^2/bit.

8.2 Single event effects with lower event rates

8.2.1 Single Event Burnout (SEB) and Single Event Gate Rupture (SEGR)

Single event burnout (SEB) and single event gate rupture (SEGR) apply only to devices such as power MOSFETs and IGBTs. As discussed in Clause 6, energetic neutrons in the atmosphere can induce SEB and SEGR in power MOSFETs, but there is an additional important device parameter involved, V_{DS}, the drain-source voltage (V_{GS}, the gate source voltage plays a minor role). Power MOSFETs are generally operated at a derated condition, i.e., operated at a V_{DS} that is lower than the rated V_{ds} of the device. A large number of power MOSFETs have undergone laboratory testing with beams of heavy ions for SEB and/or SEGR, and these have identified the value of V_{DS} (passing V_{DS}) at which no SEB or SEGR occurs. Similarly, a smaller number of power MOSFETs have been tested with beams of protons and energetic neutrons for SEB, and the results of these, the passing V_{DS} values, have been tabulated (Refs. 42, 43, 44). The proton/neutron passing V_{ds} is higher than the heavy ion passing V_{DS}. From these results we can generalise that, based on those devices that were tested, atmospheric neutrons can induce SEB in power MOSFETs rated at 400 V and above. However, if the devices are operated at a V_{DS} of <300 V, the probability of an SEB will be low enough that SEB should not be a concern. For voltages >300 V, the SEB cross section is needed in order to calculate the SEB rate, and this cross section can be obtained only from high energy proton/neutron SEB tests, such as those in (Refs. 45, 46, 47).

There is evidence that high voltage electronics has been affected by secondary neutrons at sea level. As indicated in references 37 and 42, the instances in which high power electronics have failed on the ground are all attributable to the cosmic ray neutrons.

8.2.2 Single Event Transient (SET)

Single event transient (SET) responses have been measured in a number of devices with heavy ions, but in only three different types of devices using proton beams, a comparator (Ref. 28), analogue to digital converter (Ref. 48) and a pulse width modulator (PWM) (Ref. 27). The ability of a circuit to tolerate a SET is highly dependent on the specific application. Nevertheless, the calculated SET rates for these three types of devices at aircraft altitudes considering the nominal neutron flux (see 5.3.2) can be helpful for purposes of assessing the kind of effects that could be induced, and providing an upper bound on their probability of occurrence. For the PWM, SETs led to changes in the waveform output of the device, which is usually at constant frequency and duty cycle (Ref. 27). Phase shift errors in the output were considered small events, and they have an upper bound rate of 4×10^{-6} event/device·hour at aircraft altitudes, while period mismatch errors (larger events), have an upper bound rate of 1×10^{-6} event/device·hour. With the comparator, the recorded transients were about 1 µs in duration, and the probability of such events depended on the voltage input. For a –25 mV input, the proton results lead to an upper bound SET rate 1×10^{-6} event/device-hour at aircraft altitudes, and with a –12,5 mV input, the proton results lead to an upper bound SET rate 2×10^{-5} event/device-hour at aircraft altitudes.

8.2.3 Single event Hard Error (SHE)

For single event hard error (SHE), a 64 Mbit SDRAM was recently tested with high-energy protons and stuck bits, SHEs, were recorded (Ref. 48). This is the most useful data for estimating the SHE rate at aircraft altitudes. SHE is a microdose effect, and it is not at all clear that other large SDRAMs will also have the same susceptibility to this effect as the SDRAM that was tested. Nevertheless, the calculated SHE rate for this SDRAM at aircraft altitudes is helpful in providing an upper bound on the probability of occurrence of hard errors. Using this proton data (Ref. 48) an upper bound rate of 4×10^{-6} SHE event/device·hour is obtained at aircraft altitudes due to the atmospheric neutrons. This rate is based on the assumption that each bit of the 64 Mbit SDRAM is equally susceptible.

8.2.4 Single Event Latchup (SEL)

Many CMOS devices are susceptible to SEL from heavy ions. A small number of these have also been tested with beams of energetic protons and neutrons, and have been shown to be susceptible to SEL from the protons and neutrons. References 49 and 50 contain a few of these devices that can have SEL induced by protons and neutrons and their SEL cross sections, but each year or two one or more new devices are identified by SEE researchers as susceptible to proton SEL (Ref. 51).

One approach that may be useful is to provide an upper bound rate based on the device with the highest probability of having SEL (Refs. 49 and 50) induced by atmospheric neutrons at aircraft altitudes. References 49 and 50 list a total of seven devices with proton SEL cross sections, and the two highest have SEL cross sections of $4{,}5 \times 10^{-9}$ cm^2 (DSP) and $6{,}6 \times 10^{-9}$ cm^2 (microcontroller). Unfortunately, two very recent proton-induced latch-up cross sections have been published for SRAMs (Refs. 26 and 52) and these proton-induced SEL cross sections, 7×10^{-9} cm^2 and 4×10^{-8} cm^2; both exceed the largest previous proton SEL value. Another study (Ref. 53) exposed SRAMs to the WNR neutron beam and SRAMs from three different vendors latched up, two also with high SEL cross sections. Thus an upper bound SEL rate for avionics based on the largest measured SEL cross section to date of 4×10^{-8} cm^2 and the neutron flux of 6×10^3 n/cm^2 per hour is $2{,}4 \times 10^{-4}$ latch-up/device per hour, or once in about 4 000 hours. Since this rate appears to be high enough to be of concern, the best certain alternative would be to expose all devices in a LRU to a beam of high-energy protons or neutrons, and monitor for latch-up (increase in current).

Devices that are susceptible to neutron-induced SEL could thereby be identified and alternative actions considered. This is the approach taken by a number of NASA centres and programs due to concerns of SEL by the trapped protons in space.

8.3 Single event effects with higher event rates - Single event upset data

8.3.1 General

The key to being able to deal with single event effects in avionics is to quantify the single event effect rate for an avionics box. Once an estimate can be made of the event rate, appropriate measures can be considered to accommodate the event. If the event rate is low enough, a decision might be made to tolerate it. If it is too high, a variety of fault tolerant measures can be considered for incorporation, such as Error Detection And Correction (EDAC) or redundancy. These fault tolerant measures involve architecture and systems approaches that are beyond the scope of this document.

As indicated in Clause 6, SEU, MBU and SEFI are the three single event effects that present the largest potential threat to aircraft avionics, and they are listed in order of decreasing occurrence. In addition, as discussed in 8.2.4, for a few CMOS parts, the single event latchup rate could be a concern. At a simplified level, the SEU rate depends on the number of bits in a device, and in most cases the bits serve as either memories, registers or latches. The kinds of devices that contain the largest number of volatile bits are memories, microprocessors, ASICs and field programmable gate arrays (FPGAs). When the SEU rate at aircraft altitudes is considered on a per bit basis, the SEU rate is similar for these various kinds of devices to within a range of 1 to 2 orders of magnitude.

8.3.2 SEU cross section

The SEU response of a device to a beam of particles is characterised as the SEU cross section, which is the number of upsets divided by the fluence of particles (p/cm^2, particle flux integrated over the exposure time) to which the device was exposed. Thus the cross section is given in units of cm^2/device or cm^2/bit. Various scientific and engineering organisations around the world carry out such SEU tests in order to characterise the SEU response of devices to the different particles. The vast majority of these tests are performed for electronics that are being considered for use in space. Therefore, most of the tests are with heavy ion particle beams, and some are with proton beams. A smaller number are performed using neutron beams.

Thus, in the radiation effects literature, there are three different types of SEU cross sections that are reported, heavy ion SEU cross sections, proton SEU cross sections and neutron SEU cross sections. For immediate purposes, the heavy ion SEU cross sections, which are used for electronics intended for space applications, are not directly relevant for avionics applications, however the utilisation of heavy ion SEU data for avionics purposes is further discussed in Clause B.3.

8.3.3 Proton and neutron beams for measuring SEU cross sections

For particle energies above 50 MeV, SEU cross sections measured with protons and neutrons can be taken to be essentially the same, but at lower energies this isn't true due to the coulomb barrier for the proton that is not present for the uncharged neutron. However there is a problem in making comparisons between neutron and proton data in that the proton SEU cross sections are measured using a monoenergetic proton beam, whereas it is difficult to achieve a beam of neutrons of a single energy except under special circumstances. Proton beams are available at a number of high energy accelerators around the world, for example the Indiana University Cyclotron Facility (IUCF) in the US, the Paul Scherrer Institute (PSI) in Switzerland, the Tri-University Meson Facility (TRIUMF) in Canada, etc. Each accelerator has an upper energy, but testing is often done at several energies and the SEU cross sections are reported as a function of the proton energy.

At aircraft altitudes, the spectrum of the atmospheric neutrons covers the energy range of 1 to 1 000 MeV. One neutron source is available that simulates the atmospheric neutron environment and is set up to allow experimenters to expose electronics to the beam and measure the induced single event effects. This is the Weapons Neutron Research (WNR) facility at the Los Alamos National Laboratory. One hour in the WNR beam is the equivalent to about 200 000 h at 40 000 feet (12,2 km) altitude in terms of the neutron fluence delivered. The WNR facility is now called the ICE (Irradiation of Chips and Electronics) house and was recently upgraded (year 2001), making testing more convenient. The beam intensity has also increased so that an hour in the beam is now equivalent to about 1×10^6 h at 40 000 feet (12,2 km).

The other neutron sources that are available are monoenergetic neutron generators and quasi-monoenergetic neutron beams. The neutron generators rely on the D-T reaction to produce monoenergetic beams of 14 MeV neutrons and occasionally on the D-D reaction to produce beams of ~3 MeV neutrons. The quasi-monoenergetic beams rely on a proton beam striking a lithium 7 target producing a peak of neutrons at nearly the energy of the protons, and a lower flux of neutrons with energies over the entire energy range from the peak energy down to thermal energies. This low energy “tail” constitutes a significant fraction of all of the neutrons produced. There is some uncertainty as to how to remove the SEU contribution from the neutrons in the lower energy tail in a consistent manner to yield monoenergetic neutron SEU cross sections.

However, there is another source of neutrons within an aircraft that can cause single event effects that requires an entirely different kind of neutron source for purposes of laboratory testing. These are the thermal neutrons discussed in 5.3.5. The average energy of these neutrons is 0,025 eV, but they are more generally considered to be below 1 eV; thus they are 6 to 9 orders of magnitude in energy lower than that of the high energy neutrons of primary concern, those in the 1 to 1 000 MeV range. The thermal neutrons cause single event effects by their interaction with the boron-10 isotope within the IC (glassivation layer over silicon), rather than with the silicon atoms. The reaction that is responsible for the increased SEU rate due to thermal neutrons is:

$$^{10}\text{B} + \text{neutron} \rightarrow {}^{7}\text{Li} + {}^{4}\text{He(alpha)}$$

Research nuclear reactors and other facilities (see Annex C) provide convenient sources of thermal neutrons with relatively high neutron fluxes for accelerated testing. However there have been few studies in which devices have been exposed to thermal neutrons and the resulting SEU cross section measured. Of these only two have exposed SRAMs to both thermal neutron and high-energy neutron beams and compared the SEU cross sections. In one study (Ref. 26), both the thermal and high energy neutron SEU cross sections in SRAMs from four different vendors were measured. For SRAMs from two vendors the thermal neutron cross section was higher than the high energy SEU cross section by a factor of between 1,5 and 3 for one vendor's device the ratio of the SEU cross section from thermal and high energy neutrons was about 1 and for the fourth vendor, there were no SEUs from thermal neutrons. In the second study (Ref. 54), for one SRAM the thermal neutron SEU cross section was lower than that due to the high energy neutrons by about a factor of 10, but for a second SRAM, the thermal neutron SEU cross section was higher by a factor of 2,5. The most compelling study (Ref. 55) exposed SRAMs to naturally occurring neutrons at a high altitude location, with some devices receiving the full spectrum and others having the thermal neutrons shielded out. The SEU rate due to thermal neutrons was about three times that due to the high-energy neutrons, and when account is taken of the relative magnitude of the neutrons fluxes, the SEU cross section from thermals is about four times that due to high energy neutrons. Thus the additional SEU rate from thermal neutrons is an issue for avionics. There is further discussion of thermal neutron SEE in Annex A.

Thus the neutron SEU cross section obtained from a specific test depends on the neutron source that was used. For avionics applications, cross sections measured with the WNR beam are best because these neutrons have the same energy spectrum as the atmospheric neutrons. These WNR SEU cross sections can be applied directly to the atmospheric neutrons at aircraft altitudes (Ref. 50).

The relationship between the WNR SEU cross section and proton and neutron SEU cross sections at specific energies is shown in Figure 8 for three older SRAMs. For the two devices with the SEU cross section measured in the WNR beam, it appears the WNR SEU cross section is approximately equal to the proton SEU cross section for Energy >100 MeV, and to the monoenergetic neutron SEU cross section at 100 MeV. Therefore SEU cross section from proton beams greater than 100 MeV can be used to give the equivalent cross section from WNR. The monoenergetic neutron SEU cross section data were derived from measurements made with a pseudo-monoenergetic beam and corrected for the contribution from the tail of lower energy neutrons (Ref. 56).

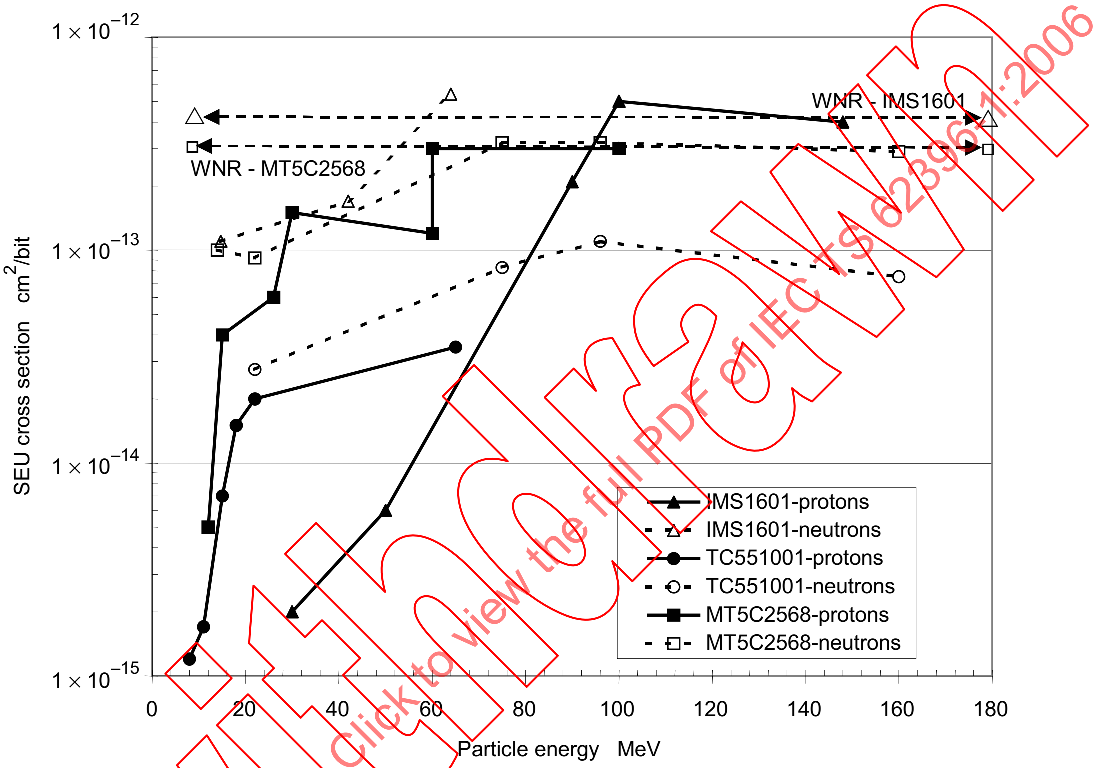

Figure 8 – Variation of RAM SEU cross section as function of neutron/proton energy

For comparison of neutron and proton measurements and significance of low energy neutrons two examples are presented Figure 9 with data on 4 Mbit SRAMs (Refs. 26, 53). The neutron upper and lower limits are derived by dividing by neutrons in peak and total neutrons respectively. Proton results are truly monoenergetic and fall in between. The neutron point at 14 MeV was obtained from a mono energetic neutron source that shows an increase in neutron SEE cross section compared to higher neutron energies which appears unusual.

Figure 9 also has the SEU cross section from thermal neutrons (less than 1 eV) in 1 device which is about a factor 1,5 to 3 higher than the SEU cross section from high energy neutrons. One other group tested included two other SRAM for SEU in a thermal neutron source and with high energy neutrons or protons. For one of these devices, the thermal neutron SEU cross section was higher by a factor 2,5 compared to the cross section for high energy neutrons, and for the other device it was a factor of 10 lower. Thus for some devices, thermal neutrons may dominate the SEU rate in avionics.

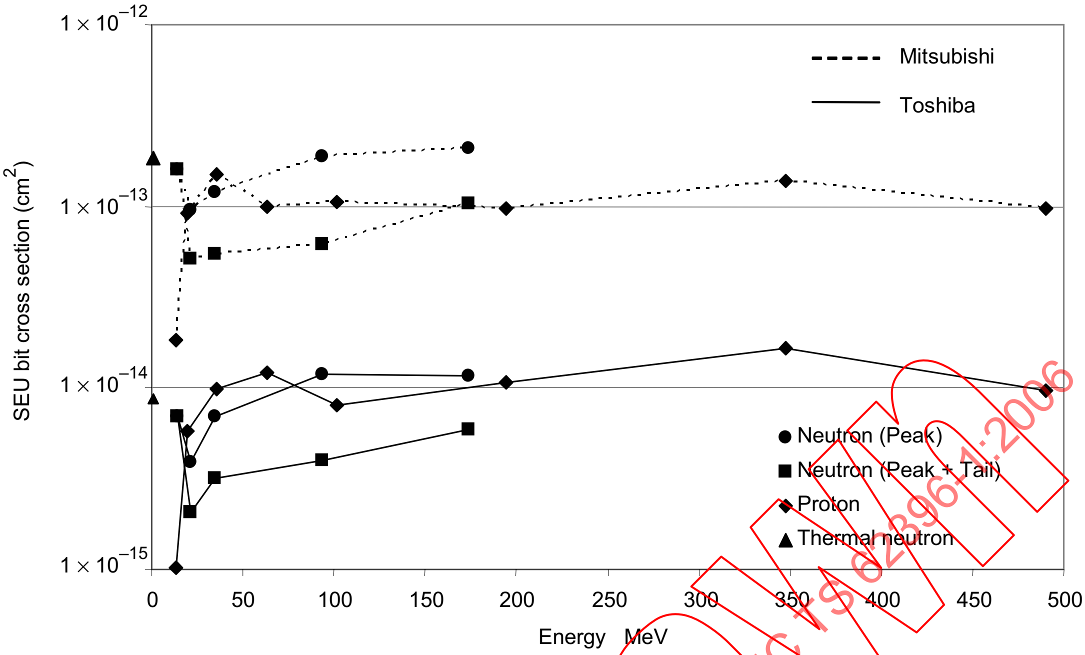

Figure 9 – Neutron and proton SEU bit cross-section data

SEU data obtained from irradiation of a series of 4 Mbit SRAMs are shown for the most and least sensitive parts identified. Proton energies of 13 to 490 MeV were obtained at the TRIUMF facility in Canada, thermal and 14 MeV neutrons at the National Physical Laboratory UK and neutron energies of 21 to 174 MeV at the Svedberg Laboratory in Sweden. The TSL neutron beams were not monoenergetic and so upper and lower limits are given based respectively on using neutrons in the peak energy region only and using total fluxes in the peak plus low energy tail.

8.3.4 SEU per bit cross section trends in SRAMs

Thus, as a practical matter, even though the best SEU data is from measurements in the WNR beam, the largest source of SEU data that can be used as a substitute for the WNR SEU cross sections are proton SEU cross sections at Energy > 100 MeV. Recognising this, tabulations were compiled in 1997 of SEU cross sections, cm^2/bit, applicable to avionics, that were derived from WNR and proton (Energy > 200 MeV) measurements for both SRAMs and DRAMs (Ref. 57). The conclusion reached in Reference 57 is that based on the original data that had been compiled, the average SEU susceptibility of both SRAMs and DRAMs was decreasing over time. However, for SRAMs the SEU sensitivity per bit was decreasing slowly, while for DRAMs the SEU sensitivity was decreasing much more rapidly.

Because this compilation of SEU cross section data as a function of the date of the device is very useful for purposes of understanding trends in the SEU susceptibility of electronics, we have updated the two curves for SRAMs and DRAMs (Ref. 58). The updating was done by plotting all of the original data, and then adding data from more recent sources to expand years covered and the breadth of parts included. The SRAM data is shown in Figure 10. In addition, two fits are shown in the Figure. The first fit is from the original paper, (Ref. 57) and is based on all of the original data. It shows a reduction in the SEU cross section over time, but with a gradual slope. In looking at Figure 10 that includes the newer data, it is difficult to justify a continuing trend in the reduction of the SEU cross section, i.e., for most parts it appears to be approaching an asymptotic value. Much of the data appears to be centred around a SEU cross section of 1×10^{-13} cm^2/bit, but more broadly within a band of a factor of 3 to 0,33 of this value.

Finally, we have also included a trend curve derived from data presented in Ref. 59 which is based on SEU rates on the ground, often called SER (Soft Error Rates) rates. SEU cross sections were derived from the SER rates using a consistent procedure, and this trend line (the Ziegler curve) shows the same trend observed above. Based on the measured SEU cross sections of individual SRAMs, for most devices there appears to be an asymptotic value of the SEU cross section within the band of 1×10^{-14} to 1×10^{-13} cm^2/bit.

The conclusion regarding the approximate asymptotic behaviour of SRAMs over time with respect to their SEU susceptibility from atmospheric neutrons should be treated with caution. It is derived primarily from the data in Figure 10, and there is no way to determine how representative the parts used in the Figure are for all SRAMs that may be used in avionics. The SRAMs used in the Figure are those that had been tested for SEU with either the WNR beam or high-energy protons. As seen in the Figure, a few SRAMs have even lower SEU cross sections than the apparent asymptotic bands that can be derived, either 1×10^{-14} to 1×10^{-13} cm^2/bit or 3×10^{-14} to 3×10^{-13} cm^2/bit.

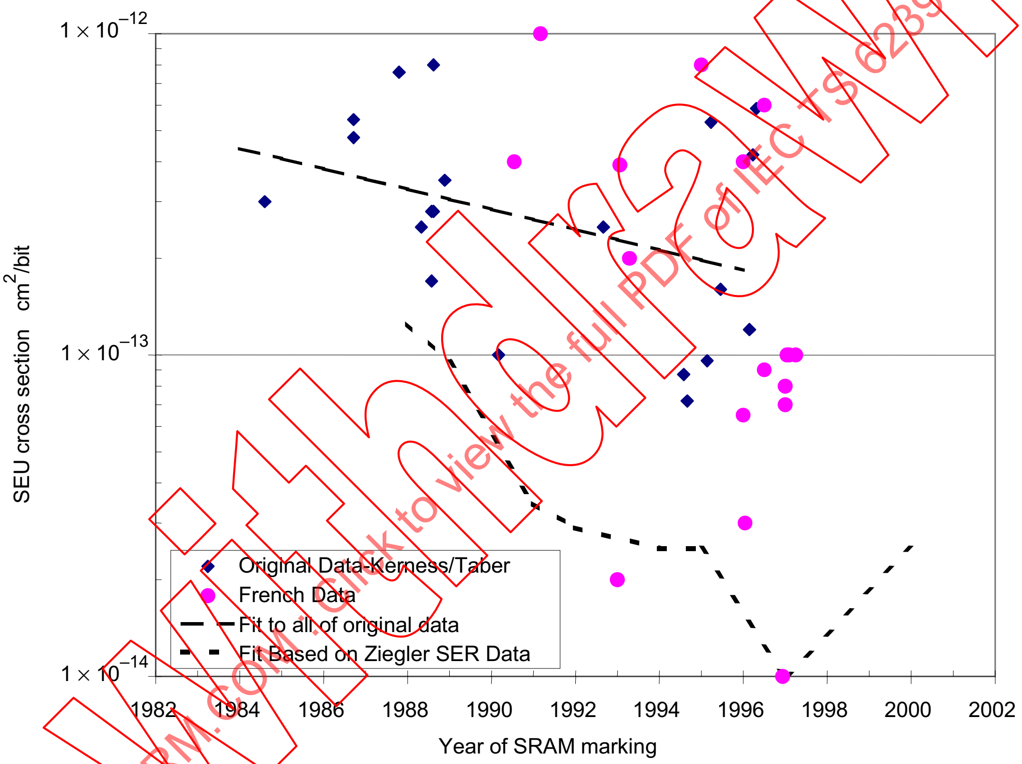

Figure 10 – SEU cross section in SRAMs as function of manufacture date

8.3.5 SEU per bit cross section trends and other SEE in DRAMs

With DRAMs the situation is different. The steep decline of the SEU cross section with year of DRAM production seen in the original data (Ref. 57) is enhanced by including more recent data. In this case, as microelectronic technologies are being modified to enable individual devices to hold an increasing larger number of bits, the net result for SEU susceptibility is a continuing decline in that susceptibility on a per bit basis. This is seen in Figure 11 which shows the original data (Ref. 57) along with SEU results from more recent tests. The original data were based mainly on 4 Mbit and 16 Mbit DRAMs, but the more recent tests, with much reduced SEU cross sections per bit, are based mainly on devices in the range of 64 to 256 Mbit. In addition, (Refs. 7 and 23) DRAMs were tested that were designed using different DRAM technologies, trench internal capacitance (TIC, utilised only by IBM and one or two other vendors) and stacked capacitance (SC, utilised by all other DRAM vendors). TIC DRAMs have a lower SEU susceptibility.

However due to the large variations between devices of differing technology and feature size designers are recommended to seek relevant data or to test the selected device.

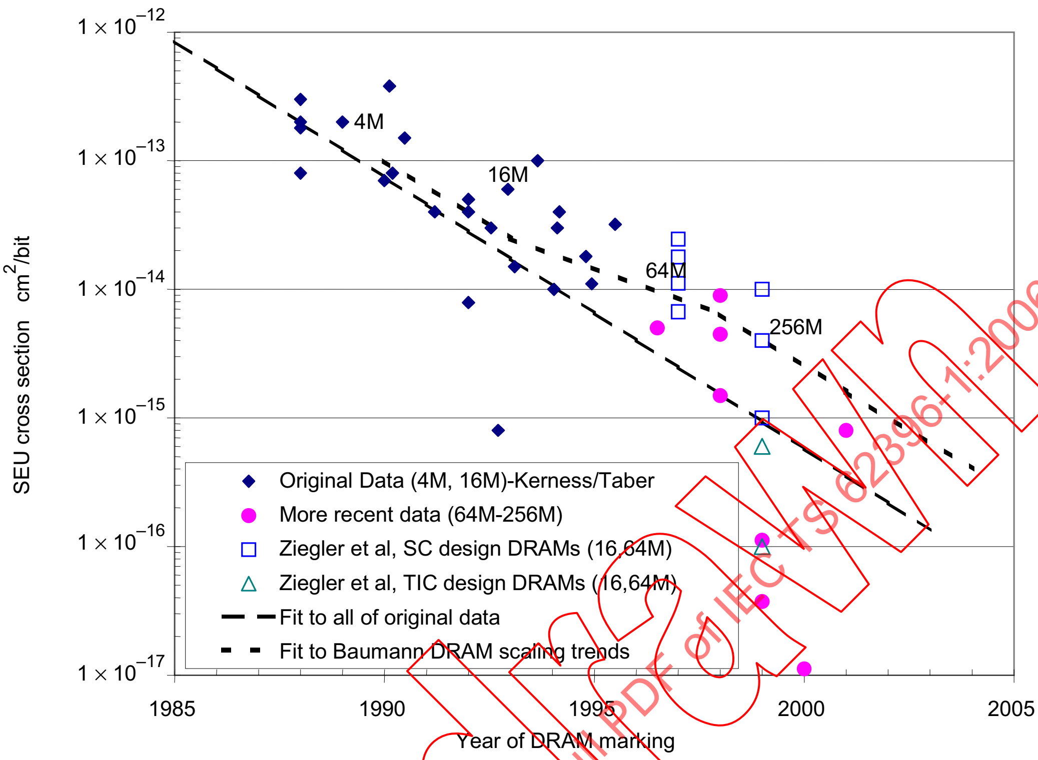

Figure 11 – SEU cross section in DRAMs as function of manufacture date

Two trend lines are shown in the Figure 11. One is the original fit to all of the data, and the second is derived from a trend analysis of other data for SC DRAMs (Refs. 59, 60, 61) (Baumann curve). This data was modified to fit the format of the Figure since the original Baumann curve is based on the size of the DRAM and not the year of manufacture. It is clear that the slope of the decrease of the SEU cross section with year from the Baumann curve is similar to that from the original data. The main point to be derived from these trend lines is that the SEU per bit cross section has continued to decrease as the size of the DRAM has increased, which appears to be related to the new DRAM technology that has been developed to achieve the higher density memories.

In most applications, the occurrence of SEU in the DRAMs that constitute main memory is protected by EDAC. With EDAC additional bits are attached to each word to enable the EDAC scheme to detect a flipped bit and correct it. However, there are also other SEE effects in DRAMs that should be considered, namely their susceptibility to multiple bit upset (MBU), stuck bits (single hard errors) and single event functional interrupt (SEFI). The new larger DRAMs appear to be susceptible to the first two of these effects, however, the SEE cross sections and therefore the SEE rates are low compared to SEU. Thus, these effects should be considered for future developments in DRAM designs.

Probably the major effect is MBU, which is generally about 1 % to 3 % of the SEU rate. However, the MBU fraction relative to the SEU rate can vary significantly from one DRAM to the next, and the impact that a MBU in a DRAM has on the operation of a board can also vary significantly due to the distribution of the bits per word in the DRAM. The method by which bits per word are physically distributed within the DRAM varies among the DRAM vendors. Stuck bits can be a concern because once such bits are stuck, the SECDED EDAC technique protecting words containing these bits no longer works for those words. The MBU fraction variation can be much higher and there is value in laser screening to give physical location of bits and relative sensitivity to MBU. If there is physical separation between the bits per word then this reduces the susceptibility to MBU in a given word.

8.4 Calculating SEE rates in avionics

Based on the SEE data shown and discussed in Clause 8, it is clear that single event effects can be induced in electronics used in avionics. Clause 8 discussed a variety of SEE tests that have been carried out in the laboratory, using both neutron and proton beams, during which SEE cross sections in microelectronics have been measured. In addition, a limited amount of data has been published of actual SEE rates recorded during flight (Refs. 5, 7, 22, 23, 24). The objective is to establish a methodology for obtaining the SEE rate in the microelectronics used in the avionics due to the atmospheric neutrons, and to addressing the impact of the SEE on the actual avionics.

The SEE rate for a particular effect is then calculated by multiplying the SEE cross section for that effect (units of cm^2) by the integrated neutron flux of 6 000 n/cm^2 (Energy > 10 MeV). This 6 000 n/cm^2 flux is a nominal value for 40 000 feet (12,2 km) altitude and 45° latitude, and may be adjusted for different altitudes and latitudes (see Annex D), and the enhancement from a solar flare, as discussed in 5.6. Using the environment described above the SEE rate may be calculated from:

$$\text{SEE rate per device-hour} = 6\,000\ (\text{n/cm}^2 \text{ per hour}) \times \text{SEE cross section } (\text{cm}^2 \text{ per device})$$

Multiple bit upset rate should be calculated for the EDAC protected memory that had been identified earlier, and had been deleted from consideration for the SEU rate. Without any specific knowledge regarding the MBU cross section in EDAC-protected DRAM, this can conservatively be taken as 3 % of the SEU rate for the DRAM. On a simplified level, this MBU rate in the protected memory is assumed to evade the EDAC scheme and lead to an error that can affect the LRU.

A four level hierarchical procedure is proposed for answering these questions regarding SEE rates and the impact of the SEE rates on the avionics, proceeding from a rigorous assessment to a conservative upper bound assessment. The primary levels involve testing of specific microelectronics devices or boards, whereas the lowest level involves utilising existing SEE cross section data to the extent possible, and applying it in a conservative manner, which therefore entails the highest level of risk. The methods are detailed in Clauses B.1 to B.6.

9 Considerations for SEE compliance

9.1 Compliance

The following steps are a means to compliance and should be documented, however alternative methods may be used where such methods can be justified.

9.2 Confirm the radiation environment for the avionics application

General guidance is given in 5.3. The degree of solar flare enhancement accommodation should be defined by the user (see 5.6).

9.3 Identify system development assurance level

The development assurance level will determine the rigour and discipline associated with the SEE accommodation.(reference Clause 7).

9.4 Assess preliminary electronic equipment design for SEE

9.4.1 Identify SEE-sensitive electronic components

As part of the equipment manufacturer Electronic Component Management Plan (ECMP), there is a requirement for the equipment to be able to function in the application avionics environment – see 4.2.6 of IEC 62239. Guidance for the identification of SEE-sensitive electronic components is given in Clauses 6 and 8.

9.4.2 Quantify SEE rates

Quantify SEE rates based on the rigour required by 7.4 and the calculation approach defined in 8.4.

9.5 Verify that the system development assurance level requirements are met for SEE

9.5.1 Combine SEE rates for entire system

The accumulation of SEE-induced hard faults may impact on the MTBF of the system. Unaccommodated soft faults may impact the MTBUR and also the MTBF. The soft SEE-induced faults may be accommodated by hardware and/or software measures refer to Clause 7.

9.5.2 Management of parts control and dependability

Refer to 4.5 of IEC 62239 and 8.4 of this part of IEC 62396. Changes by the semiconductor vendor to electronic components may affect their SEE rates.

9.6 Corrective actions

To take corrective actions if necessary.

Annex A
(informative)

Thermal neutron assessment

It is important to assess the contribution that thermal neutrons make to the overall SEU rate. The thermal neutrons can play a major role for two main reasons:

1) it appears that the thermal neutron flux inside an airliner is 1 to 2 times the high energy (>10 MeV) neutron flux and
2) for many devices the SEU cross section due to thermal neutrons is higher (by a factor of 1,5 to 3) than the SEU cross section due to >10 MeV neutrons.

There are confounding issues that make this assessment difficult and uncertain for both of the factors. Regarding the thermal neutron flux, it varies significantly within a commercial airliner, due to the proximity of hydrogenous materials which produce them, but the magnitude of the variation has yet to be quantified through rigorous measurements. The high energy (>10 MeV) neutron flux within the aircraft is essentially the same as the flux in the atmosphere right outside the aircraft structure. This is not true for the thermal neutrons. The thermal neutron flux within the aircraft is approximately 10 times higher than it is outside the aircraft because as the atmospheric high energy neutrons interact with the materials of the aircraft, the flux of thermal neutrons builds up inside the aircraft. Anecdotal information regarding measurements in a stripped down military 707 indicates variations of up to a factor of 3 in a thermal neutron detector as it was moved inside the aircraft, but this aircraft contained far less hydrogenous material compared to modern airliners. Based on the one detailed calculation that has been carried out for a crudely modelled 747, it can be estimated that within an aircraft, the thermal neutron flux may be a factor of 1 to 2 times the high energy neutron flux. By comparison, within the atmosphere, the thermal neutron flux may be a factor of 0,15 to 0,25 times the high energy neutron flux.

Regarding thermal neutron SEU cross sections, from the limited number of devices in which this has been measured (refs. 26, 54, 55), most have a thermal neutron SEU cross section comparable or larger than the high energy SEU cross section, but a few devices are not susceptible to SEU from thermal neutrons. These latter devices should not contain any BPSG, the major source of boron-10 which leads to the SEU by the thermal neutrons. However, these devices do contain boron in much lower concentrations through other constituents in the die (for example p dopant). Thus the thermal neutron SEU cross section from these other boron sources would be reduced by 2 to 3 orders compared to that in BPSG and hence may be ignored. At present, it appears that SRAMs are the only devices which have been tested with thermal neutrons and found to have a thermal neutron SEU cross section. However it is very likely that other devices such as DRAMS, microprocessors and FPGAs are also susceptible to SEU from thermal neutrons, but that has not yet been verified by measurements.

In the SRAMS in which thermal neutron SEU has been measured, for most devices, the ratio of the thermal neutron SEU cross section to the high energy SEU cross section is >1, generally in the range of 1,5 to 3. However, for devices from some vendors there is notable part-to-part variation in the ratio, which is generally higher than the part-to-part variation of the individual SEU cross sections. For the highest ratio measured to date, the thermal neutron SEU cross section to high energy SEU cross section ratio is approximately 7. Thus when combined with the fact that the thermal neutron flux in an airliner may be 1 to 2 times higher than the high energy neutron flux, the SEU rate due to thermal neutrons could be as high as a factor of 10 or more greater than the SEU rate due to high energy neutrons. This appears to be a bounding value, but is nevertheless important since the remainder of this technical specification is devoted to SEU from the high energy neutrons.

Annex B
(informative)

Methods of calculating SEE rates in avionics electronics

B.1 Proposed in-the-loop system test – Irradiating avionics LRU in neutron/proton beam, with output fed into aircraft simulation computer

This is the highest level of testing and is expected to give the most accurate answer and lowest risk for how the SEEs induced by the atmospheric neutrons will affect actual avionics. It involves an in-the-loop test in which an avionics LRU is exposed to a beam of high energy neutrons or protons, and the signals from the LRU are interfaced into a host computer containing a simulation of the aerodynamic responses for the aircraft of interest. No such test system exists today, however an experimental "proof of principle" is being proposed that would utilise the WNR neutron beam and the expertise of the Systems and Airframe Failure Emulation Testing and Integration (SAFETI) Laboratory at NASA-LaRC. At the present time this should be viewed as a future and unique testing capability involving the combining of specialised facilities at two laboratories.

At the present time, one hour in the WNR beam (2002 calibration) is equivalent to approximately 1×10^6 hours at 40 000 feet (12,2 km). With this normalisation factor, the number of upsets that affect the avionics system in one hour of exposure in the WNR beam can be adjusted to obtain the rate at aircraft altitudes.

Alternatively, the typical high energy neutron flux being suggested for use in avionics single event effects evaluations (see 5.3) is the integrated neutron flux of 6 000 n/cm^2 per hour (Energy > 10 MeV). Thus, for a lifetime of 100 000 flight hours, the lifetime fluence is 6×10^8 n/cm^2. The contribution to the SEE rate by neutrons of energies < 10 MeV is small enough, as seen in Figure 8, that it can be neglected. This does not, however, consider SEU induced by thermal neutrons.

B.2 Irradiating avionics LRU in neutron/proton beam

This approach also involves radiation testing of an avionics LRU, but in this case, the operability of the LRU is the basis for how the neutron-induced SEE effects are manifested. The output of the LRU is not fed into a simulation computer. This test is similar to those that have been conducted for space applications, in which an LRU was exposed to a beam of high-energy protons. A number of different exposures will probably be required because the collimated proton beam is usually not large enough to fully encompass the entire LRU.

NASA-JSC has used this kind of testing to identify parts that are prone to proton (or neutron) induced single event latch-up; these parts have generally been deleted from consideration, irrespective of the SEL rate. The tests have also involved many SEUs in a variety of devices; in all cases the effects of the SEU have propagated in such a way that the LRU indicates that normal operation has been interrupted. Thus, this is a dynamic type of testing, in which the original SEU in one device may propagate to an error in another device which causes the LRU to malfunction and reboot. Compared to the Clause B.1 testing approach, this methodology requires the test/analysis team to project how the non-normal operation of the LRU will impact the avionics system. The architecture of the avionics subsystem may have built in fault tolerance measures, such as various types of redundancy, which could over-ride an unexpected or erroneous signal from the LRU due to a SEU or other cause. However, without rigorous testing of the entire system, or a specified procedure for how the fault tolerance is to be implemented, it will generally be necessary to be conservative and assume that the SEE rate in the LRU will be directly propagated to the avionics system.

If this kind of testing is carried out, it will be advantageous to expose the LRU to fluences much greater than the expected lifetime fluence for avionics (100 000 flight hours) of 6×10^8 n/cm^2. As an example, if a LRU were exposed to a proton fluence of 1×10^{10} p/cm^2 and 5 events were recorded in which the LRU malfunctioned, the LRU upset cross section would be 5×10^{-10} cm^2 (5 events/1×10^{10} p/cm^2). For avionics purposes, the LRU rate per hour would be 5×10^{-10} cm^2 $\times$ 6 000 n/cm^2 or 3×10^{-6} event/LRU per hour.

B.3 Utilising existing SEE data for specific parts on LRU

B.3.1 Neutron proton data

This approach is much simpler than Clause B.2 because it attempts to rely on existing neutron or proton SEE data for the few main parts on the LRU that will be susceptible to SEE. An extension of this approach could be to carry out SEE testing of individual parts utilising a neutron or proton beam. In both cases, this approach relies on the static SEE response of a device to neutrons or protons, and ignores dynamic effects in the LRU, such as propagated errors.

The disadvantage of this approach is that the number of parts which have been tested for SEE response to high energy protons or neutrons in all of the databases is relatively small. A list of some of the more useful sources of such proton/neutron SEE data is given in Table B.1, and it includes both web sites and journal compilations. In addition, commercially available parts are continuously changing, so by the time that some of the data is incorporated into a database, the part may no longer be available, or a next generation part has replaced it. As seen in Figure 8, proton SEE data at high energies, i.e., Energy > 100 MeV, may be used to represent the SEE response due to the atmospheric neutron spectrum.

Table B.1 – Sources of high energy proton or neutron SEU cross section data

Organisation	Publications	Internet Site
NASA – Goddard Space Flight Center (Rad Effects & Analysis Section)	Yearly publication of SEE results (w/ protons and heavy ions) in IEEE Radiation Effects Data Workshop	Http://radhome.gsfc.nasa.gov/radhome/parts.htm
NASA – Jet Propulsion Laboratory (JPL)	Biannual publication of SEE results in (w/ protons and heavy ions) in IEEE Radiation Effects Data Workshop	Http://radnet.jpl.nasa.gov/SEE.htm Http://radnet.jpl.nasa.gov/Compendia/P/ProtonSeeCompendium.htm
European Space Agency	"Proton SEE Results – A Summary of ESA's Ground Test Data," R. Harboe-Sorensen, 1997 RADECS Conference Data Workshop, p. 89.	Http://www.escies.org/public/radiation/database.html

B.3.2 Heavy ion data

A less accurate approach is to utilise the available SEE cross sections on parts that were exposed to heavy ions, and transform this data into proton/neutron SEE cross sections. This is not straightforward and should only be carried out by engineers and scientists who are experienced in utilising this kind of single event effects data. A number of models have been developed that allow for this heavy ion SEU data to be used to calculate the corresponding proton SEU cross sections or rates. However, care should be taken in correctly utilising the data and employing the models, since there are ample opportunities for the heavy ion SEE data to be erroneously applied. References to some of these models are included in Table B.2. Almost all of this SEE data (heavy ion or proton) are for parts that were or are being considered for use in space applications; very little are for parts specifically being targeted for aircraft avionics.

Table B.2 – Some Models for the Use of Heavy Ion SEE Data to Calculate Proton SEE Data

Model	Author	Reference
PROFIT	P. Calvel	"An Empirical Model for Predicting Proton Induced Upset," IEEE Trans. Nucl. Sci, 43, 2827, 1996
FOM (Figure of Merit)	E. L. Petersen	"The SEU Figure of Merit and Proton Upset Rate Calculations," IEEE Trans. Nuc. Sci., 45, 2550, 1998; also J. Barak *et al.*, "On the Figure of Merit Model ...," IEEE Trans. Nuc. Sci., 46, 1504, 1999
	J. M. Palau	"A New Approach for the Prediction of the Neutron-Induced SEU Rate," IEEE Trans. Nuc. Sci., 45, 2915, 1998
	L. D. Edmonds	"Proton SEU Cross Sections Derived from Heavy-Ion Test Data," IEEE Trans. Nuc. Sci., 47, 1713, 2000
	J. Barak	"A Simple Model for Calculating Proton Induced SEU," IEEE Trans. Nuc. Sci., 43, 979, 1996; also "A Akkerman *et al.*, "A Practical Model for Calculation of the Proton Induced SEU ...," Proceedings 1991 RADECS, p. 509
BGR	E. Normand	"Extensions of the Burst Generation Rate Method for Wider Application to Proton/Neutron-Induced Single Event Effects," IEEE Trans. Nuc. Sci., 45, 2904, 1998
SEUSIM	C. Inguimbert	"Proton Upset Rate Simulation by a Monte Carlo Method: the Importance of Elastic Scattering Mechanism," IEEE Trans. Nuc. Sci., 44, 2243, 1997
IMDC	C.S.Dyer	"Microdosimetry Code Simulation of Charge-Deposition Spectra, Single Event Upsets and Multiple-Bit Upsets," IEEE Trans.Nuc. Sci., 46, 1486, 1999
CUPID	P. McNulty	"Proton Induced Spallation Reactions," Radiat. Phys. Chem., 43, 139, 1994

In general, proton/neutron SEE response data needs to be found for just a few of the devices on an LRU, those part types that are judged to be susceptible to SEE. This consists primarily of RAMs, microprocessors and FPGAs, devices that contain a large number of bits, which can upset. However, only those bits that are used are susceptible to SEUs that can be recognised as errors, and often only a fraction of all of the bits on a device are utilised in the way it operates on the LRU. Therefore, without specific knowledge of the fraction of bits that are actually used in a device on the LRU, the conservative approach is to assume that 1) all of the bits are used and therefore susceptible to SEU, and 2) all of these SEUs will cause the LRU to malfunction.

Any memory that is protected by EDAC should be deleted from consideration for single event upset, because these upsets are corrected by the EDAC. The combined neutron SEU cross section for the LRU is obtained by adding the SEU cross sections for each of the LRU parts types that were identified (RAMs, microprocessors and FPGAs), multiplied by the number of each part type on the board.

B.4 Applying generic SEE data to all parts on LRU

In this case the LRU has a number of parts that are likely to be susceptible to SEE by the atmospheric neutrons, but there is no SEE data available for one or more of these parts. Calculating the SEU rate for such parts by this approach has the least technical basis in terms of specific data and therefore has to be, of necessity, the most conservative. Like the approach in Clause B.3, it evaluates only the static SEE response of a device to neutrons or protons, and ignores dynamic effects in the LRU, such as propagated errors.

Overall, the procedure is quite similar to the approach in Clause B.3. Susceptible devices are divided into two categories, DRAMs, and all others (SRAMs, microprocessors and FPGAs). For a DRAM with no available proton or neutron SEU cross section data, we look at Figure 11 to obtain the per bit SEU cross section. The Figure clearly shows that there are large differences in the per bit SEU cross section, but this is strongly influenced by the size of the DRAM. As indicated, most DRAMs in LRUs are protected by EDAC, but this has to be verified for each LRU. Even if the DRAM is protected by EDAC so that the SEU rate can be deleted as a matter for concern, the MBU rate needs to be calculated, and this is conservatively taken to be 3 % of the SEU rate.