

INTERNATIONAL STANDARD



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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**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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International Standard IEC 62396-1 has been prepared by IEC technical committee 107: Process management for avionics.

This second edition cancels and replaces the first edition published in 2012. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) removed, in Clause 7 related to system design, reference to level A Type I and Type II (system and references). As Clause 7 is now for guidance, "shall" statements have been changed to "should" and in 9.5.2 the requirement for electronic component management is clarified;

- b) all current definitions included in Clause 3 are those used within the IEC 62396 family of documents;
- c) incorporated in Annex G related to new technology or latest news reference to some new papers and issues which have appeared since 2011;
- d) solar flares and extreme space weather reference added in 5.6 to a proposed future Part 6;
- e) reference added in 7.1 to a proposed new Part 7 on incorporating atmospheric radiation effects analysis into the system design process;
- f) reference added in 6.2.10 d) to a proposed future Part 8 on other particles including protons, pions and muons;
- g) clarification on calculating event rates where cross-sections have been obtained with non-atmospheric radiation like neutron sources, addition of a new Annex H, and changes to 5.3 and 8.2.

The text of this standard is based on the following documents:

FDIS	Report on voting
107/271/FDIS	107/275/RVD

Full information on the voting for the approval of this standard 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.

A list of all the parts in the IEC 62396 series published under the general title *Process management for avionics – Atmospheric radiation effects*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This industry-wide International Standard informs avionics systems designers, electronic equipment manufacturers, 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 and protons) 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 ARP4754A (accommodation of hard and soft fault rates in general) will also accommodate atmospheric radiation effect rates.

In addition, this International Standard refers to the JEDEC Standard JESD 89A, which relates to soft errors in electronics by atmospheric radiation at ground level (at altitudes less than 10 000 ft (3 040 m)).

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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

1 Scope

This part of IEC 62396 is intended to provide guidance on atmospheric radiation effects on avionics electronics used in aircraft operating at altitudes up to 60 000 ft (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 International Standard is intended to help avionics 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 documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62239-1:2015, *Process management for avionics – Management plan – Part 1: Preparation and maintenance of an electronic components management plan*

IEC 62396-2:2012, *Process management for avionics – Atmospheric radiation effects – Part 2: Guidelines for single event effects testing for avionics systems*

IEC 62396-3, *Process management for avionics – Atmospheric radiation effects – Part 3: System design optimization to accommodate the single event effects (SEE) of atmospheric radiation*

IEC 62396-4:2013, *Process management for avionics – Atmospheric radiation effects – Part 4: Design of high voltage aircraft electronics managing potential single event effects*

IEC 62396-5, *Process management for avionics – Atmospheric radiation effects – Part 5: Assessment of thermal neutron fluxes and single event effects in avionics systems*

EIA-4899, *Standard for Preparing an Electronic Components Management Plan*

3 Terms and definitions

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

NOTE Users of this international standard can use alternative definitions consistent with convention within their companies.

3.1

aerospace recommended practice

documents relating to avionics which are published by the Society of Automotive Engineers (SAE)

3.2

analogue single event transient

ASET

spurious signal or voltage produced at the output of an analogue component by the deposition of charge by a single particle

3.3

availability

probability that a system is working at instant t , regardless of the number of times it may have previously failed and been repaired

Note 1 to entry: For equipment, availability is the fraction of time the equipment is functional divided by the total time the equipment is expected to be operational, i.e. the time the equipment is functional plus any repair time.

3.4

avionics equipment environment

<aeronautical equipment> applicable environmental conditions (as described per the equipment specification) that the equipment is able to withstand without loss or degradation in equipment performance during all of its manufacturing cycle and maintenance life

Note 1 to entry: The length of the maintenance life is defined by the equipment manufacturer in conjunction with customers.

3.5

capable

ability of a component to be used successfully in the intended application

3.6

certified

assessed and compliant to an applicable standard, with maintenance of a certificate and registration

3.7

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

3.8

component application

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

3.9

component manufacturer

organisation responsible for the component specification and its production

3.10

could not duplicate

CND

reported outcome of diagnostic testing on a piece of equipment

Note 1 to entry: Following receipt of an error or fault message during operation, the error or fault condition could not be replicated during subsequent equipment testing (see IEC 62396-3).

3.11**critical charge**

smallest charge that will cause an SEE if injected or deposited in the sensitive volume

Note 1 to entry: For many electronic components, the unit applied is the pico coulomb (pC); however, for small geometry components, this parameter is measured in femto coulomb (fC).

3.12**cross-section** σ

<in proton and neutron interactions> combination of sensitive area and probability of an interaction depositing the critical charge for a SEE

Note 1 to entry: The cross-section may be calculated using the following formula:

σ = number of errors/particle fluence

Note 2 to entry: The units for cross-section are cm² per electronic component or per bit.

3.13**double error correction triple error detection****DECTED**

system or equipment methodology to test a digital word of information to determine if it has been corrupted, and if corrupted, to conditionally apply a correction

Note 1 to entry: This methodology can correct two-bit corruptions and can detect and report three-bit corruptions. (Used within IEC 62396-3.)

3.14**digital single event transient****DSET**

spurious digital signal or voltage, induced by the deposition of charge by a single particle that can propagate through the circuit path during one clock cycle

Note 1 to entry: See 6.2.4.

3.15**electron**

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

3.16**electronic components management plan****ECMP**

equipment manufacturer's document that defines the processes and practices for applying electronic components to an equipment or range of equipment

Note 1 to entry: Generally, it addresses all relevant aspects of the controlling components during system design, development, production, and post-production support.

3.17**electronic component**

electrical or electronic device that is not subject to disassembly without destruction or impairment of design use

EXAMPLE Resistors, capacitors, diodes, integrated circuits, hybrids, application specific integrated circuits, wound components and relays.

Note 1 to entry: An electronic component is sometimes called electronic device, electronic part, or piece part.

3.18**electronic equipment**

item produced by the equipment manufacturer, which incorporates electronic components

EXAMPLE End items, sub-assemblies, line-replaceable units and shop-replaceable units.

3.19
electronic flight instrumentation system
EFIS

avionics electronic system requiring system development assurance level A and for which the pilot will be within the loop (within the control loop) through the pilot/system information exchange

3.20
expert

person who has demonstrated competence to apply knowledge and skill to the specific subject

3.21
firm error

<semiconductor community> circuit cell failure within an electronic component that cannot be reset other than by rebooting the system or by cycling the power

Note 1 to entry: Such a failure can manifest itself as a soft fault in that it could provide no fault found during subsequent test and impact the value for the MTBUR of the LRU.

Note 2 to entry: See also soft error.

3.22
firm fault

<aircraft function level> failure that cannot be reset other than by rebooting the system or by cycling the power to the relevant functional element

Note 1 to entry: Such a fault can impact the value for the MTBF of the LRU and provide no fault found during the subsequent test.

3.23
fly-by-wire
FBW

avionics electronic system requiring system development assurance level A and for which the pilot will not be within the aircraft stability control loop

3.24
functional hazard assessment
FHA

assessment of all hazards against a set of defined hazard classes

3.25
giga electron volt
GeV

energy gained when an electron is accelerated by an electric potential of 10^9 volts, that is, radiation particle energy of giga electron volts (thousand million electron volts)

Note 1 to entry: The SI equivalent energy is 160,2 pico joules.

3.26
gray
Gy

SI unit of ionising radiation dose, defined as the absorption of one joule (J) of radiation energy per one kilogram (kg) of matter

Note 1 to entry: Related units are centigray (cGy) and rad. 1 cGy is equal to 1 rad.

3.27**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

Note 1 to entry: Hard errors can include SEB, SEGR and SEL. Such a fault would be manifest as a hard fault and can impact the value for the MTBF of the LRU.

3.28**hard fault**

<aircraft function level> permanent failure of a component within an LRU

Note 1 to entry: 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 can impact the value for the MTBF of the LRU repaired.

3.29**heavy ion**

positively charged nucleus of the elements heavier than hydrogen and helium

3.30**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 can be from an electronic fixture external to the beam to enable a closed loop system

Note 1 to entry: The electronic fixture can contain a host computer for the aircraft simulation model. The electronic fixture can also contain appropriate signal conditioning for compatibility with the LRU. In the case of an automatic control function, the outputs from the LRU can 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.

3.31**integrated modular avionics****IMA**

implementation of 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)

3.32**latch-up**

triggering of a parasitic p-n-p-n circuit in bulk CMOS, resulting in a state where the parasitic latched current exceeds the holding current

Note 1 to entry: This state is maintained while power is applied.

Note 2 to entry: Latch-up can be a particular case of a soft fault (firm/soft error) or in the case where it causes electronic component damage, a hard fault.

3.33**linear energy transfer****LET**

energy deposited per unit path length in a semiconductor along the path of the radiation

Note 1 to entry: The units applicable are MeV·cm²/mg.

3.34**linear energy transfer threshold****LET_{th}**

for a given component, the minimum LET to cause an effect at a particle fluence of 1×10^7 ions·cm⁻²

3.35

line replaceable unit

LRU

piece of equipment that may be replaced during the maintenance cycle of the system

3.36

mega electron volt

MeV

energy gained when an electron is accelerated by an electric potential of 10^6 volts, that is, radiation particle energy of mega electron volts (million electron volts)

Note 1 to entry: The SI equivalent energy is 160,2 femto joule.

3.37

mean time between failure

MTBF

measure of reliability, which is the mean time between failure of equipment or a system in service

Note 1 to entry: MTBF is a term from the world airlines' technical glossary referring to the mean time between failure of equipment or a system in service such that it generally requires the replacement of a damaged component before a system/system architecture can be restored to full functionality and thus it is a measure of reliability requirements for equipment or systems.

3.38

mean time between unscheduled removals

MTBUR

measure of reliability, which is the mean time between unscheduled removal of equipment or a system in service

Note 1 to entry: MTBUR is a term from the world airlines' technical glossary referring to the mean time between unscheduled removal of equipment or a system in service that can be the result of soft faults and thus is a measure of reliability for equipment or systems. MTBUR values can have a major impact on airline operational costs.

3.39

multiple bit upset

MBU

energy deposited in the silicon of an electronic component by a single ionising particle and which causes upset to more than one bit in the same word

Note 1 to entry: The definition of MBU has been updated due to the introduction of the definition of MCU, multiple cell upset.

3.40

multiple cell upset

MCU

energy deposited in the silicon of an electronic component by a single ionising particle and which induces several bits in an integrated circuit (IC) to upset at one time

3.41

neutron

elementary particle with atomic mass number of one and which carries no charge

Note 1 to entry: It is a constituent of every atomic nucleus except hydrogen.

3.42

no fault found

NFF

reported outcome of diagnostic testing on a piece of equipment

Note 1 to entry: Following receipt of an error or fault message during operation, the equipment is found to be fully functional and within specification during subsequent equipment testing. See IEC 62396-3.

3.43**particle fluence**

<unidirectional beam of particles> number of particles crossing the unit surface area at right angles to the beam

Note 1 to entry: For isotropic flux, this is the number entering a sphere of unit cross-sectional area.

Note 2 to entry: The units applicable are particle·cm⁻².

3.44**particle flux**

fluence rate per unit time

Note 1 to entry: The units applicable are particle·cm⁻²·s⁻¹.

3.45**pion**

sub-atomic particle

Note 1 to entry: The charge possibilities are (+1, -1, 0) and they are produced by energetic nuclear interactions.

Note 2 to entry: The term "pi-meson" can be used in lieu of "pion" in some documents or standards.

3.46**preliminary system safety assessment****PSSA**

systematic evaluation of a proposed system architecture and implementation based on the functional hazard assessment and failure condition classification to determine safety

Note 1 to entry: See ARP4761:1996, 2.2 [126]¹.

3.47**proton**

elementary particle with an atomic mass number of one and a positive electric charge and which is a constituent of all atomic nuclei

3.48**reliability** **$R(t)$**

for a system with constant failure rate, the conditional probability that a system will remain operational over the time interval 0 to t given by:

$$R(t) = e^{-\lambda t} \text{ and } \lambda = 1/\text{MTBF}$$

3.49**risk**

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

3.50**single bit upset****SBU**

<semiconductor device> radiation absorbed by the electronic component which is sufficient to change a single cell's logic state

Note 1 to entry: After a new write cycle, the original state can be recovered.

¹ Numbers in square brackets refer to the Bibliography.

3.51

single event burnout

SEB

burnout of a powered electronic component or part thereof as a result of the energy absorption triggered by an individual radiation event

3.52

single error correction, double error detection

SECDED

system or equipment methodology to test a digital word of information to determine if it has been corrupted, and if corrupted, to conditionally apply a correction

Note 1 to entry: This methodology can correct one-bit corruption and can detect and report two-bit corruptions.

3.53

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

3.54

single event functional interrupt

SEFI

occurrence of an upset, usually in a complex electronic component (e.g. a microprocessor), such that a control path is corrupted, leading the electronic component to cease to function properly

Note 1 to entry: This effect has sometimes been referred to as lockup, indicating that sometimes the electronic component can be put into a "frozen" state (see 6.2.6).

Note 2 to entry: SEFI can be recoverable by resetting the configuration register (F/F) to default values.

3.55

single event gate rupture

SEGR

<gate of a powered insulated gate component> radiation charge absorbed by the electronic component, which is sufficient to cause gate rupture and is destructive

3.56

single event latch-up

SEL

in an electronic component containing a minimum of 4 semiconductor layers (p-n-p-n), fixed state of a component that occurs when the radiation absorbed by the component is sufficient to cause a node within the powered semiconductor component to be held whatever input is applied until the component is de-powered

Note 1 to entry: Single event latch-up can be destructive or non-destructive.

Note 2 to entry: The ionization deposited by the interaction of a single particle of radiation in an electronic component causes triggering of a parasitic p-n-p-n circuit in semiconductor materials (including bulk CMOS) to occur, resulting in a state where the parasitic latched current exceeds the holding current; this state is maintained while power is applied. Single event latch-up can be a particular case of a soft fault (firm/soft error) or in the case where it causes electronic component damage, a hard fault.

3.57

single event transient

SET

momentary voltage excursion (voltage spike) at a node in an integrated circuit caused by a single energetic particle strike

Note 1 to entry: The specific terms ASET (analogue single event transient) and DSET (digital single event transient) may be used.

Note 2 to entry: See 6.2.4.

3.58
single event upset
SEU

<semiconductor component> radiation absorbed by the electronic component which is sufficient to change a cell's logic state

Note 1 to entry: After a new write cycle, the original state can be recovered.

Note 2 to entry: A logic cell may be a memory bit cell, register bit cell, latch cell, etc.

3.59
single hard error
SHE
single event induced hard error

radiation (in a single event) absorbed by the electronic component, which is sufficient to cause a permanent stuck-bit in the component, and a hard error within the equipment

3.60
soft error

erroneous output signal from a latch or memory cell that can be corrected by performing one or more normal functions of the electronic component containing the latch or memory cell

Note 1 to entry: As commonly used, the term refers to an error caused by radiation or electromagnetic pulses and not to an error associated with a physical defect introduced during the manufacturing process.

Note 2 to entry: Soft errors can be generated from SEU, SEFI, MBU, MCU, and or SET. The term SER has been adopted by the commercial industry while the more specific terms SEU, SEFI, etc., are typically used by the avionics, space and military electronics communities.

Note 3 to entry: The term "soft error" was first introduced (for DRAMs and ICs) by May and Woods of Intel in their April 1978 paper at the IEEE International Reliability Physics Symposium (IRPS) [135] and the term "single event upset" was introduced by Guenzer, Wolicki and Allas of Naval Research Laboratory, Washington DC, in their 1979 IEEE Nuclear & Space Radiation Effects Conference (NSREC) paper [136].

3.61
soft fault

<aircraft function level> characteristic of invalid digital logic cell(s) state changes within digital hardware electronic circuitry

Note 1 to entry: 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 can 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 can impact the value for the MTBF of the LRU repaired.

Note 2 to entry: Logic cell(s) include(s) logic gates and memory elements.

3.62
solar energetic particle event
SEP event

enhancement of solar particles (protons, ions and some neutrons) caused by solar flare activity or coronal mass ejections

Note 1 to entry: 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.

3.63
substitute component
component used as a replacement in equipment after the equipment design has been approved

Note 1 to entry: In some contexts, the term “alternate component” is used to describe a substitute component that is “equal to or better than” the original component.

3.64

system safety assessment

SSA

assessment performed to verify compliance with the safety requirements

3.65

system

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

3.66

total ionising dose

TID

cumulative radiation dose that goes into ionization that is received by an electronic component during a specified period of time

3.67

total mitigation

100 % mitigation

mitigation achieved for certain types of SEE by control of certain stressors within defined parameters in the application

Note 1 to entry: For example SEL and SEB can be 100 % mitigated by limiting supply voltage below the threshold where SEL and SEB occur.

3.68

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

3.69

white neutron source

source providing energetic neutrons with a wide range of energies, the spectrum of which is similar to that of the natural atmospheric or terrestrial radiation up to the maximum energy of the source

4 Abbreviations and acronyms

AC	advisory circular
AIR	atmospheric ionizing radiation
ANITA	Atmospheric-like Neutrons from thick TArget (TSL, Sweden)
ARP	aerospace recommended practices
ASET	analogue single event transient
ASIC	application specific integrated circuit
BL1A, BL1B, BL2C	beam line designations at the TRIUMF facility (Canada) [see IEC 62396-2]
BIT	built-in test
BPSG	borophosphosilicate glass
CECC	CENELEC electronic components committee
CMOS	complementary metal oxide semiconductor
COTS	commercial-off-the-shelf
D-D	deuterium-deuterium

DOE	Department of Energy (USA)
DRAM	dynamic random access memory
DSET	digital single event transient
DSP	digital signal processor
D-T	deuterium-tritium
DUT	device under test
<i>E</i>	energy
ECMP	electronic components management plan
EDAC	error detection and correction
EEPROM	electrically erasable programmable read only memory [see IEC 62396-2]
EPROM	electrically programmable read only memory [see IEC 62396-3]
EFIS	electronic flight instrumentation system
ESA	European Space Agency
eV	electron volt
EXPACS	EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum
FBW	fly-by-wire
FHA	functional hazard assessment
FIT	failure in time
FPGA	field programmable gate array
GCR	galactic cosmic rays
GeV	giga electron volt
GLE	ground level event
GNEIS	Gatchina Neutron Spectrometer (Russia) [used within IEC 62396-2]
GSFC	Goddard Space Flight Center
GV	giga-volt (rigidity unit)
HW	hardware
IBM	International Business Machines
IC	integrated circuit
ICE	irradiation of chip and electronics (WNR)
IEEE	Institute of Electrical and Electronics Engineers
IEEE Trans. Nucl. Sci.	IEEE Transactions on Nuclear Science
IGBT	insulated gate bipolar transistor
IGRF	International Geomagnetic Reference Field
IMA	integrated modular avionics
IRPP	integral rectangular parallelepiped
IUCF	Indiana University Cyclotron Facility (USA)
JEDEC	JEDEC Solid State Technology Association
JESD	JEDEC standard
JPL	Jet Propulsion Laboratory (USA)
LANSCE	Los Alamos Neutron Science Center (USA)
LET	linear energy transfer
LET_{th}	linear energy transfer threshold

LRU	line replaceable unit
MBU	multiple bit upset (in the same word)
MCU	multiple cell 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 Administration (USA)
PCN	product change notification
PIF	Proton Irradiation Facility (TRIUMF, Canada)
PNPI	Petersburg Nuclear Physics Institute (Russia) [see IEC 62396-2]
PSG	phosphosilicate glass [used within IEC 62396-2]
PSI	Paul Scherrer Institute (Switzerland)
PSSA	preliminary system safety assessment
PWM	pulse width modulator
QARM	Quotid Atmospheric Radiation Model
QMN	quasi mono-energetic neutrons
RADECS	RADIation Effects on Components and Systems
rad	deprecated Gaussian-cgs (centimeter-gram-second) unit of radiation absorbed dose
RAL	Rutherford Appleton Laboratory
RAM	random access memory
RCNP	Research Center of Nuclear Physics (Osaka, Japan) [used within IEC 62396-2]
RPP	rectangular parallelepiped
SAFETI	Systems and Airframe Failure Emulation Testing and Integration
SBU	single bit upset
SC	stacked capacitance
SDRAM	synchronous dynamic random access memory
SEB	single event burnout
SEDED	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-up
SEP	solar energetic particles
SER	soft error rate
SET	single event transient
SEU	single event upset
SHE	single event induced hard error
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
TNF	TRIUMF neutron facility (TRIUMF, Canada)
TRIUMF	Tri-University Meson Facility (Canada)
TSL	Theodor Svedberg Laboratory (Sweden)
WNR	Weapons Neutron Research Los Alamos National laboratory (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 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. GCR 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 $3 \text{ particle}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$, and at aircraft altitudes, the flux of all secondary particles is about $10 \text{ particle}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$. 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 $0,1 \text{ particle}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$.

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 electronic devices within aircraft avionics systems and cause single event effects (SEEs) 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 electronic 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:

- a) the variations of the upset rates against altitude and geographic latitude followed the variation of the neutron flux with altitude and latitude;

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

5.3.2 Atmospheric neutrons energy spectrum and SEE cross-sections

5.3.2.1 Natural 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 MeV 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 four neutron spectra at an altitude of approximately 40 000 ft (12,2 km) are plotted. These include the original measurements made by Hess in 1959 [1], a calculation by Armstrong in 1973 [2], a fit to measurements by Hewitt et al at NASA in 1977 [3], and the recent DOE measurements by a fit to measurement by Goldhagen in an ER-2 aircraft during 1997 [4].

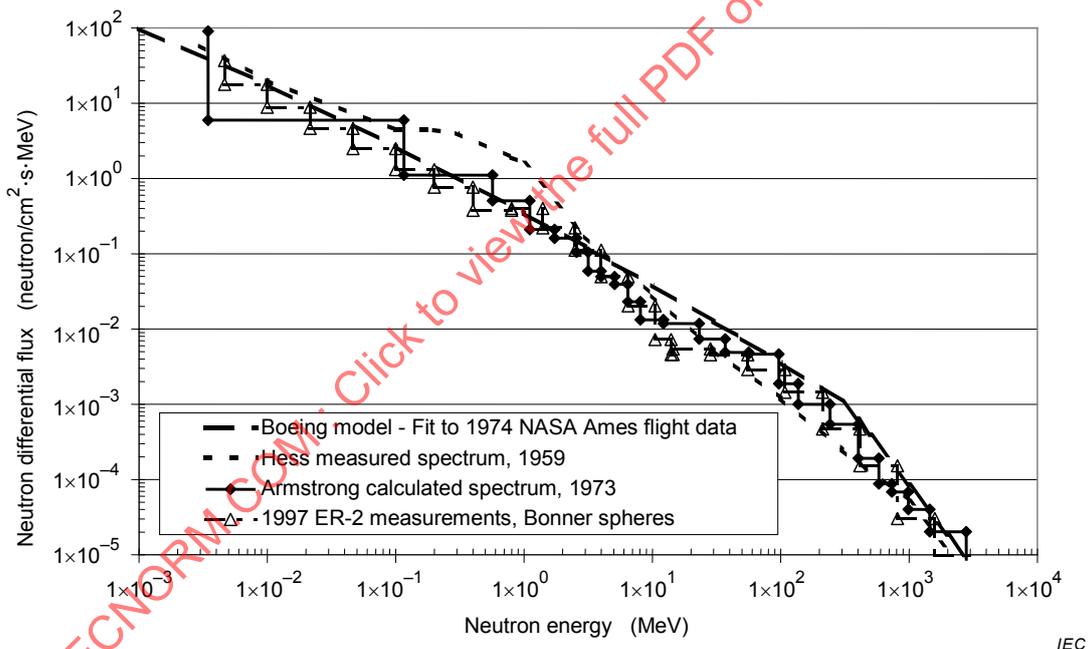


Figure 1 – Energy spectrum of atmospheric neutrons at 40 000 ft (12 160 m), latitude 45°

A fit to the NASA Ames Research Center’s 1974 flight 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 measurement data. It should be noted that when this differential flux is integrated for energy 10 MeV, the integrated neutron flux is ~5 600 neutron·cm⁻²·h⁻¹ which can be rounded up to 6 000 neutron·cm⁻²·h⁻¹. This nominal high energy neutron flux of 6 000 neutron·cm⁻²·h⁻¹ at 40 000 ft (12,2 km) and geographic latitude 45° may be treated as a typical or nominal in-flight envelope and scaled for different avionics applications (for example, for altitude variation per measurements). The modified spectrum is given, with energy in MeV, as

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

It should be noted that when this differential flux is integrated for energy > 10 MeV, the integrated neutron flux is $\sim 5\,600$ neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ which can be rounded up to 6 000 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$. This nominal high energy neutron flux of 6 000 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ at 40 000 ft (12,2 km) and geographic latitude 45° may be treated as a typical or nominal in-flight envelope and scaled for different avionics applications (for example, for altitude variation as in 5.3.3 and for latitude variation as in 5.3.4). For lower energies, the model gives a flux of 3 200 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ for $1\text{ MeV} < E < 10\text{ MeV}$, with 1 600 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ in the range of $1\text{ MeV} < E < 3\text{ MeV}$ and 1 600 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ in the range of $3\text{ MeV} < E < 10\text{ MeV}$. This flux of 6 000 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ for $E > 10\text{ MeV}$ is conservative by a factor of approximately 2 compared to the ER-2 aircraft measurement results. At ground level the flux is approximately a factor of 300 lower than at 40 000 ft (12,2 km), thus on the ground, the flux for energy $> 10\text{ MeV}$ is 20 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$, [5] and this agrees with an independently derived calculation for New York City [6].

The greater than 10 MeV neutrons will be the dominant cause of SEE on sensitive electronic devices with geometric feature size above 150 nm, however for devices with feature size at and below 150 nm the contribution of neutrons with energy between 1 MeV and 10 MeV may be significant. Therefore for electronic device feature sizes 150 nm and below the effects due to neutrons with energy in the range $1\text{ MeV} < E < 10\text{ MeV}$ shall be included when calculating SEE rates.

In order to make relevant SEE calculations for electronic devices with feature sizes below 150 nm, it can be valuable to understand how the available SEE cross-section(s) was/were determined.

5.3.2.2 White neutron spectrum cross-sections

If the available cross-section(s) was/were determined from neutron experiments where a white neutron energy spectrum representative of the atmospheric spectrum was used (the test beam includes neutrons with energy in the range $1\text{ MeV} < E < 10\text{ MeV}$ and above 10 MeV, representative of the atmospheric spectrum), the experimental results include SEE caused by neutrons with energy in the range $1\text{ MeV} < E < 10\text{ MeV}$. Therefore, the calculated cross-section includes those SEE contributions from neutrons with energy in the range $1\text{ MeV} < E < 10\text{ MeV}$ (if any). For those cross-sections, the neutron fluence reference energy originally used to calculate the cross-section (if JESD 89A is used, the neutron fluence at 10 MeV is specified) provides the key for the applicable energy range for the use of neutron flux that will yield appropriate use condition SEE rates. Facilities which provide high energy white neutron radiation sources include WNR, TRIUMF (TNF), ISIS (RAL), ANITA (TSL) and terrestrial facilities.

Because a cross-section measured with a white spectrum atmospheric neutron beam contains SEE contributions at lower energies, the white neutron spectrum cross-section can be used without modifications for all energy ranges covered by the cross-section tests. For example, for cross-sections measured in a white neutron spectrum beam and following JESD 89A (JESD 89A specifies the cross-section be calculated using the 10 MeV fluence), the nominal neutron flux at 10 MeV of 6 000 neutron \cdot cm $^{-2}\cdot$ h $^{-1}$, may be used to determine the appropriate SEE rate. Thus the nominal event rate for such cross-sections ($E > 10\text{ MeV}$) is given by:

$$\text{Nominal event rate} = \text{cross-section } (E > 10\text{ MeV}) \times 6\,000 \text{ events per hour}$$

Sometimes the white neutron cross-sections are quoted for neutrons with energy above 1 MeV, and the nominal event rate for such cross-sections ($E > 1\text{ MeV}$) is then given by:

$$\text{Nominal event rate} = \text{cross-section } (E > 1\text{ MeV}) \times 9\,200 \text{ events per hour}$$

Using cross-sections and fluxes based on a $> 1\text{ MeV}$ threshold introduces additional uncertainty. Therefore, this should only be done if, for some reason, the $> 10\text{ MeV}$ cross-section is unavailable.

5.3.2.3 Non-white neutron spectrum cross-sections or unknown cross-sections

For cases where the SEE cross-sections were measured by methods where the SEE contributions from neutrons with energy in the range $1 \text{ MeV} < E < 10 \text{ MeV}$ potentially have not been included, the contributions from these lower energy ranges can be estimated for some electronic devices by using an enhanced figure for neutron flux in the error rate calculation. Non-atmospheric spectrum beam types include mono-energetic proton beams and quasi-mono-energetic neutron beams. Because beam spectra are not representative of the natural atmospheric radiation spectra the tolerance on the error rate is larger than in 5.3.2.2.

- For electronic devices with feature size above 160 nm the nominal SEE rate is calculated using the $E > 10 \text{ MeV}$ cross-section and nominal neutron flux of $6\,000 \text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$. For feature sizes above 160 nm this flux is considered to be sufficiently conservative to accommodate the effects from lower energy neutrons.
- For electronic devices with geometric feature size 160 nm and below the effects due to lower energy neutrons shall be included, and consideration of the low energy thresholds for smaller geometry devices is provided in Annex H. Table H.1 provides the approximate neutron energy thresholds versus electronic device technology feature size. Table H.2 provides the recommended nominal neutron fluxes for different electronic device technology feature sizes when using non-white neutron (non-atmospheric like) radiation sources. The method to calculate nominal event rates for the smaller geometry electronic devices is given in Clause H.3.

NOTE 1 The original guidance based on reference [7] that the contribution from the $1 \text{ MeV} < E < 10 \text{ MeV}$ neutrons to the overall SEE rate is 10 % is no longer recommended for the smaller geometry electronic devices.

NOTE 2 The values of neutron flux given in Table H.2 can be scaled to other altitudes and latitudes, using the Tables D.1 and D.2.

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 ft (18,3 km), called the Pfozter maximum that can be seen in Figure 2. The figure compares the altitude variation of the 1 MeV to 10 MeV neutron flux. A much more rigorous approach was taken by NASA-Langley in developing a model that is currently called AIR [10]. It utilised measurements made on aircraft during the 1960s and 1970s, and developed a model that gives the 1 MeV to 10 MeV neutron flux as a function of three parameters, the atmospheric depth ($\text{g}\cdot\text{cm}^{-2}$), vertical rigidity cut-off (GV) and solar weather conditions.

A still more rigorous model has been developed based on extensive calculations incorporating three key steps, the calculation of the initial cosmic ray spectrum, the rigidity cut-off calculation and a Monte Carlo code to generate and transport the secondary particle radiation through the atmosphere. This code package is called the Quotid Atmospheric Radiation Model (QARM) [12] and it can be accessed and utilised via the Internet link [11]. It can provide estimates of the secondary cosmic ray particle fluxes and spectra at all locations for all particles including neutrons and protons. A similar code package that is also available via the Internet is called EXPACS (Excel-based programme for calculating atmospheric cosmic-ray spectrum [13]), and is based on analytical functional fits to Monte Carlo-generated spectra [14]. QARM and EXPACS yield similar results for the atmospheric neutron spectrum [15]. Predicted SEU rates in the atmosphere based on using QARM for six different SRAMs are about a factor of 2 lower than rates calculated using the neutron spectrum (see 5.3.2) in this standard [15].

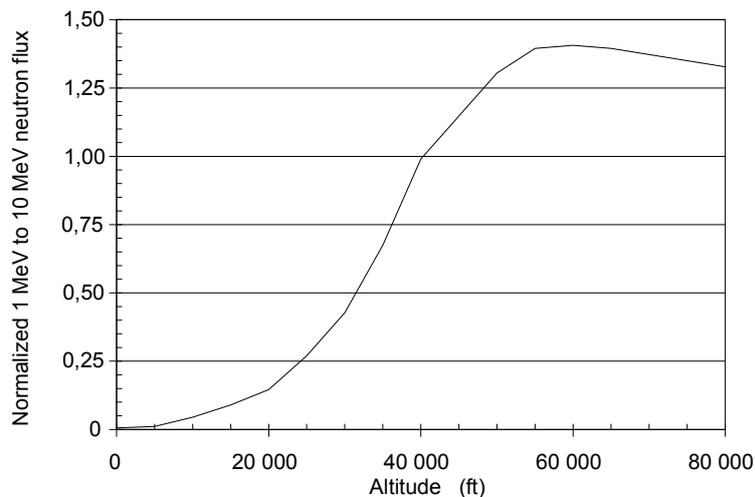


Figure 2 – Model of the atmospheric neutron flux variation with altitude (see Annex D)

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 ($R \sim 15$ 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 [16] is shown in Figure 3.

Figure 3 shows the distribution of vertical rigidity cut-off curves across the globe based on the 1980 epoch that was developed in [16], combining measurements and calculations, with the rigidity cut-offs being averaged over geographical longitude for each 5° in geographical latitude. The reference [16] authors updated their rigidity cut-off model with a new set of data from the year 1995 and it is tabulated in JESD 89A. This newer set of calculations and measurements produced a model with rigidity values within $1^\circ \times 1^\circ$ accuracy. These rigidity values were averaged over broader angular bins (5° in latitude \times 15° in longitude) and these averaged values are tabulated in Annex A of JESD 89A:2006. Based on a comparison of the updated rigidity values from JESD 89A (1995 epoch) with the older values in Figure 3 (1980 epoch), the rigidity cut-off values have decreased slightly. A comparison was carried out at a longitude of 0° and for latitudes ranging between 30° and 60° . In most cases the change was a decrease of $\sim 0,15$ to $0,2$ in the overall vertical rigidity across all latitude levels. Since the change in rigidity was approximately constant, the percentage change was much higher at higher latitudes where the absolute value of the rigidity is smaller. Thus, for latitudes $< 50^\circ$, the percentage decrease was $< 5\%$, for 50° to 55° it was between 5% and 7% , and for 60° it was $\sim 15\%$. These variations in the vertical rigidity cut-offs due to changes in the geomagnetic field over a 15-year period appear to be small enough to indicate that the corresponding change in the atmospheric neutron flux will be relatively small, and Figure 3 is still useful. Fully up to date cut-off rigidities are available through the QARM model [12] using trajectory integrations in the latest IGRF magnetic field plus external source terms dependent on the geomagnetic disturbance index (K_p) using the Tsyganenko 2001 model. The QARM model can be accessed and utilised via the internet link [11]. These rigidities can be computed on-line for any selected location. For flight path calculations a set of 49 pre-calculated maps is used. Geomagnetic disturbances can significantly lower the cut-off rigidity (by about a factor 2

for $K_p = 6$ for a 1 GV cut-off at zero disturbance). The influence on particle fluxes can be about 10 % for galactic cosmic rays but by factors of 5 or more during solar particle events.

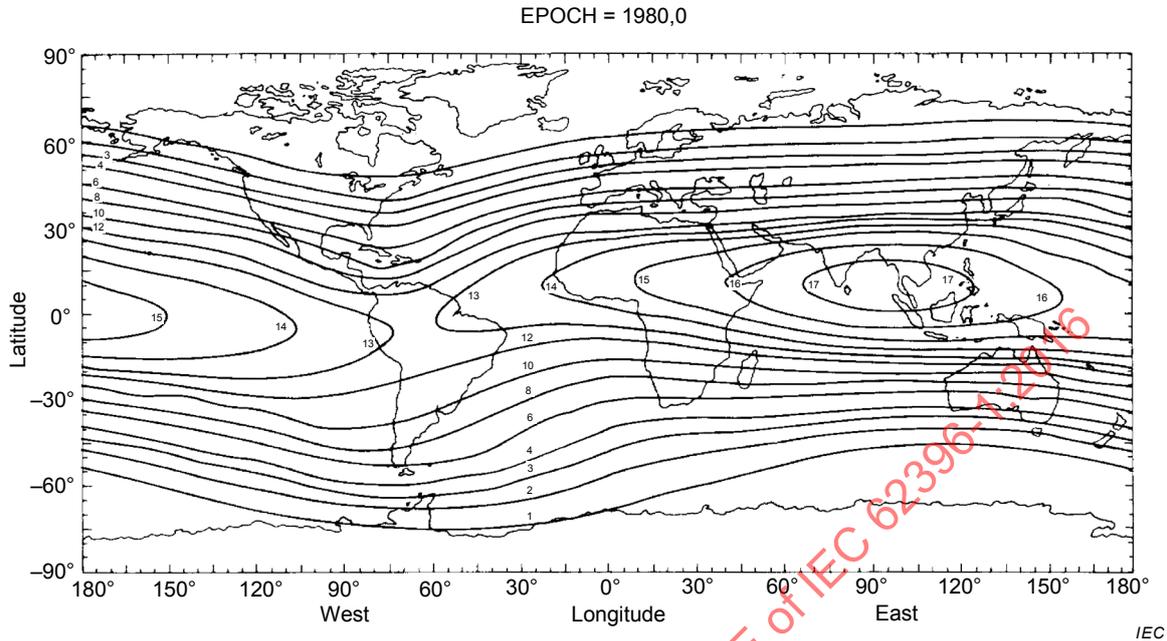


Figure 3 – Distribution of vertical rigidity cut-offs around the world

Two models are also available for the variation of the 1 MeV 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 [17]. 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 MeV to 10 MeV neutron flux, originally given as a function of rigidity cut-off, to be converted to a curve of the 1 MeV to 10 MeV neutron flux as a function of latitude and this is shown in Figure 4.

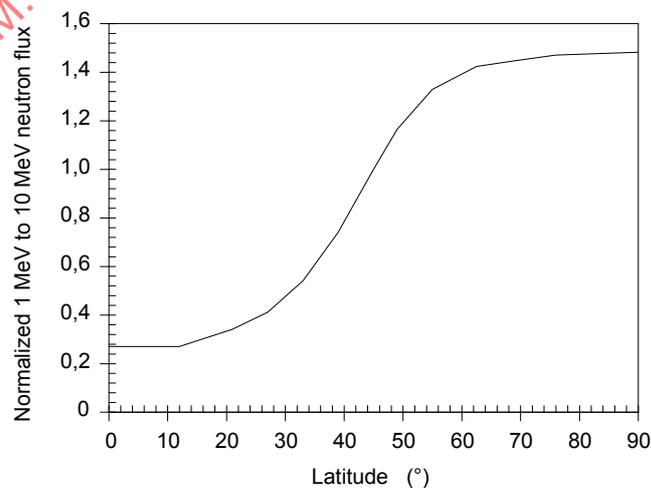


Figure 4 – Model of atmospheric neutron flux variation with latitude

The variation of the neutron flux with altitude shown in Figure 2 for energies 1 MeV to 10 MeV has also been shown to apply for neutrons with higher energies [9]. Therefore Figure 2 and Figure 4 can be used to scale the greater than 10 MeV neutron flux of $6\,000\text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ which applies at 40 000 ft (12,2 km) and 45° latitude to other altitudes and latitudes. It should be noted that there is a strong dependence of cut-off rigidity and hence particle fluxes on longitude and this is shown in the QARM model. For example, at 45° latitude there is a factor 5 variation in cut-off rigidity with longitude and this translates into a factor 3 variation in neutron fluxes from galactic cosmic rays.

The 1 MeV to 10 MeV neutrons have a significant SEE contribution for electronic devices with geometries 150 nm and below (see 5.3.2).

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 an electronic device with a combined 2,3 MeV of energy; if this energy is deposited within the sensitive volume of an electronic device, it can lead to SEU.

To date, only one study has attempted to calculate the thermal neutron flux within an aeroplane [18]. The hydrogenous materials within an aeroplane, the fuel, the passengers, the 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. The number of measurements of SEU cross-sections in electronic devices induced by thermal neutrons is very limited (see 8.3.3), but more recent references significantly expand on this data [19, 20, 21, 22].

The subject of thermal neutron effects is covered in more detail in IEC 62396-5.

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, [23, 24]) and from one balloon experiment [24]. The mountain-top data indicates a peaking in the differential proton flux at about 200 MeV 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 $100\text{ MeV} < E < 750\text{ MeV}$, the variation with altitude is very similar to that of the neutrons [25], i.e., there is a maximum at $\sim 80\text{ g}\cdot\text{cm}^{-2}$ (55 000 ft (16,8 km)), the Pfozter 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 $6\,000\text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ ($E > 10\text{ MeV}$) is conservative, the contribution of the protons to the SEE rate can be considered as being included within the neutron-induced SEE rate.

Nevertheless as discussed in 6.2.10, item c), in the low energy domain, protons may interact through ionization and contribute to the error rate of technologies below 90 nm.

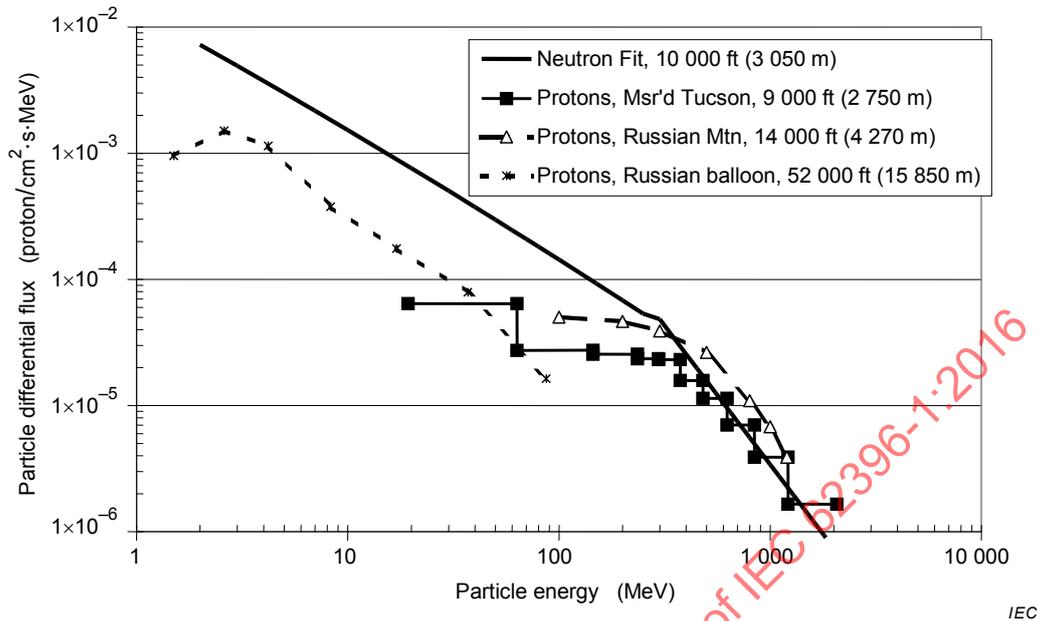


Figure 5 – Energy spectrum of protons within the atmosphere

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 $\sim 0,1$, and it applies at both aircraft altitudes, $500 \text{ g}\cdot\text{cm}^{-2}$ (20 000 ft (6,1 km)), as well as at ground level [26]. At 40 000 ft (12,2 km) and at an energy of 1 GeV, the differential pion flux has been calculated to be $\sim 1/30$ that of the neutrons and protons (the differential neutron and proton fluxes are about equal), and at 100 MeV, the differential pion flux is $\sim 1/100$ that of the neutron flux [27]. 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. The QARM model [12] can provide detailed flux and spectrum information within the atmosphere for these other cosmic ray secondary particles, including protons. Annex E provides consideration of effects at higher altitudes, above 60 000 ft (18 290 m).

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 an 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 is 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 $\text{g}\cdot\text{cm}^{-2}$ 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 ft (18,3 km) may additional consideration need to be given for the effects of heavy ions [28, 29], as well as for the effects from primary cosmic rays and their secondary fragments. At present, the QARM model [12] does not provide information on the reduced fluxes of primary cosmic ray heavy ions and their secondary fragments within the atmosphere although enhancements are in hand.

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 [30, 31]. The SEP enhancement in the atmospheric neutron flux, relative to the background flux (>10 MeV) of $6\,000$ neutron \cdot cm $^{-2}\cdot$ h $^{-1}$ 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 $39\,000$ ft (12 km) are 41 and $1,6$ for rigidities of 0 GV and 3 GV respectively, and at an altitude of $56\,000$ ft (17 km) the factors increase to 73 and $2,4$ respectively. With the February 1956 flare, for which the incoming particle spectrum is less well characterized, the enhancement factor is 263 at 0 GV and $39\,000$ ft (12 km). Thus, extremely high SEE rates could occur in the high latitude regions ($R \leq 1$ GV) during worst case flares that could be enhanced by a factor as high as 300 at $39\,000$ ft (12 km). Such very large events are termed extreme space weather, with, typically, enhancements of more than 100 times nominal fluxes. This subject will be covered in more detail in a future new part of the IEC 62396 series (IEC TS 62396-6).

These events are usually of short duration (several hours) and for worst case take-off times are contained within the duration of long haul flights. Hence although the worst case instantaneous rate enhancement is as high as a factor of 263 the increased SEE rate averaged over a high latitude flight would be more like 25 times the solar minimum quiet-time rate. The QARM model includes seven solar particle events which have been modelled in detail [32]. Five of these have been compared favourably with the limited available flight data on air crew dose. Use of these events in QARM enables the worst case flight scenarios with respect to take-off time to be determined. The February 1956 event is the worst case available, and based on ground level data is the worst since such monitoring commenced in 1942 . However, based on the indirect evidence of nitrate samples in ice cores, the first solar flare ever observed (the Carrington event of 1 September 1859) could have been four times worse [33, 34]. In addition analysis of events with respect to air crew dose [35] shows that four other events in the 1940 s could have exceeded 10 times the normal flight-averaged dose or SEE rate at high latitude and $39\,000$ ft. With the more recent events of 29 September 1989 and 20 January 2005 (this fortunately only at high southern latitudes due to large anisotropy in arrival directions) also in this category, the frequency of such worst case events should be taken as seven in 67 years. Some 23 other events (e.g. 15 April 2001) could have given route-averaged rates at high latitude ranging from 10% to 200% of quiet time over this time period.

5.7 High altitudes greater than $60\,000$ ft ($18\,290$ m)

Although neutrons are the dominant cause of SEEs up to about $40\,000$ ft ($12,2$ km) other particles become increasingly important at higher altitudes. Protons contribute to the neutron rate at $60\,000$ ft ($18,3$ km) and above $60\,000$ ft ($18,3$ km), while above this altitude there is significant penetration of cosmic ray heavy ions and their secondary fragments. In addition the importance of solar particle events increases and the February 1956 event would have

been six times worse at 60 000 ft (18,3 km) compared to 40 000 ft (12,2 km). Currently models such as QARM include neutrons and protons but not heavy ions.

Heavy ions produce SEE by direct ionization and techniques such as CREME96 [36, 37] are used for space systems. These are based on the characterisation of the environment by the spectrum of particles as a function of linear energy transfer (LET). This is usually plotted in integral form, i.e. the flux of particles having greater LET. The path length distribution through a parallelepiped representation of an electronic device sensitive volume is then employed to give the spectrum of charge depositions and hence a number greater than a device threshold for SEE. Earlier work [28] has presented LET spectra for the upper atmosphere using semi-empirical cross-sections for heavy ion interactions and the generation of fragments. Modern Monte Carlo radiation transport codes such as FLUKA [38] now contain physics modules to deal with ion-ion collisions and these are being applied to generate response functions for the atmosphere.

Annexes E and F give details of the high altitude environment and calculation of SEE rates produced by heavy ions as well as neutrons and protons. Figure E.6 and Figure E.7 can be effectively used to estimate the SEU contribution from the three particles (neutrons, secondary protons and primary cosmic ray heavy ions) within the atmosphere as a function of altitude, based on the SEU response of a particular SRAM. From Figure E.6 and Figure E.7 the neutron SEU contribution is seen to decrease at altitudes above 60 000 ft, the proton contribution reaches a plateau at 60 000 ft and the heavy ion contribution increases significantly above 80 000 ft.

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 Clause 6, single event effects, total ionising dose and displacement damage. It is shown that some single event effects have an impact on 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 neutrons.

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 (SEEs)

6.2.1 General

All single event effects (SEEs) are caused by the deposition of energy within an electronic device by a single particle that interacts with the device. The energy deposition, which occurs either directly or indirectly, leads to a charge being collected. When the incoming particle is charged (for example, cosmic ray heavy ion), the ionization 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 LET (linear energy transfer), energy/path length), the more likely 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 and has a low LET in silicon but has been shown to cause SEE by direct ionization in electronic devices with geometry at and below 90 nm. 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 electronic 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, SEEs have been observed in electronic devices used in aircraft since the early 1990s [5, 8, 39, 40, 41]. In the existing literature, SEUs in memory devices 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 sensitive to SEU has increased geometrically over the last decade (more bits per electronic device, greater functionality leading 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)

A single event upset (SEU) is the most common type of a single event effect. SEU is caused by the deposition of charge in an electronic device by a single particle that is sufficient to change the logic state of a single bit from one binary state to the other. SEUs are sometimes called soft errors because they are readily corrected by reinitialising the bits. Electronic devices sensitive to SEUs generally have been memory bits, register bits or latches. Random access memories are generally the most sensitive electronic 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 sensitivity increases as the applied supply voltage decreases.

More recently the potential for SEU due to thermal neutrons has been observed in high density complex electronic devices that have very small feature size and a low critical charge for upset. Thermal neutrons are produced when 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 (see 8.3.3). These electronic 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 electronic 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) and multiple cell upset (MCU)

Multiple bit upset (MBU) refers to multiple bits (bits that are in the same logical word) being upset during the same SEE interaction. MBU differs from multiple cell upset (MCU) in which two or more bits (cells) are upset, usually bits physically located near each other, but not necessarily in the same logical word. The multiple cell upset (MCU) fraction (probability of MCU/probability of SEU or MCU cross-section (multiplicity > 1)/SEU cross-section) increases with the decreasing feature size and with more recent IC fabrication in a dramatic way. This is

believed to be due to charge sharing, i.e., the charge deposited by the energetic neutron interacting with the SRAM is being shared by a number of adjacent memory bits.

With regard to SRAMs, those fabricated in around 2003 had an MCU fraction of ~3 % for 130 nm electronic devices but of ~6 % for 90 nm electronic devices when tested in a spallation neutron beam in Japan [42]. However, based on a later compilation of such data [43] from eight different sources, including reference [42], the MCU fraction was definitely increasing with decreasing feature size, however there appear to be two separate trendlines. For one set of electronic devices the MCU fraction starts relatively low, similar to reference [42] (~2 % for 150 nm electronic devices), but increases by about a factor of 20 as the feature size decreases from 150 nm to 50 nm. For the other set of electronic devices the MCU fraction starts much higher, for example ~40 % for 150 nm electronic devices, but increases much more slowly, by about a factor of 2 as the feature size decreases from 150 nm to 50 nm. Further, more recent data has shown substantially wider variations, with data points falling in between the two trendlines. What is consistent with the two trendlines is that when extrapolating out to a feature size of ~35 nm, the MCU fraction will be 1,0 i.e. all SEUs will result in two or more bits being upset.

One of the recent papers [44] also investigated the effect of changing the angle of incidence of the neutron beam striking the electronic device on the MCU fraction. The MCU fraction increased with the angle of incidence, it was lowest for normal incidence and highest for grazing incidence (90°), but the overall measured increase over normal incidence was at most ~80 % at 90° and ~30 % at 45°.

The variation of the MCU fraction with energy was examined [45] via testing with mono-energetic protons and the overall conclusion is that the MCU fraction decreased very slightly with decreasing energy. The variation with proton energy was not uniform, but the approximate decrease in the MCU fraction was from ~25 % for $E = 200$ MeV to 20 % for $E = 46$ MeV for the first electronic device, and from ~18 % for $E = 200$ MeV to ~15 % for $E = 32$ MeV for the second device.

Thus for SRAMs, the MCU rate as a fraction of the SEU rate primarily depends on the feature size (and more crudely the year of fabrication) of the electronic device, with the neutron/proton energy having a very small effect and the angle of incidence having a larger effect. The large variation in the MCU fraction in the various SRAMs tested by the different researchers cited above should be duly noted. As a result, only the conservative upper bounds summarized below can be provided for the MCU fraction in SRAMs, and even these are not the most conservative values that could be used. If these values are considered too high, individualized SEE testing would be required to measure the MCU fraction in actual devices.

For older electronic devices, fabricated prior to 2003, the guidance in the original IEC TS 62396-1:2006 was that an MCU fraction of 3 % should be used. For electronic devices fabricated between 2003 and 2006, an MCU fraction of 10 % may be used. For electronic devices fabricated after 2006 and in particular for feature sizes of <100 nm, an upper bound of 30 % may be used.

For DRAMs the situation is much different, because DRAMs contain control logic in their periphery. Thus when this logic is upset, entire bitlines and rows can be upset, resulting in thousands of bits being in error due to a single neutron hit. Such thousand bit errors are called burst errors and can often be considered as a SEFI rather than a multiple cell upset.

The MBU / MCU fraction relative to SEU increases with incident particle energy and has been observed to be 7 % for 63 MeV protons on 16 Mbit DRAMs. Multiplicities up to 4 have been observed for protons and of 19 for ions [46, 47].

Utilising the data from [48], the situation regarding MCU in DRAMs can be generalized based on the feature size, similar to the crucial role played by feature size regarding MCU in SRAMs. At a feature size of 180 nm, the MCU fraction is about 5 %, and for electronic devices

with larger feature sizes, the guidance in the original IEC TS 62396-1:2006 indicates that an MCU fraction of 3 % should be used. However, for the 180 nm electronic devices, multi-thousand bit upsets are possible, but there is wide variation in the SEFI response of the two SDR DRAMs in which it was measured. The SEFI/SBU ratio varied between 0,3 % to 24 % and the absolute cross-section varied between $3,5 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$ to $1,3 \times 10^{-10} \text{ cm}^2 \cdot \text{device}^{-1}$.

For 110 nm DRAMs, the fraction for classical MCU is very uncertain because of the tremendous variation in the MCU fraction, which varies from 2 % to 100 % in the three different electronic devices tested, all 512 Mbit DDR2 devices. However, in terms of absolute MCU cross-section the variation is much smaller, between $\sim 1 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$ to $3,5 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$. For the SEFI type of event that results in 1×10^3 to 1×10^4 erroneous bits, SEFI was much more likely than SBU. Thus, the SEFI/SBU ratio (per device basis) varied between ~ 1 to 20, with an average value of ≈ 5 , and the absolute SEFI cross-section varied between $1 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$ and $2 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$.

For 90 nm DRAMs, the situation is similar to that of the 110 nm DRAMs. However, only one of the four 90 nm DDR2 devices tested exhibited the classical MCU, and for this electronic device, the MCU fraction was 14 %. All four DDR2 showed the SEFI type of response of thousands of errors, but in this case, SBU was more likely than SEFI, and for these four the SEFI/SBU ratio was ~ 15 %. The absolute SEFI cross-section varied between $4 \times 10^{-12} \text{ cm}^2 \cdot \text{device}^{-1}$ and $4 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$. However, in a separate test of DDR and DDR2 DRAMs of 90 nm to 110 nm [49], electronic devices from two vendors exhibited burst errors, while four separate electronic devices from a third vendor showed no burst errors. Thus, the sensitivity to burst errors varies among DRAM vendors, some electronic devices being immune.

In summary, it appears that the multi-thousand bit burst or SEFI events are more of a problem than the classical 2-bit or 3-bit MCU, but DRAMs from some vendors are sensitive to the burst errors, though not from all vendors. For electronic devices that are sensitive to burst errors, the overall trend in the absolute SEFI cross-section appears to be gradually decreasing with feature size, from $\sim 1 \times 10^{-10} \text{ cm}^2 \cdot \text{device}^{-1}$ for 180 nm to $\approx 1 \times 10^{-11} \text{ cm}^2 \cdot \text{device}^{-1}$ for 90 nm. For high density memories, due to the more complex architecture of peripheral parts/functions a higher SEFI distribution can be expected [50].

6.2.4 Single effect transients (SETs)

An SEU-related event in some electronic devices can lead 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 by 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. In analogue devices the SET may be manifested as a change in the timing of voltage or current signals, and is dependent on the magnitude of the driving differential voltage. 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 [51, 52, 53], hence the atmospheric neutrons also cause this kind of effect.

A digital single event transient (DSET) is a spurious digital signal or voltage, induced by the deposition of charge by a single particle that can propagate through the circuit path during one clock cycle. As the frequency of digital electronics has risen above 100 MHz the potential for DSET has increased. A DSET that is clocked into a flip flop or register may appear as an SEU in that element.

An analogue single event transient (ASET) is a spurious signal or voltage produced at the output of an analogue device by the deposition of charge by a single particle. This erroneous

output may persist long enough to provide false values to monitoring circuit elements, for example analogue to digital converters, effectively providing corrupt data.

6.2.5 Single event latch-up (SEL)

A single event latch-up (SEL) is a regenerative current flow condition in which a parasitic n-p-n-p pathway in a silicon electronic 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 ($> 10 \mu\text{m}$) 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 sensitive to proton and neutron-induced latch-up [54, 55]. SEL sensitivity 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 [56]; other specialized mechanisms have been observed to impact bipolar devices [57, 58].

6.2.6 Single event functional interrupt (SEFI)

A single event functional interrupt (SEFI) refers to an SEU in an electronic device, usually a complex electronic device (for example, a microprocessor), such that a control path is corrupted, leading the device to cease to function properly. This effect has sometimes been referred to as lockup, indicating that the electronic device has been put into a “frozen” state. Generally, SEFI is brought about by an 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 electronic device vendor only for pre-screen testing. In some electronic devices such as DRAMs [59] and FPGAs [60], 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)

Electronic 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 sensitive 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 electronic 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 [61]. 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 electronic devices, those with a rated V_{DS} of $\geq 400 \text{ V}$, 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 [62]. 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 electronic devices in avionics is a potential concern. Laser testing may be used to determine sensitivity of high voltage electronic devices to SEB (see B.5). The effects of atmospheric radiation on high voltage electronics and design mitigation are detailed in IEC 62396-4.

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 electronic devices [62] 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 electronic devices such as field programmable gate arrays (FPGAs) 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 (SHEs). 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 then produces an observable error. In the early occurrences of these hard errors, the errors 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 electronic devices (in this case a 64 Mbit DRAM, [63]), protons, and hence atmospheric neutrons, are capable of inducing stuck bits.

6.2.10 SEE potential risks based on future technology

As technology develops in the future the impact of atmospheric radiation on electronic devices will increase and the following list highlights potential impact.

- a) Effects of MBU and MCU for future electronic devices of ≤ 35 nm: an MCU fraction of 100 % should be expected.

The MCU rate for SRAM devices fabricated before 2003 with feature sizes 200 nm and above is typically a few per cent. As feature sizes of more recent SRAM devices have reduced to 150 nm, the MCU rate has increased to about 40 % and the expectation is that for feature sizes of 35 nm and below, an MCU fraction of 100 % will result.

- b) Effects on small geometry flash ROM

Traditionally the non-volatile ROM memory has been very tolerant of the neutrons in atmospheric radiation. However at feature sizes approaching and lower than 100 nm the memories may become sensitive to various SEEs, including SEFI.

- c) Direct ionization by protons is significant for 65 nm and below

Testing of SOI SRAMs at feature sizes of 90 nm and below shows that there is no threshold energy for proton-induced upsets in some electronic devices, and the cross-section in fact increases below 1 MeV [64, 65]. Direct ionization by protons at high LET values near the end of the track, as opposed to nuclear reactions, is sufficient to give SEU in such electronic devices. These low energy, or stopping, protons are generated in materials local to the electronic device and will add to the SEU rates.

For electronic devices used in large fielded systems such as aircraft, the greater the mass surrounding the electronics the more unlikely that the electronics within will be sensitive to SEU from direct ionization from external low energy protons. This is because the "end of track" distance within which the highest proton LET is achieved in silicon (required to produce an SEU) is 1 μm to 2 μm ($\sim 4 \times 10^{-5}$ to 8×10^{-5} inches), compared to the centimetres of material that surround the electronic devices, making energy deposition

from the protons within the sensitive 1 μm to 2 μm unlikely. However the electronic devices will be sensitive to higher energy protons which will lose energy due to the mass surrounding the electronics and then will be in the low energy domain. Additionally, the electronic devices will also be sensitive to secondary protons generated locally in materials surrounding the device.

d) Direct ionization by muons

Muons behave like electrons but are 200 times heavier and come from pion decay. Pions are created just like neutrons during nuclear reactions between cosmic ray protons and the oxygen and nitrogen in the atmosphere. Because muons are weakly interacting they do not cause upsets by interacting with silicon and so can only cause upset through direct ionization. Muons are the most dominant particle in cosmic rays at ground level but most have energies of 1 000 MeV or higher. However some will be produced at lower energy or be degraded to lower energy. For SEE from direct ionization to take place the muons have to be 1 MeV or below. The impact of additional particles, for example pions and muons, on electronic devices with very small geometry, will be covered in more detail in a proposed future new part of the IEC 62396 series (IEC TS 62396-8).

6.3 Total ionising dose (TID)

Total ionising dose (TID) effects refer to the cumulative effect of ionization (charge build-up) in an electronic 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, inducing the build-up of charge which leads to device degradation. The main mechanisms are the build-up of the positive oxide trap charge in the oxide and of the interface-trap charge in the interface between the silicon and the silicon dioxide. Large concentrations of oxide-trap charge cause increased leakage current in an electronic 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 electronic 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 specification is 1 000 cGy (e.g. deposited in silicon). For the vast majority of electronic devices, including almost all commercial off the shelf (COTS) electronic 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 avionics.

All of the major particles that constitute the radiation environment within the atmosphere, i.e., neutrons, protons, electrons, photons, etc, contribute to the ionising dose. Based on measurements made in a commercial airliner [66], the maximum dose rate from all of the particles is $\sim 70 \text{ nGy}\cdot\text{min}^{-1}$ ($\sim 0,4 \text{ mrad}\cdot\text{h}^{-1}$ or $\sim 4 \mu\text{Gy}\cdot\text{h}^{-1}$). For a nominal 100 000 flight hours, this results in $\sim 40 \text{ cGy}$ 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 ft (16,8 km), the dose rate doubles to $8 \mu\text{Gy}\cdot\text{h}^{-1}$ 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 electronic device might receive from an X-ray inspection is 1 mGy. This is extrapolated from the maximum dose that objects may receive from X-ray machines used to inspect luggage (10 μGy), and is also consistent with the approximate range of doses known to be received from commercial X-ray inspection systems (200 μGy to 500 μGy). 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 electronic 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 electronic 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.

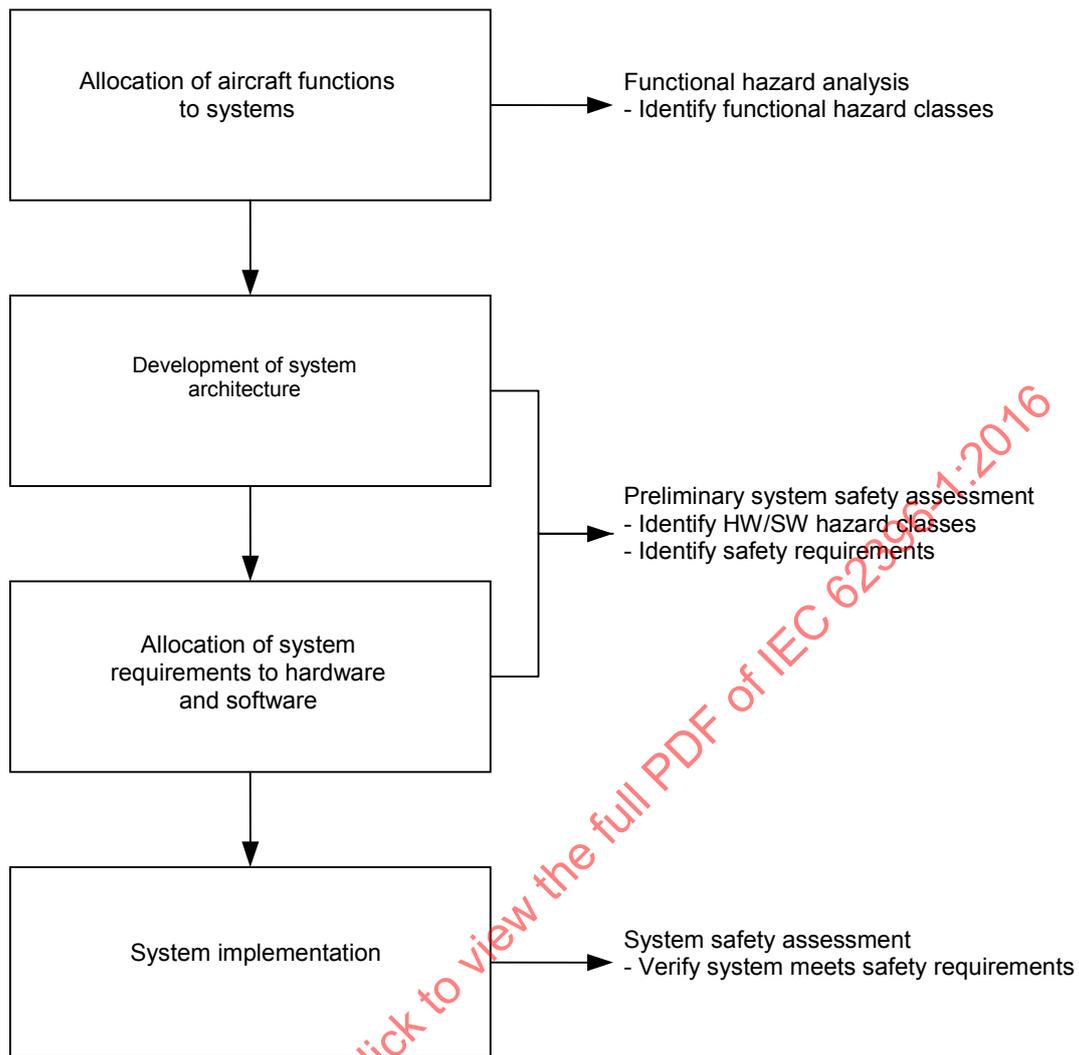
Based on previous experience of testing dozens of electronic devices for displacement damage, an effective lower bound on the minimum neutron fluence that causes an electronic device to operate out of spec is 1×10^{10} neutron-cm⁻². The 1×10^{10} neutron-cm⁻² value is based on displacement damage in sensitive optocouplers [67]. For electronic 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 electronic 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 gallium arsenide (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 MeV to 1 000 MeV) is 8×10^3 neutron-cm⁻²-h⁻¹. Thus assuming the electronics are exposed for 1×10^5 flight hours, this results in a neutron fluence of 8×10^8 neutron-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 $2,4 \times 10^9$ neutron-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 electronic devices. Hence displacement damage is not a problem for electronic devices, based on a minimum 1 MeV neutron fluence of 1×10^{10} neutron-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 an outline of this process. The flowchart is consistent with the aerospace recommended practices (ARP) contained in ARP4754A and ARP4761. In addition to the ARPs, quantitative requirements for the availability of aircraft functions are provided in AC23.1309-1C and AC25.1309-1A. Additional guidance for system designers for SEE mitigation is provided in IEC 62396-3. A future new part of the IEC 62396 series, (IEC TS 62396-7) will address specifically the subject of incorporating atmospheric radiation effects analysis into the system design and reporting process.



IEC

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 relatively to potential hazards, which could impact aircraft safety, by use of a functional hazard assessment (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 according to the assigned development assurance level and should be tailored accordingly.

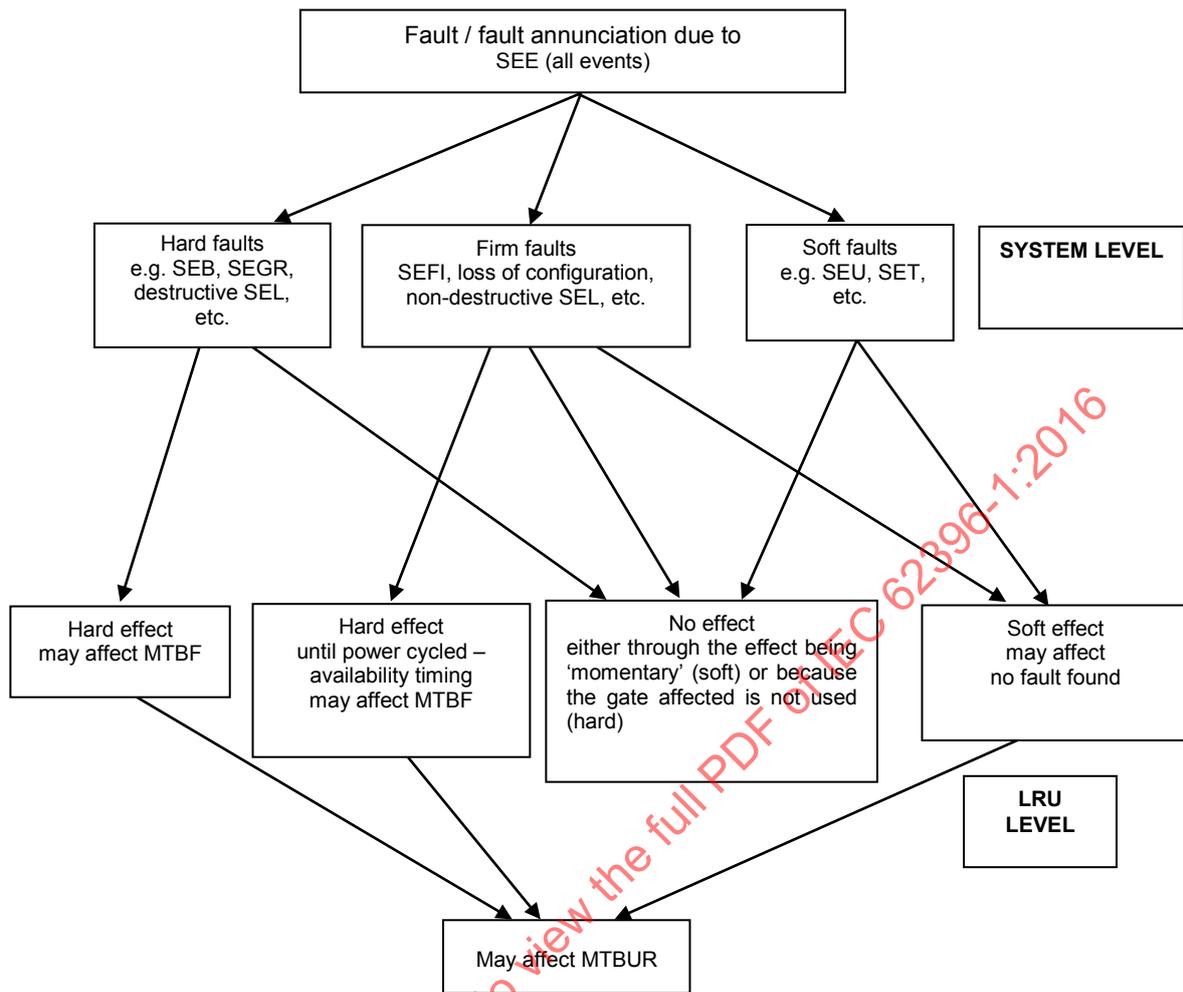
Systems that implement aircraft functions are classified by the failure effects of the functions they implement. Table 1 provides a cross-reference between functional failure effects and the classification of systems that implement the corresponding function.

Table 1 – Nomenclature cross reference

Functional failure condition classification (AC23.1309-1C, AC25.1309-1A and ARP4754A / EUROCAE ED-79A)	System development assurance level (ARP4754A / EUROCAE ED-79A)
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 the 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 the 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.



IEC

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 requires system architectures with some degree of equipment monitoring and redundancy. The degree of redundancy is dictated by equipment component failure rates that 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 should 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, MCU, 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 an electronic 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 electronic devices that are sensitive 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 1 000 FITs (1×10^{-7} failure·device⁻¹·h⁻¹ to 1×10^{-6} failure·device⁻¹·h⁻¹ [68] for avionics).

The SEU rates for individual electronic devices may be obtained from a variety of data sources, and the two main approaches that can be utilised 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 electronic devices affect the subsystem, but few such tests have been carried out. Very few electronic devices have been documented to be sensitive 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 utilised to demonstrate the lack of sensitivity 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 mitigate 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 electronic device to a determination of similarity to a class of devices with a known SEE rate. An electronic 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. Likewise, an SEE rate impacting a Level B system should be quantified with greater rigor (see 7.4.3) than that 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 purposes of this document, soft errors result in error or loss of function which is recoverable for example by reset or power cycle. Hard errors result in equipment failure that is permanent and only recoverable through 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 the integrated modular avionics (IMA) technology, the determination of the development assurance level should 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 Electronic devices characterisation and control

7.4.1 Rigour and discipline

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

7.4.2 Level A systems

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. Level A systems include functions for which the pilot will not be part of the operational loop, for example FBW, etc., and also functions for which the pilot will be within the loop through pilot/system information exchange, for example EFIS, etc.

One of the following methods should be employed:

- a) SEE rates in electronic devices may be derived from neutron testing on the specific devices 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 for alternative simulators). The accuracy of this method is approximately a factor of 2 on the event rate.
- b) SEE rates in electronic devices may also be derived from proton testing on the specific devices 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). The accuracy of this method is approximately a factor of 3 on the event rate.
- c) At system level, “in-the-loop” type of SEE testing of avionics equipment or systems may be used as described in Clause B.1. The accuracy of this method is approximately a factor of 2 to 3 on the event rate dependent on particle beam used.
- d) Where such data is not available or testing is impractical then the methods of 7.4.3 may be used to derive event rates, however a suitable minimum factor in event rates over values calculated by these methods should be applied.

The type A systems require the most robust electronic devices performance and electronic device technology controls. Technology controls should be in place to monitor electronic component 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) less rigorous/disciplined approach using one of the following methods:
 - 1) 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 a factor of 2 on the event rate).
 - 2) Irradiation of individual avionics equipment items containing a variety of potentially sensitive electronic devices as described in Clause B.2.
 - 3) Any of the following SEE engineering tools that should be applied by SEE radiation effects experts:

- i) 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.
 - ii) Use of neutron/proton SEE data on specific electronic device types (see Clause B.3). Accuracy is approximately a factor of 10 on event rate.
 - iii) 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 electronic devices. Accuracy is approximately a factor of 10 on the event rate because this is an inherently conservative method.
 - iv) Use of component SEE testing by laser simulation using a laser that has been calibrated using a reference electronic device of the same functional type (for example SRAM) and similar technology and feature size (see Clause B.5). Accuracy using calibration electronic devices is approximately a factor of 10 on the event rate.
- c) SEE failure/fault rates traceable to SEE tests on similar electronic devices using test results from non-neutron testing facilities (see Clauses B.3, B.4 and B.5).

These types of systems require moderate electronic device and technology control with periodic assurance 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 rigor / discipline; or
- b) SEE failure/fault rates traceable to testing results via an 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 electronic device control and change notification practices. Changes should be reviewed for potential impact on SEE failure/fault rates. The impact of an electronic device 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 normal electronic devices 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 electronic devices are sensitive to SEEs 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 electronic devices available at the beginning of the 21st century, the main effects that need to be dealt with are SEU, MBU, MCU 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 electronic 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 majority of CMOS devices are not sensitive to SEL due to the atmospheric neutrons, a few electronic devices are sensitive, and the atmospheric neutron SEL rate for some of these may not be considered small enough to ignore. The potential for SEL may change as a result of die revision of existing electronic devices.

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 electronic devices that are used in the LRU. The SEE rate per electronic device-hour is calculated by the following equation:

$$\text{SEE rate} = \text{atmospheric neutron flux (neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}) \times \text{SEE cross-section (cm}^2\cdot\text{device}^{-1}) \quad (2)$$

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 electronic devices. The subject of single event testing of avionics systems is covered in more detail in IEC 62396-2.

The SEE response of an electronic 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 (proton $\cdot\text{cm}^{-2}$, the particle flux integrated over the exposure time) to which the device was exposed. Thus the cross-section is given in units of $\text{cm}^2\cdot\text{device}^{-1}$ or $\text{cm}^2\cdot\text{bit}^{-1}$.

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 electronic 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 electronic 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 [69, 70, 71]. 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 electronic devices that were tested, atmospheric neutrons can induce SEB in power MOSFETs rated at 400 V and above. However, if the electronic devices are operated at a V_{DS} of < 300 V, the probability of a 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 [72, 73, 74].

There is evidence that high voltage electronics has been affected by secondary neutrons at sea level. As indicated in [62, 69], 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 electronic devices with heavy ions, but in only three different types of devices using proton beams, a comparator [52], analogue to digital converter [75] and a pulse width modulator (PWM) [51]. The ability of an electronic device to tolerate a SET is highly dependent on the specific application. Nevertheless, the calculated SET rates for these three types of electronic 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 electronic device, which is usually at constant frequency and duty cycle [51]. Phase shift errors in the output were considered small events, and they have an upper bound rate of 4×10^{-6} event $\cdot\text{device}^{-1}\cdot\text{h}^{-1}$ at aircraft altitudes, while period mismatch errors (larger events), have an upper bound rate of 1×10^{-6} event $\cdot\text{device}^{-1}\cdot\text{h}^{-1}$. 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 $^{-1}$ ·h $^{-1}$ 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 $^{-1}$ ·h $^{-1}$ 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 [63]. This is the most useful data for estimating the SHE rate at aircraft altitudes. SHE is a micro-dose effect, and it is not at all clear that other large SDRAMs will also have the same sensitivity 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 [63] an upper bound rate of 4×10^{-6} SHE event·device $^{-1}$ ·h $^{-1}$ 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 sensitive.

8.2.4 Single event latch-up (SEL)

Many CMOS devices are sensitive 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 sensitive to SEL from the protons and neutrons. References [76, 77] contain a few of these electronic devices that can have SEL induced by protons and neutrons and their SEL cross-sections, but each year or two one or more new electronic devices are identified by SEE researchers as sensitive to proton SEL [78].

One approach that may be useful is to provide an upper bound rate based on the electronic device with the highest probability of having SEL [76, 77] induced by atmospheric neutrons at aircraft altitudes. References [76, 77] list a total of seven electronic 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 [47, 79] 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 [80] 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 neutron·cm $^{-2}$ ·h $^{-1}$ is $2,4 \times 10^{-4}$ latch-up·device $^{-1}$ ·h $^{-1}$, or once in about 4 000 h. Since this rate appears to be high enough to be of concern, the best certain alternative would be to expose all electronic devices in an LRU to a beam of high-energy protons or neutrons, and monitor for latch-up (increase in current). For latch-up screening, the pulsed laser approach constitutes also an efficient solution. The laser is used only to determine whether or not an electronic device will latch up following an ionization event [81]. This testing provides a relevant and reproducible answer for electronic device assessment during design phase but also to control die changes influence on SEL sensitivity.

Electronic devices that are sensitive 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, MCU 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 devices, the single event latch-up rate could be a concern. At a simplified level, the SEU rate depends on the number of bits in an electronic device, and in most cases the bits serve as either memories, registers, or latches. The kinds of electronic 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 electronic devices to within a range of 1 to 2 orders of magnitude.

8.3.2 SEU cross-section

The SEU response of an electronic 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 (proton·cm⁻², particle flux integrated over the exposure time) to which the device was exposed. Thus the cross-section is given in units of cm²·device⁻¹ or cm²·bit⁻¹. Various scientific and engineering organisations around the world carry out such SEU tests in order to characterise the SEU response of electronic 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 is not 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 mono-energetic 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. Therefore SEU cross-section from proton beams greater than 100 MeV can be used to give the equivalent cross-section from WNR.

At aircraft altitudes, the spectrum of the atmospheric neutrons covers the energy range to greater than 1 000 MeV. One type of 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 spallation neutron source, examples of which are given in Annex C; these sources can be designed so that their spectrum simulates the atmospheric radiation environment (white neutron source) up to the maximum energy of the accelerator. Such sources can produce neutron fluxes that are orders of magnitude greater than that of the atmospheric radiation environment and enable highly accelerated testing of electronics.

The other neutron sources that are available are mono-energetic neutron generators and quasi-mono-energetic neutron beams. The neutron generators rely on the D-T reaction to produce mono-energetic beams of 14 MeV neutrons and occasionally on the D-D reaction to produce beams of ~3 MeV neutrons. The quasi mono-energetic 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 mono-energetic neutron SEU cross-sections.

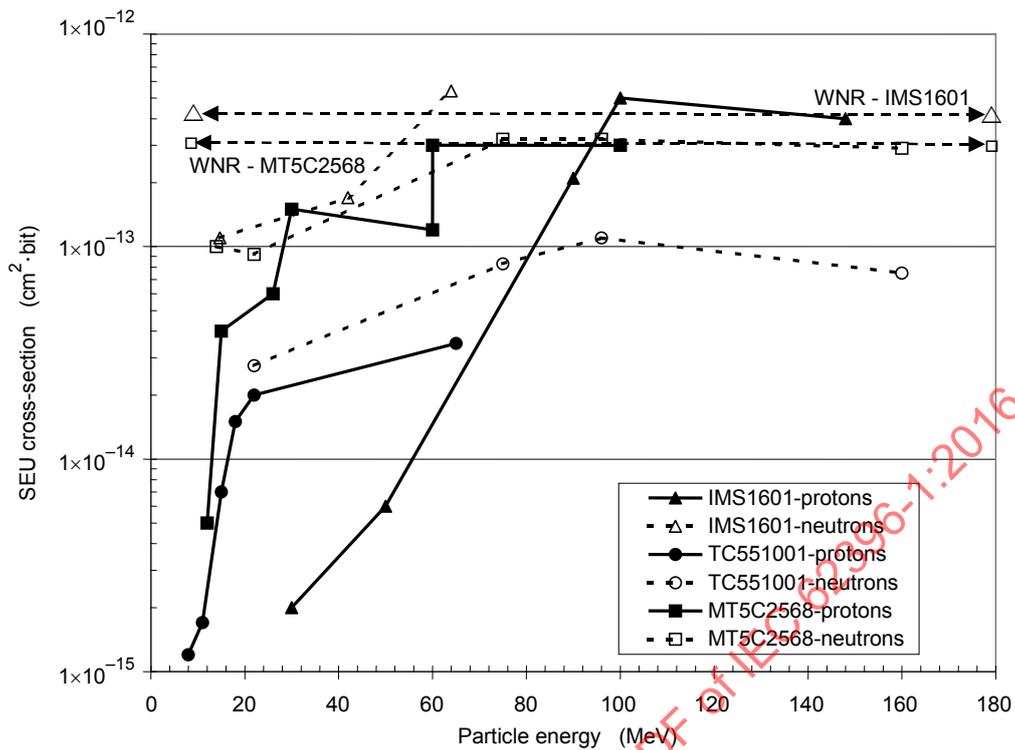
However, there is another source of neutrons within an aircraft that can cause SEEs that requires an entirely different kind of neutron source for purposes of laboratory testing. These are the thermal neutrons discussed in 5.3.5. The average energy of these neutrons is 0,025 eV, but they are more generally 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 MeV 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:



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 electronic devices have been exposed to thermal neutrons and the resulting SEU cross-section measured. Of these only a small number have exposed SRAMs to both thermal neutron and high-energy neutron beams and compared the SEU cross-sections. In one study [47], 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 electronic 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 a second study [82], 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 [83] exposed SRAMs to naturally occurring neutrons at a high altitude location, with some electronic 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. Additional comparison between high energy and thermal neutron cross-sections for SRAMs is made in [22]. Thus the additional SEU rate from thermal neutrons is an issue for avionics. There is further discussion of thermal neutron SEE in Annex A and in IEC 62396-5.

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 [77].

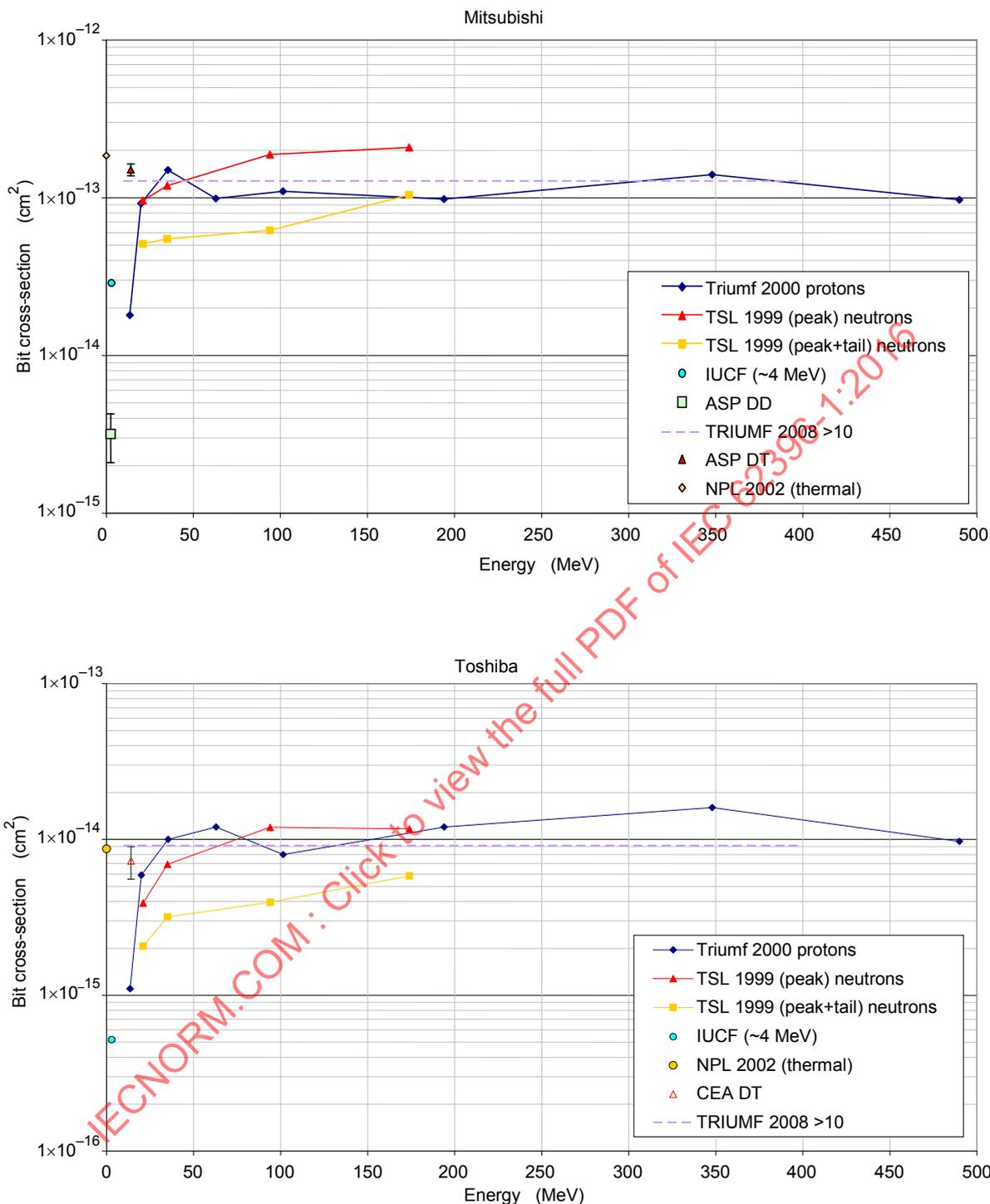
The relationship between the WNR SEU cross-section and proton and neutron SEU cross-sections at specific energies is shown in Figure 8 for three older SRAMs. For the two electronic devices with the SEU cross-section measured in the WNR beam, it appears the WNR SEU cross-section is approximately equal to the proton SEU cross-section for energy > 100 MeV, and to the mono-energetic 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 mono-energetic neutron SEU cross-section data were derived from measurements made with a pseudo mono-energetic beam and corrected for the contribution from the tail of lower energy neutrons [84]. Further, based on more recent testing [21], SEU cross-sections obtained from testing with mono-energetic proton beams (> 100 MeV) in SRAMs, FPGAs and microprocessors are expected to be within less than a factor of 2 of those that would be obtained from testing with the WNR neutron beam.



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

For the comparison of neutron and proton measurements and the significance of low energy neutrons, two examples are presented in Figure 9, with data on 4 Mbit SRAMs [21, 47]. The feature size of these electronic devices was 0,4 μm and this figure gives data for the most and least sensitive electronic devices from this sample. For the results obtained from neutron energies of 21 MeV to 174 MeV at TSL, the neutron upper and lower limits are derived by dividing by neutrons in the peak and total neutrons respectively. Proton results at 13 MeV to 490 MeV from TRIUMF are truly mono-energetic and fall in between. The neutron point at 14 MeV was obtained from mono-energetic neutron sources (D-T) and is higher than the lowest energy TSL point. The cross-sections obtained at the TRIUMF spallation neutron source are averaged over the spectrum > 10 MeV and are shown as the dotted lines. These are in good agreement with the plateau cross-sections obtained from mono-energetic proton and quasi mono-energetic neutron testing. Further data points at 3 MeV and 4 MeV were obtained from ASP (D-D) and IUCF facilities (3 MeV to 5 MeV) and are one to two orders of magnitude below the high energy plateau. Additional data comparing 3 MeV to 5 MeV data with spallation neutron sources are available in [21] and indicate the former to be less by factors ranging from 5 to 600.



IEC

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

Figure 9 also has the SEU cross-section from thermal neutrons (less than 1 eV) obtained at the NPL facility. For one electronic device this is about a factor 1,5 to 3 higher than the SEU cross-section from high energy neutrons and for the other it is comparable. Further examples of test data on thermal neutron sensitivity are given in references [21, 22] and these show that for some electronic devices, thermal neutrons could dominate the SEU rate in avionics, while for others the contribution could be minor. Full discussion on how to deal with the thermal neutron problem is given in IEC 62396-5.

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 ($\text{cm}^2\cdot\text{bit}^{-1}$), applicable to avionics, that were derived from WNR and proton ($E > 200$ MeV) measurements for both SRAMs and DRAMs [85]. The conclusion reached in reference [85] is that based on the original data that had been compiled, the average SEU sensitivity 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 electronic device is very useful for purposes of understanding trends in the SEU sensitivity of electronics, the two curves for SRAMs and DRAMs [86, 87] have been updated. 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 electronic devices included. The SRAM data is shown in Figure 10, and Figure 11 shows the corresponding data for DRAMs. However, since the SEE cross-section data changes so rapidly with changes in IC technology, as better characterized by feature size rather than electronic device date, Annex G has been added. It contains the latest SEE response data (for feature sizes down to < 50 nm) and guidance (SEU, MCU, SEFI, SEL, SET and SEB).

Figure 10 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 electronic devices it appears to be approaching an asymptotic value. Much of the data appears to be centred around an SEU cross-section of $1 \times 10^{-13} \text{ cm}^2\cdot\text{bit}^{-1}$, but more broadly within a band of a factor of 3 to 0,33 of this value.

The conclusion regarding the approximate asymptotic behaviour of SRAMs over time with respect to their SEU sensitivity 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 electronic devices used in Figure 10 are for all SRAMs that may be used in avionics. The SRAMs used in Figure 10 are those that had been tested for SEU with either the WNR beam or high-energy protons. As seen in Figure 10 a few SRAMs have even lower SEU cross-sections than the apparent asymptotic bands that can be derived, either $1 \times 10^{-14} \text{ cm}^2\cdot\text{bit}^{-1}$ to $1 \times 10^{-13} \text{ cm}^2\cdot\text{bit}^{-1}$ or $3 \times 10^{-14} \text{ cm}^2\cdot\text{bit}^{-1}$ to $3 \times 10^{-13} \text{ cm}^2\cdot\text{bit}^{-1}$.

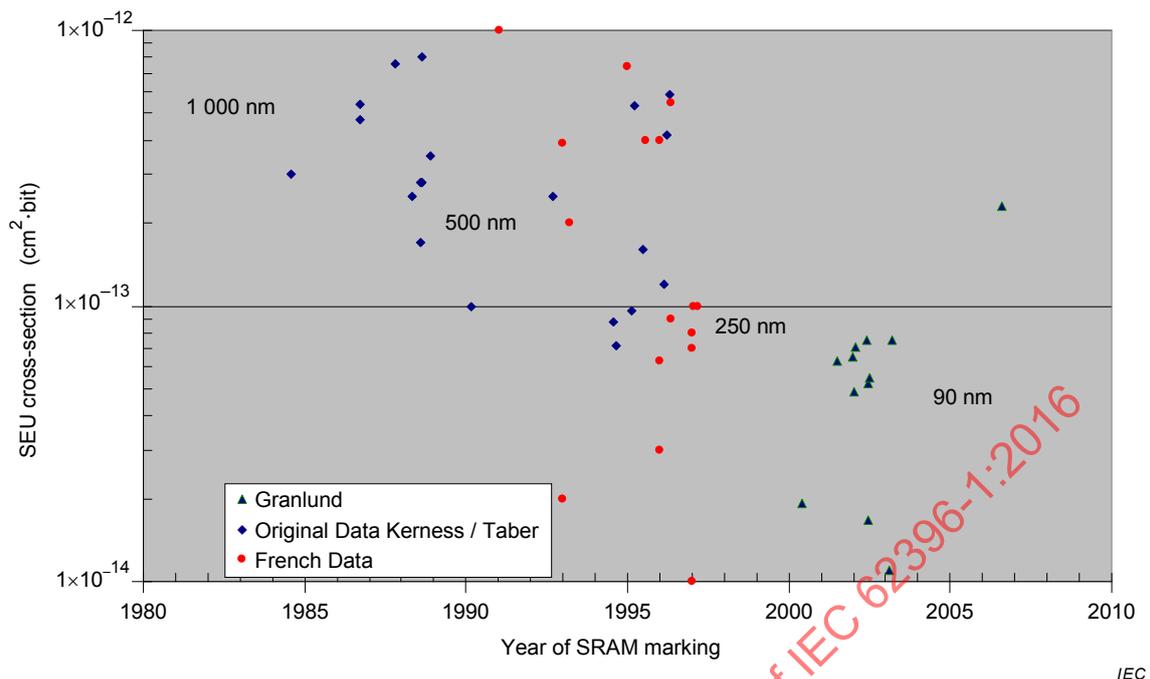


Figure 10 – SEU cross-section in SRAMs as function of the manufacture date

The SRAM SEU data in Figure 10 includes SRAMs that had feature sizes of > 500 nm and others down to below 100 nm; the approximate technology feature sizes have been added in nm. Compilations of SEU cross-sections from more recent electronic devices, down to feature sizes of 180 nm [88, 89, 90] have shown a gradual decline in the cross-sections, with most of the cross-sections falling into the range of 1×10^{-13} $\text{cm}^2 \cdot \text{bit}^{-1}$ to 1×10^{-14} $\text{cm}^2 \cdot \text{bit}^{-1}$ but a few, mostly those for < 200 nm, lying between 1×10^{-14} $\text{cm}^2 \cdot \text{bit}^{-1}$ to 1×10^{-15} $\text{cm}^2 \cdot \text{bit}^{-1}$. As the feature sizes have continued to decline, a few SRAMs have exhibited an increased sensitivity at low neutron energies, i.e., $E < 10$ MeV, compared to most previous electronic devices. While the rule of thumb that the SEU contribution in the atmospheric neutron environment from neutrons with $1 \text{ MeV} < E < 10 \text{ MeV}$ is less than 10 % of the total rate [7] generally applies, for these few electronic devices the ratio of [SEU cross-section ($E > 10 \text{ MeV}$)] / [SEU cross-section (E between 3 MeV to 5 MeV)] has been $\sim 1,0$. Thus for such electronic devices the SEU contribution from neutrons with $E < 10 \text{ MeV}$ will be greater than 10 % [21].

A related but different effect is being seen in SRAMs with feature sizes of < 90 nm and this relates to upsets being caused by direct ionization from low energy protons ($E \sim 0,1 \text{ MeV}$) [64]. Neutrons of all energies can produce secondary protons with such low energies. Thus, SEUs from such low energy secondary protons are a new mechanism through which neutrons can cause SEUs in SRAMs [91] (see 6.2.10 for further discussion). Low energy protons are part of the environment.

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 [85] is enhanced by including more recent data. In this case, as microelectronic technologies are being modified to enable individual electronic devices to hold an increasing larger number of bits, the net result for SEU sensitivity is a continuing decline in that sensitivity on a per bit basis. This is seen in Figure 11 which shows the original data [85] along with SEU results from more recent tests. For more detailed information and more recent data, see Annex G. The original data was 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 electronic devices in the range of 64 Mbit to 256 Mbit. In addition, [8, 40] 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 sensitivity.

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

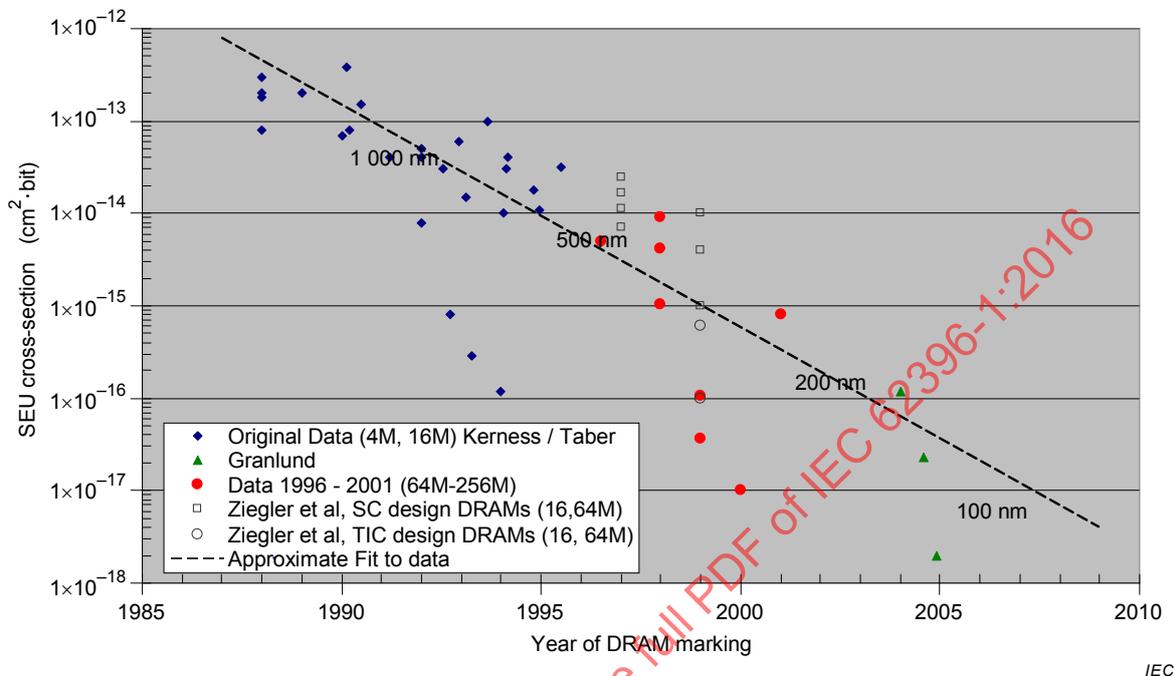


Figure 11 – SEU cross-section in DRAMs as function of manufacture date

An approximate trend line is shown in Figure 11, together with approximate generic technology feature size. The data on DRAM was obtained from several sources, including data for SC DRAMs [87, 92, 93]. This data was modified to fit the format of the figure since the original Baumann curves were based on the size of the DRAM and not the year of manufacture. The main point to be derived from the trend line 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 the 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 sensitivity to multiple cell upset (MCU), stuck bits (single hard errors) and single event functional interrupt (SEFI). The new larger DRAMs (Gbit size arrays) may be sensitive to all of these effects [48, 49]. Regarding MCU, two different kinds of effects are possible, standard MCU in which two or three errors are induced per neutron strike in the memory array, and a burst type of effect in which thousands of errors are induced due to a neutron strike in the logic portion of the DRAM (see 6.2.3). The sensitivity of new DRAMs to burst errors varies significantly with DRAM vendor and so this effect needs to be considered for future developments in the usage of DRAM designs. Thus, these effects should be considered for future developments in DRAM designs.

Probably the major effect is MCU, which had been about 1 % to 3 % of the SEU rate for older electronic devices, but for more recent electronic devices with feature sizes below 180 nm MCUs increase and burst errors affecting > 1 000 bits may be important (see 6.2.3). However, the MCU fraction relative to the SEU rate can vary significantly from one DRAM to the next, and the impact that an MCU 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 MCU fraction variation can be much higher, and there is value in laser screening to give the physical location of bits and the relative sensitivity to MCU. If there is physical separation between the bits per word then this reduces the sensitivity 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 SEEs 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 [5, 8, 39, 40, 41]. 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 address the impact of the SEE on the actual avionics.

The simplified method of calculating the SEE rate for a particular effect as defined in this standard is to multiply the SEE cross-section for that effect (units of cm^2) by the integrated neutron flux of $6\,000 \text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ ($E > 10 \text{ MeV}$). This $6\,000 \text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ flux is a nominal value for $40\,000 \text{ ft}$ ($12,2 \text{ km}$) altitude and 45° latitude, and may be adjusted for different altitudes and latitudes (see Annex D), as well as the enhancement from a solar flare, as discussed in 5.6. In the nominal atmospheric radiation environment described above and when the cross-section has been determined with an atmospheric-like (white neutron) source the SEE rate may be calculated from:

$$\text{SEE rate per electronic device-hour} = 6\,000 \text{ (neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}) \times \text{SEE cross-section (cm}^2 \cdot \text{device)} \quad (4)$$

The above calculation applies for all geometries because the conditions are atmospheric like.

The greater than 10 MeV neutrons will be the dominant cause of SEE on sensitive electronic devices with geometric feature size above 150 nm , however for electronic devices with feature size at and below 150 nm the contribution of neutrons with energy between 1 MeV and 10 MeV may be significant, although, for such electronic devices, based on [7], the contribution from the $1 < E < 10 \text{ MeV}$ neutrons to the overall SEE rate is 10% . This estimated contribution has been derived using geometries between 150 nm and 90 nm and needs to be kept under review as further low energy neutron test data on small feature size electronic devices (below 150 nm) becomes available. However, even if the equivalent contribution for smaller feature size electronic devices is much higher, this will in any case be automatically reflected in SEU cross-sections measured at white spectrum neutron facilities.

The other method of calculating the SEE rate is by integrating the SEE cross-section as a function of energy (e.g., as in Figure 8) with the neutron spectrum (as in Figure 1) over all the neutron energies. However, in the vast majority of cases (for example with WNR SEE) the measured spallation neutron is available for electronic devices but the cross-section as a function of energy is not. In comparing calculated SEU rates in six SRAMs ($0,5 \mu\text{m} < \text{feature size} < 0,35 \mu\text{m}$) based on the integration method using the QARM neutron spectrum [15], the rates from the simplified method of this standard are in good agreement with the integration method rates, though higher by about 50% , but may not be applicable for smaller geometries if non atmospheric-like sources are used to determine cross-sections (see also Annex H).

The multiple cell upset (MCU) rate should be calculated for the EDAC protected memory that has been identified earlier, and has been deleted from consideration for the SEU rate. Because the MCU/SEU fraction has been changing so rapidly with decreasing feature size and RAM type, as described in 6.2.3, the MCU rate should be calculated only after considering the guidance provided in 6.2.3. On a simplified level, this MCU 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 electronic 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.

8.5 Calculation of availability of full redundancy

8.5.1 General

Most modern avionics equipment utilises state-of-the-art electronic components that have submicron feature size integrated circuits within the design. Such components may be SEE sensitive due to the avionics atmospheric radiation. The result of such SEE is to generate errors or faults within the equipment that could have an impact on the functionality of the equipment. Mitigation features can be incorporated as necessary in order to satisfy the avionics system requirements for the higher design categories A to C (see Clause 7). The equipment may contain some method of detecting the error or fault and utilise some level of redundancy to avoid any impact on the function. However, the affected element will not recover until some form of correction is applied for the original SEE; during this time, the time to recover the full redundancy is not available [94]. The correction can be made by a regular process such as "scrubbing" (memory refresh from uncorrupted data at fixed intervals) or rely on correction when an error or fault is discovered. As an example, consider the availability, A , of a block of memory. If the mean time to recover is t_{rec} , the mean rate of recovery $\mu = 1/t_{rec}$, and if the mean time between SEE error generation is t_{SEE} , the mean SEE rate $\lambda = 1/t_{SEE}$. The availability of full redundancy is then given by the equation:

$$A = \mu / (\lambda + \mu) \quad (5)$$

When the recovery rate is much higher than the SEE rate the availability tends towards 1, i.e. full availability. System availability is considered for three different types of SEE event:

- a) Transient errors and upset (e.g. SEU, MCU) with correction applied quickly after the event or as the data is required.
- b) Firm errors and faults (e.g. SEFI, non-destructive latch), which persist until the power to the electronic device is cycled. If there is no facility during normal equipment operation for power cycling, the condition will persist until the end of the operational period.
- c) Hard faults (e.g. stuck bits and destructive latch up) which are permanent and require maintenance activity on the unit. These events are considered in the same manner as any other component failure (see Clause 7).

The first two of these SEE types do not require maintenance activity since they recover for the next operational use without any external intervention. Examples of full redundancy availability for the first two types of SEE event are given below.

8.5.2 SEU with mitigation and SET

Consider SEU in SRAM, with applied mitigation such as EDAC, ECC or multiple strings (redundancy) along with voting. In such cases, the recovery time for ECC or redundancy with voting can be very fast; if 1 ms is assumed, then the recovery rate is $1/1\ 000 = 1\ 000\ s^{-1}$, which is 3,6 million per hour. For SRAM with 5 Mbits of used locations, and with the SEU cross-section between $10^{-13}\ cm^2 \cdot bit^{-1}$ and $10^{-14}\ cm^2 \cdot bit^{-1}$ (see Figure 10), the corresponding SEU rates vary from $3 \times 10^{-3}\ upset \cdot device^{-1} \cdot h^{-1}$ to $3 \times 10^{-4}\ upset \cdot device^{-1} \cdot h^{-1}$. In this example, the recovery rate is orders of magnitude larger than the SEU rate, and therefore the availability is very close to 1. There would be no significant impact on the equipment availability, but the availability could be significantly impacted if the memories were very large and the scrubbing operation not carried out at a sufficiently high rate (low periodicity).

Single event transients (SETs) can persist for up to 10 μs , after which the electronic device recovers to normal operation. For a typical recovery time of 10 μs , the recovery rate would be $1/10^{-5} = 100\,000\text{ s}^{-1}$ or $360\,000\,000\text{ h}^{-1}$. The SET rate during flight for a comparator or a pulse width modulator ranges from $10^{-7}\text{ event}\cdot\text{device}^{-1}\cdot\text{h}^{-1}$ to $2 \times 10^{-5}\text{ event}\cdot\text{device}^{-1}\cdot\text{h}^{-1}$ (see 8.2.2). In this example, the recovery rate is again orders of magnitude greater than the SET rate and the availability is very close to 1.

8.5.3 Firm errors and faults

Consider SEFI, where electronic device functionality is recovered by cycling power or rebooting. If the avionics equipment is not able to cycle power or reboot automatically, the fault will persist for the remaining flight duration (10 h or more) and full redundancy will be unavailable for this period. For triple modular redundant systems, the recovery time from the first event is immediate, but the occurrence of another event during the recovery time will cause that element of the system to fail. For a typical SDRAM device (in READ mode, taken from [43]) with a SEFI cross-section of $3 \times 10^{-11}\text{ cm}^2\cdot\text{device}^{-1}$, the SEFI rate will be $2 \times 10^{-7}\text{ event}\cdot\text{device}^{-1}\cdot\text{h}^{-1}$, and again the recovery rate would be orders of magnitude greater than the SEFI rate, and the availability near 1.

As indicated in Figure 7, events such as SEFI may impact the MTBUR and MTBF if they are identified as failures by any built-in test system.

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 the system development assurance level

The development assurance level will determine the rigour and discipline associated with the SEE accommodation (see 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 4.3.7 in IEC TS 62239-1:2015 or EIA-4899). Guidance for the identification of SEE-sensitive electronic components is given in Clauses 6 and 8 of this standard.

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 the entire system

The accumulation of SEE-induced hard faults may impact 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). Where any SEE is totally (100 %) mitigated in the application by limitation of stressors this shall be clearly defined.

Whilst the equipment recovers from radiation induced soft errors some redundancy elements are not available, and the recovery time shall be demonstrated as acceptable at system level.

9.5.2 Management of electronic components control and dependability

Refer to 4.3.7 in IEC TS 62239-1:2015 or EIA-4899, and to 8.4 of the present standard. Changes by the semiconductor vendor to electronic components can affect their atmospheric radiation SEE sensitivity and SEE rates. As a result change to potentially SEE-sensitive electronic components shall be reviewed for impact on SEE sensitivity throughout the operating service life of the equipment. Atmospheric radiation is part of the electronic component management plan addressed by IEC TS 62239-1 or EIA-4899.

9.6 Corrective actions

Take corrective actions if necessary.

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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:

- a) it appears that the thermal neutron flux inside an airliner is 1 to 2 times the high energy (> 10 MeV) neutron flux; and
- b) for many electronic 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 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 electronic devices in which this has been measured [47, 82, 83], most have a thermal neutron SEU cross-section comparable to or larger than the high energy SEU cross-section, but a few electronic devices are not sensitive to SEU from thermal neutrons. These latter electronic devices should not contain any BPSG, the major source of boron 10 which leads to the SEU by the thermal neutrons. However, these electronic devices do contain boron in lower concentrations through other constituents in the die (for example p dopant). Thus in older electronic devices without BPSG, 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 can be ignored, but in more recent SRAMs [48, 95] without BPSG, the SEU contribution from thermal neutrons is somewhat reduced compared to BPSG, but may not be ignored. At present, it appears that SRAMs are the only electronic 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 electronic devices such as DRAMS, microprocessors and FPGAs are also sensitive 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 electronic 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 electronic 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 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 international standard is devoted to SEU from the high energy neutrons. The effects of thermal neutrons on electronics are covered in more detail in IEC 62396-5.

Annex B (informative)

Methods for 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, 1 h in the WNR beam (2002 calibration) is equivalent to approximately 1×10^6 h at 40 000 ft (12,2 km). With this normalisation factor, the number of upsets that affect the avionics system in 1 h 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 $6\,000 \text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ ($E > 10 \text{ MeV}$). Thus, for a lifetime of 100 000 flight hours, the lifetime fluence is $6 \times 10^8 \text{ neutron}\cdot\text{cm}^{-2}$. The contribution to the SEE rate by neutrons of energies $< 10 \text{ MeV}$ 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 a 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. If the proton or neutron beam is not large enough to encompass the whole LRU then a number of different exposures will be required.

NASA-JSC has used this kind of testing to identify electronic devices that are prone to proton (or neutron) induced single event latch-up; these electronic devices have generally been deleted from consideration, irrespective of the SEL rate. The tests have also involved many SEUs in a variety of electronic 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 electronic device may propagate to an error in another electronic device which causes the LRU to malfunction and reboot. Compared to Clause B.1's 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 override an unexpected or erroneous signal from the LRU due to an 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 neutron·cm⁻². As an example, if an LRU were exposed to a proton fluence of 1×10^{10} proton·cm⁻² and 5 events were recorded in which the LRU malfunctioned, the LRU upset cross-section would be 5×10^{-10} cm² (5 events/ 1×10^{10} proton·cm⁻²). For avionics purposes, the LRU rate per hour would be 5×10^{-10} cm² × 6 000 neutron·cm⁻²·h⁻¹ or 3×10^{-6} event·LRU⁻¹·h⁻¹.

B.3 Utilising existing SEE data for specific electronic components 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 electronic devices on the LRU that will be sensitive to SEE. An extension of this approach could be to carry out SEE testing of individual electronic devices utilising a neutron or proton beam. In both cases, this approach relies on the static SEE response of an electronic 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 electronic devices 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 electronic devices are continuously changing, so by the time that some of the data is incorporated into a database, the electronic device may no longer be available, or a next generation electronic device has replaced it.

As seen in Figure 8, proton SEE data at high energies, i.e., $E > 100$ MeV, may be used to represent the SEE response due to the atmospheric neutron spectrum. Further, based on more recent testing [21, 53], SEU and SEFI cross-sections obtained from testing with mono-energetic proton beams (> 100 MeV) in SRAMs, FPGAs and microprocessors are expected to result in SEU/SEFI cross-sections that are within less than a factor of 2 of those that would be obtained from testing with the WNR neutron beam. However, in testing for SEL, only high energy beams ($E \geq 100$ MeV) of either neutrons or mono-energetic protons should be used to obtain SEL cross-sections expected to be within a factor of 2 of those that would be obtained from the WNR neutron beam (for $E_{\text{proton}} > 200$ MeV, the SEL cross-section may be conservatively higher, [21]). Further, for other SEE effects in other kinds of electronic devices, only high energy beams ($E \geq 100$ MeV) of either neutrons or mono-energetic protons should be used in place of a spallation neutron source to obtain the relevant SEE cross-sections.

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

Organisation	Publications	Internet site
NASA – Goddard Space Flight Center (GSFC), (Rad Effects & Analysis Section)	Yearly publication of SEE results (with 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 (with protons and heavy ions) in IEEE Radiation Effects Data Workshop.	General NAS JPL internet link: http://parts.jpl.nasa.gov/organization/group-5144/ NASA JPL database internet link: http://radcentral.jpl.nasa.gov/ (use of search engine provides link to database links area of "Spacedew")
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 electronic devices 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 electronic devices that were or are being considered for use in space applications, very little are for electronic devices specifically being targeted for aircraft avionics.

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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. Nucl. Sci., 45, 2550, 1998; also J. Barak <i>et al.</i> , "On the Figure of Merit Model ...," IEEE Trans. Nucl. Sci., 46, 1504, 1999
	J. M. Palau	"A New Approach for the Prediction of the Neutron-Induced SEU Rate," IEEE Trans. Nucl. Sci., 45, 2915, 1998
	L. D. Edmonds	"Proton SEU Cross-sections Derived from Heavy-Ion Test Data," IEEE Trans. Nucl. Sci., 47, 1713, 2000
	J. Barak	"A Simple Model for Calculating Proton Induced SEU," IEEE Trans. Nucl. Sci., 43, 979, 1996; also "A Akkerman <i>et al.</i> , "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. Nucl. Sci., 45, 2904, 1998
SEUSIM	C. Inguibert	"Proton Upset Rate Simulation by a Monte Carlo Method: the Importance of Elastic Scattering Mechanism," IEEE Trans. Nucl. Sci., 44, 2243, 1997
IMDC	C.S.Dyer	"Microdosimetry Code Simulation of Charge-Deposition Spectra, Single Event Upsets and Multiple-Bit Upsets," IEEE Trans Nucl. Sci., 46, 1486, 1999
CUPID	P. McNulty	"Proton Induced Spallation Reactions," Radiat. Phys. Chem., 43, 139, 1994
METIS	C. Weulersee	"A Monte Carlo engineer tool for the prediction of SEU proton cross-section from heavy ion data", 12th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Publication, Year: 2011; RADECS 2011 Proceedings: pages 376 – 383

In general, proton/neutron SEE response data needs to be found for just a few of the electronic devices on an LRU, those device types that are judged to be sensitive to SEE. This consists primarily of RAMs, microprocessors and FPGAs, electronic devices that contain a large number of bits, which can upset. However, only those bits that are used are sensitive to SEUs that can be recognised as errors, and often only a fraction of all of the bits on an electronic 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 an electronic device on the LRU, the conservative approach is to assume that 1) all of the bits are used and therefore sensitive 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 electronic devices 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 electronic components on LRU

In this case the LRU has a number of electronic devices that are likely to be sensitive to SEE through the atmospheric neutrons, but there is no SEE data available for one or more of these electronic devices. Calculating the SEU rate for such electronic device 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 an electronic 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. Sensitive electronic 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 and MCU rates need to be calculated, and the MCU rate is conservatively taken to be 3 % of the SEU rate at feature sizes 350 nm and above.

For all of the other electronic devices, the per bit SEU cross-section will be based on the data for SRAMs shown in Figure 10. The number of bits in all of the SRAMs, microprocessors and FPGAs needs to be added together. From Figure 10, we choose a conservative SEU cross-section of $5 \times 10^{-13} \text{ cm}^2 \cdot \text{bit}^{-1}$, and with the integral flux of $6 \times 10^3 \text{ neutron} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$, a SEU rate of $3 \times 10^{-9} \text{ upset} \cdot \text{bit}^{-1} \cdot \text{h}^{-1}$. This rate is multiplied by the total number of bits in all of the electronic devices to obtain the SEU rate for the LRU due to SEUs in all of the devices except DRAMs. If, for example, there were a total of 10 Mbits on the LRU, the SEU rate would be $3 \times 10^{-2} \text{ upset} \cdot \text{LRU}^{-1} \cdot \text{h}^{-1}$, or one upset every 30 h. In looking at Figure 10 we see that this is clearly a conservative approach, as SEU cross-sections at least an order of magnitude lower are available, but this approach is being used because no SEE data is available for the specific electronic devices on the LRU. Thus a trade-off could be made between a high SEU rate for the LRU with no specific SEU data, resulting in a high error rate for the LRU, or efforts to more accurately quantify the SEU response of the electronic devices on the LRU by testing or analysis of relevant electronic devices data. This approach also ignores the architecture of the avionics subsystem and any built-in fault tolerance measures it may have that would override unexpected or erroneous signals from the LRU due to an SEU or other cause.

B.5 Component level laser simulation of single event effects

It is feasible to use focused ps-pulsed laser facilities to measure microchip SEU cross-sections (as a function of LET) by delivering large arrays of laser pulses at a range of pulse energies [96,97]. Methodologies and codes have also been devised for converting LET cross-section curves to neutron SEU upset rates [98]. However, these methodologies further require an estimate of the sensitive volume of the microchip cells. For crude calculations, the sensitive volume may be estimated; but it has also recently been shown that it is possible to use a laser facility directly to measure the sensitive volume by testing microchips at a range of different wavelengths [99, 97]. It should be noted that the empirical techniques reported in references [96, 99] were demonstrated using three commercial 4 Mbit SRAM types.

These methodologies provide a basis for employing laser facilities to measure the neutron and proton SEU sensitivity of electronic devices. The use of such facilities potentially circumvents the apparent high costs and occasional long lead times, which can arise from the use of neutron and proton beam facilities to assess components. Laser simulation is suitable not only for initial test of SEU sensitive components but also for the ongoing monitoring of the effects on SEU of proposed die changes to such components as notified by product change notifications (PCNs) (see IEC TS 62239-1).

Laser systems are potentially effective for identifying excessively sensitive and selecting relatively insensitive electronic device types, where a range of equivalent electronic devices from alternative manufacturers is under consideration for inclusion in an avionics system. Nevertheless, laser assessment is not a fully mature technology and will normally be less accurate and reliable than neutron beam testing, so the latter should be preferred where relatively precise results are justified by the cost-benefit analysis. Furthermore laser testing is indirect, in that it relies on integrating the results of several assessment steps. However as more experience is accumulated the relative accuracy and efficiency of laser testing would be expected to improve.

Electronic devices need to have their active chip exposed for laser testing (also necessary for ion beam testing, but not for neutron or proton beam testing). The laser technique may

therefore be relatively more beneficial in cases where the bare die within the component is readily accessible.

Laser beams are also effective to characterize the sensitivity of power electronic devices such as power MOSFETs or IGBTs to single-event burnout. Even if cross-correlation between laser and proton or neutron data remains limited, laser testing has been demonstrated as efficient to determine the safe operating area (SOA) of a power electronic device [100, 97]. This additional input could be very useful for designers to select the most appropriate electronic device for dedicated applications and establish with the full knowledge of the SOA the adequate mitigation technique notably on the voltage de-rating.

It should also be noted that the availability of cross-correlation data between laser and neutron testing is currently very limited. The laser simulation testing for a component may be calibrated using the cross-correlation data results (neutron/proton test to laser simulation) of components from the same functional type (for example SRAM) having similar semiconductor technology and feature size. However, some studies have shown distinct differences in the SEU response among electronic devices of the same functional type [47] and in how poorly proton and heavy ion SEU data sometimes correlate [79]. Therefore the user should be very cautious when applying this laser simulation method for obtaining the high energy neutron SEU response of electronic devices.

B.6 Determination of SEU rate from service monitoring

This procedure can provide a measure of the SEU rate of monitored electronics in operational service for these systems where error detection and correction (EDAC) or another kind of error checking scheme is used to identify erroneous bits which are then recorded. The errors should be stored in non-volatile memory (similar to a fault code store) and can subsequently be used to identify the errors that have occurred due to SEU from the atmospheric neutrons. This can generally be done by obtaining a bit error rate from the service monitoring, and assuring, by comparison with rates that can be calculated from 8.3 and 8.4, that it is consistent with an SEU bit error rate from the atmospheric neutrons.

There are several issues that should be addressed when considering this method.

- a) The system will record that an error has taken place. The recorder/monitor will only be effective if it reliably identifies and stores error data.
- b) The extent of the system that is monitored and recorded for errors should be clearly identified and some elements of the system will not be addressed by the monitor. Those participating in the post-removal analysis should understand how other effects not related to the atmospheric neutrons (power transients, vibration transients, software problems, etc.) may contribute to the errors.
- c) The information obtained will always be historical, i.e. the system will be in operation.
- d) Where the errors are corrected (not a hard fault), the errors will be recorded in the errors' non-volatile memory area but how this is enunciated to the aircraft system should be determined on a case-by-case basis and any action taken as a result. The data may be regularly recorded and cleared during scheduled maintenance, or as the memory fills.
- e) The recovery of the data from such store memories during maintenance requires the co-operation of the fleet operators and equipment manufacturer customer's support facilities.
- f) The procedure for the processing of such data should be clearly defined. This should be done by a person experienced in analysing SEU data. Since the bit upset rate is so important in verifying that the errors are indeed due to the atmospheric neutrons, the number of bits potentially sensitive to SEU by the neutrons in the particular system being monitored should be known or reliably estimated. An understanding of the normal SEU rates may indicate potential response during periods of high SEP activity.
- g) The coverage of the store and the route to data and analysis of results for SEU should be auditable including by customer and third party (including atmospheric radiation experts).

- h) It would be extremely helpful if additional information were recorded that is related to the location and altitude when an SEU takes place as this will assist correlation of the SEU data. Following an SEU, the altitude and location data would need to be requested from the flight control computer.

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Annex C (informative)

Review of test facility availability²

C.1 Facilities in the USA and Canada

C.1.1 Neutron facilities

Facility	Description	Availability
Los Alamos Neutron Science Center –LANSCE (alt. WNR (Weapons Neutron Research) facility or ICE (Irradiation of Chip and Electronics) House), located in Los Alamos, NM	Facility with neutron beam having an energy spectrum (neutrons with energies up to 700 MeV) providing the most accurate simulation of the atmospheric neutrons. Eight beam lines, with the beam line labelled 30 Left used for SEE testing (the ICE House). Facility upgraded in 2003, making it very convenient to use for SEE tests. Since 2000, 1 h in beam is equivalent to $\sim 1 \times 10^6$ h at 39 000 ft (11 860 m). The neutron spectrum is recorded accurately each run using a fission ionization chamber. LANL staff provide fluence for each run ($E > E_{\text{thresh}}$, with E_{thresh} specified by user; per this international standard E_{thresh} should be 10 MeV). Spot size typically 2,5 cm to 8 cm diameter with other options possible.	Facility is open for ~8 months/year. Numerous users want to use this beam, so LANSCE personnel schedule outside users for one session/year. See "The Los Alamos National Laboratory Spallation Neutron Sources," P. Lisowski <i>et al.</i> , <i>Nucl. Sci. Eng.</i> v. 106, p. 208, 1990 and http://wnr.lanl.gov . Facility contact: Steve Wender wender@lanl.gov , 505-667-1344)
TRIUMF Neutron Facilities (TNF, BL2C, BL1B) of the Tri-University Meson Facility (TRIUMF) located on the University of British Columbia (Vancouver, Canada) campus	The TNF Facility has a neutron flux with similar spectrum to that of atmospheric neutron (highest energy ~400 MeV). Unique facility because beam also contains a thermal neutron component (approximately 30 % of the >10 MeV neutron flux). For >10 MeV neutron flux is $\sim 1 \times 10^6$ times the atmospheric neutron flux at 39 000 ft. Neutron SEU cross-sections due to >10 MeV and thermal neutrons can be determined from two successive SEE tests (with and without cadmium plate over the IC). Not too convenient to use since test card has to be lowered 5 m down a channel on a mounting plate connected to a pulley system. Fluxes are determined for each run based on a neutron monitor that has been calibrated against activation foil measurements and calculations with FLUKA code. In 2005, a "flood" beam of neutrons, beam size 50 cm to 100 cm in diameter at the test point was developed at the proton test facility. Neutrons are produced by stopping either 115 MeV BL2C or 480 MeV BL1B protons in a lead target. The >10 MeV neutron flux is variable from 1 000 neutron·cm ⁻² ·s ⁻¹ to >100 000 neutron·cm ⁻² ·s ⁻¹ and is designed for testing large electronic systems. In 2013 the higher energy facility was upgraded with improved shielding for a factor 5 intensity upgrade.	The TNF facility is available about 8 months per year and is presently scheduled about 30 % of the time. The BL2C flood beam (neutrons to 115 MeV) is scheduled 1 week per month Apr to Dec. The BL1B flood/collimated beam (neutrons to 450 MeV) is scheduled 4 times per year. See www.triumf.ca/pif-nif for beam schedule, costs and availability. Reference: "Intensity Upgrade to the TRIUMF 500 MeV Large-Area Neutron Beam", IEEE REDW 2014, pp 275-279.
Boeing Radiation Effects Laboratory (BREL), Seattle, WA	This is a 14 MeV neutron generator, capable of producing fluxes as high as 1×10^8 neutron·cm ⁻² ·s ⁻¹ to 5×10^8 neutron·cm ⁻² ·s ⁻¹ at close proximity (3 cm to 6 cm) to the generator head, emitted in 4 π geometry. It was upgraded with a new source and control electronics in 2009. For recent SRAMs (after the year 2000) testing has shown that the SEU cross-section from 14 MeV neutrons is very close to that from the high energy neutrons. Latch-up testing is not recommended using 14 MeV neutrons. Fluence is determined using an electronic neutron dosimeter. After an exposure, a 20 min cool-down time is required to re-enter the neutron chamber.	Availability is ~10 months per year (contact Jerry Wert at jerry.wert@boeing.com);

² This list of test facilities is given for the convenience of the users of this standard and does not constitute an endorsement by the IEC.

Facility	Description	Availability
NCNR (NIST Center for Neutron Research), National Institute of Standards and Technology, Gaithersburg, MD	Two different types of facilities are available at the NCNR to provide thermal neutrons, the thermal column and a cold neutron facility. The thermal column provides a collimated beam of thermal neutrons with a diameter of 1 in to 2 in (2,54 cm to 5,1 cm), and a flux of 1×10^8 neutron-cm ⁻² .s ⁻¹ . Epithermal neutrons and gamma rays are also in the beam at much lower levels, but they do not cause any SEUs. Occasionally another facility, the neutron beam imaging area, having a much larger thermal neutron beam spot, may be available. The second type of source is that of cold neutrons, having energies well below 0,025 eV. At present the cold neutron facility that had been used for electronics testing is about to be retired. A cold neutron beam area, the "bench top facility" was available for electronics testing. The cold neutron beams are pure, having no other particles, and have a higher effective thermal flux since the B-10 neutron cross-section increases with decreasing energy.	The thermal column is currently (2010) out of service, with a return to service of, at the earliest, sometime during 2012. The neutron imaging facility is available.
Nuclear Science Center, Texas Engineering Experiment Station, Texas A&M University, College Station, TX	The TRIGA research reactor operates at 1 MW _{thermal} and has beam ports available that can be used for exposing electronics to thermal neutrons. One beam port can provide a neutron beam of thermal neutrons (0,025 eV) with an average flux of 1×10^6 neutron-cm ⁻² .s ⁻¹ . The reactor has a dry irradiation cell that can be used for irradiating electronics and the average thermal flux can be close to 1×10^{10} neutron-cm ⁻² .s ⁻¹ . The reactor also supports isotope production and there are irradiation locations in the core where the neutron flux on the order of 10^{13} neutron-cm ⁻² .s ⁻¹ can be expected.	The cost of usage of beam port, the dry cell as well as core irradiation locations vary with time and usage. See: http://nuclear.tamu.edu/facilities/lab08/

C.1.2 Proton facilities

Facility	Description	Availability
Los Alamos Neutron Science Center -LANSCE (alt. WNR (Weapons Neutron Research) facility or Target-2 or Blue Room) located in Los Alamos, NM	Facility with 800 MeV proton beam with 10^8 protons/pulse. Beam spot size typically 1 cm diameter with other options possible. Proton currents up to approximately 80 nA or 5×10^{11} proton/s.	For cost and availability contact Leo Bitteker (lbi@lanl.gov 505-667-0333)
Indiana University Cyclotron Facility (IUCF), Indiana University, Bloomington, IN	Within the RERP (Radiation Effects Research Program) of the IUCF, two separate beam lines (radiation effects research stations), were available to provide protons, RERS-1 and RERS-2. At RERS-1, protons were available with energies in the range of 30 MeV to 200 MeV. The lower energies were achieved by the use of Cu degraders. The diameter of the beam spot was 2 cm to 20 cm, but the usual diameter was 7 cm, with a uniformity of >70 %. During normal operation the maximum beam flux was $\sim 1 \times 10^9$ proton-cm ⁻² .s ⁻¹ , but at night and on weekends it could be higher. Typical particle fluences of 1×10^{10} proton-cm ⁻² to 1×10^{11} proton-cm ⁻² were usually obtained in a few minutes. Dosimetry was by means of secondary electron monitor. Although the RERS-2 beam line (operational December 2003) was similar to RESR-1, exposures with proton energies < 200 MeV mainly performed at this station using Be degraders. Electronic devices to be tested were mounted on an adjustable x, y, z table which could be moved remotely, and alignment with the beam was assured by means of a laser.	The facility closed in December 2014. Fluxes $> 1 \times 10^9$ proton-cm ⁻² .s ⁻¹ were obtained only at night and on weekends. See "Opportunities for Single Event and Other Radiation Effects Testing and Research at the IUCF," C. C. Foster <i>et al.</i> , <i>Workshop Record</i> , 1996 IEEE Radiation Effects Data Workshop, p. 84

Facility	Description	Availability
Francis H. Burr Proton Therapy Center (formerly Northeast Proton Therapy Center) (FHBPTC), Massachusetts General Hospital, Boston, MA	As of 2002, the FHBPTC has replaced the Harvard Cyclotron Laboratory as the facility used for exposing both patients and electronics to proton beams. The FHBPTC beam can provide energies in the range of 90 MeV to 230 MeV via a magnetic energy selection system, and beams down to 20 MeV using degraders. The diameter of the beam spot can be <1 cm and up to 30 cm, but the usual diameter is 5 cm to 10 cm, with uniformity variation of <10 %. Beam flux is available from 10^2 proton·cm ⁻² ·s ⁻¹ to $\sim 2 \times 10^{11}$ proton·cm ⁻² ·s ⁻¹ . Dosimetry to a device under test (DUT) is by means of a thin foil transmission ion chamber calibrated to the Faraday cup or thimble chamber. A scintillator/phototube system is available for low flux runs. A laser alignment system is used to centre the DUT in the beam.	Because the main customers are cancer patients, the beam is available for radiation effects testing only on weekends. See "The Proton Irradiation Program at the Northeast Proton Therapy Center," E. Cascio <i>et al.</i> ," <u>Workshop Record</u> , 2003 IEEE Radiation Effects Data Workshop, p. 141
Tri-University Meson Facility, (TRIUMF) located on University of British Columbia (Vancouver, Canada) campus	Since 1995 the Proton Irradiation Facility (PIF) has been providing two separate beams of mono-energetic protons, covering the range of 65 MeV to 500 MeV. Beam line BL2C provides protons with energies up to 120 MeV, and beam line BL1B provides protons with energies in the range of 180 MeV to 500 MeV. The facility has been optimized to provide fluxes of $\sim 1 \times 10^8$ proton·cm ⁻² ·s ⁻¹ , with uniform beam diameters of up to 7,5 cm. However, by reducing the beam spot, fluxes of 1×10^{10} proton·cm ⁻² ·s ⁻¹ can be achieved. Beam dosimetry is achieved using a miniature ion chamber and also a Faraday cup for high flux beams. Absorbers are used in conjunction with collimators to lower the beam energy, and scattering foils to broaden the beam. A beam profile monitor is employed upstream and lasers are used to align positioning of the DUT within the beam.	The facility is available about 8 months per year during which time BL2C is available for week-long periods approximately once per month, but 8 h to 16 h test periods can be scheduled at other times on BL2C with several week's advance notice. BL1B is available during four week-long periods per year. See www.triumf.ca/pif-nif for beam schedule, costs and availability. Reference: "Improved Capabilities for Proton and Neutron Irradiations at TRIUMF," IEEE REDW 2003 pp149-155.
University of California at Davis, Crocker Nuclear Laboratory (CNL), Davis, CA	Since the 1970s CNL has been providing industry and government agencies access to the variable energy 76 in isochronous cyclotron. The cyclotron can accelerate protons from 1 MeV to 68 MeV. In the Radiation Effects Facility (REF) the maximum proton energy to the DUT is 66 MeV. The spatial spreading of the beam is accomplished by passing the beam through a Ta diffuser foil. Lower energies can also be obtained by choosing a cyclotron proton energy combined with a proper diffuser foil to give an acceptable beam energy spread. Typically the beam energy spread is kept below 600 keV. In the REF the flux can be in the range of 1 proton·cm ⁻² ·s ⁻¹ to 1×10^{10} proton·cm ⁻² ·s ⁻¹ , although typical beam fluxes for exposing electronics are 1×10^4 proton·cm ⁻² ·s ⁻¹ to 1×10^9 proton·cm ⁻² ·s ⁻¹ . For this beam line the diameter of the beam spot can be up to 6 cm, with a uniformity of 92 %. A second beam line, 1C, has recently become available for higher flux beams, up to 1×10^{12} proton·cm ⁻² ·s ⁻¹ , but with a beam spot of 2 cm in diameter. A compound x-y table is provided for locating the DUT, the range on translation is 7,37 in and 19,59 in in the X and Y direction respectively (this table can also be remotely controlled); two laser beams are used to align the positioning of the DUT within the beam. A vacuum box 16,5 in × 16,5 in and 25 in tall can be attached at the end of the REF beam line to use cyclotron proton beams lower than 7 MeV without subjecting them to the energy spreading due to the exit foil or the air path. Beam dosimetry is accomplished by means of a secondary electron emission monitor (SEEM) combined with a removable Faraday cup. Beam uniformity is monitored with a segmented secondary electron emission monitor (SSEEM).	The facility is available ~10 months/year, but needs an agreement w/U of Cal. Contact: Carlos Castaneda (530) 752-4228, see "Crocker Nuclear Laboratory (CNL) Radiation Effects Measurement and Test Facility," C. Castaneda <i>et al.</i> , <u>Workshop Record</u> , 2001 IEEE Radiation Effects Data Workshop, p. 77; http://cyclotron.crocker.ucdavis.edu/ Crocker/Website/b_Information/index.php.

C.1.3 Laser facilities

Facility	Description	Availability
Pulsed Laser Test Facility at the Naval Research Laboratory, Washington DC.	The NRL test facility contains two separate pulsed laser systems, one for doing single-photon absorption (SPA) experiments at a wavelength of typically 590 nm and tunable from 570 nm to 620 nm and the other for doing two-photon absorption (TPS) experiments at a nominal wavelength of 1 260 nm that allows through-wafer testing. The electronic device under test is mounted on an XYZ stage that is computer controlled for doing three-dimensional scanning to determine sensitive volumes. In both cases, the light is focused onto the device using long-working distance microscope objective lens that produces a focused beam with a spot size of just over 1 μm in diameter. Pulse rate is adjustable from single shot to 40 MHz for the SPA laser, and from single shot to 1 kHz for the TPA laser. Both setups contain illumination optics for viewing the DUT as well as the focused laser spot. Maximum laser pulse energies are equivalent to LETs >>100 MeV·cm ² ·mg ⁻¹ .	Contact Dale McMorrow for scheduling at mcmorrow@ccs.nrl.navy.mil Tel: (202) 767-5469

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C.2 Facilities in Europe

C.2.1 Neutron facilities

Facility	Description	Availability
<p>The Svedberg Laboratory (TSL) at Uppsala University, Uppsala, Sweden</p>	<p>Two neutron beam facilities are available at TSL:</p> <p>(1) Atmospheric-like Neutrons from thick Target (ANITA), (2) Quasi-Mono-energetic Neutrons (QMN).</p> <p>The ANITA and QMN facilities share the same area with ~30 m² floor space available for users. At both the facilities, the neutron flux is continuously recorded by calibrated monitors based on neutron fission (FIC, TFBC) and on integration of the primary proton beam current.</p> <p>(1) The ANITA facility, built in 2007, provides neutrons with atmospheric-like spectrum up to the highest energy of ~180 MeV. The neutron flux above 10 MeV is:</p> <ul style="list-style-type: none"> – up to 10⁶ cm⁻².s⁻¹ at the conventional user area, – up to 10⁷ cm⁻².s⁻¹ at the Close User Position (CUP), constructed and characterized in 2013-2014. <p>At the conventional user area, any beam size between 1 cm and 120 cm can be selected by the user and varied during the campaign. At the CUP, the beam size is ~20 cm × 20 cm.</p> <p>The flux is promptly variable within a factor of at least 150. The thermal neutron flux, relative to the flux >10 MeV, is ~1 % at the conventional user area and ~20 % at the CUP.</p> <p>(2) The QMN facility, upgraded in 2003, provides neutrons with energy controllable in the range 20 MeV to 180 MeV, with roughly half the neutrons in the high-energy peak and the rest in the low-energy tail. The peak neutron flux is 3 × 10⁴ neutron.cm⁻².s⁻¹ to 1,5 × 10⁵ neutron.cm⁻².s⁻¹, depending on the energy. Any beam size between 1 cm and 80 cm can be user selected and varied during the campaign.</p>	<p>Availability: ~9 months/year. Lead time at ANITA 2-8 weeks. The beam time request form is available at http://www.tsl.uu.se.</p> <p>Cost (2015): ANITA: EUR 520/h, QMN: EUR 580/h. See pricing policy at http://www.tsl.uu.se.</p> <p>Contact: beams@tsl.uu.se, or http://www.tsl.uu.se/About_TSL/Contact/.</p> <p>Facility descriptions: ANITA: A.V. Prokofiev et al., 2009 IEEE REDW, pp. 166-173, http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05336295 ANITA-CUP: A.V. Prokofiev et al., IEEE Transactions on Nuclear Science, v.61, pp. 1929-1936 (2014), http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-234423 QMN: A.V. Prokofiev et al., Rad. Prot. Dosim. v. 126, pp. 18-22 (2007), http://rpd.oxfordjournals.org/content/126/1-4/18.full.</p>
<p>ISIS Pulsed Neutron and Muon Source, Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, OX11 0QX, UK</p>	<p>ISIS is a facility that is primarily used for condensed matter physics, operating two separate target stations that can provide neutrons with an energy spectrum up to 800 MeV and which contain epithermal, thermal and cold neutrons.</p> <p>The VESUVIO beam line on Target Station One is immediately available for SEE testing having been characterised through Monte Carlo (MCNPX) simulation and activation foil analysis. The fast neutron content of the beam is 5,8 × 10⁴ neutron.cm⁻².s⁻¹ (> 10 MeV) with a strong well characterised cold/thermal and epithermal component. This beam is highly collimated with a diameter of 2 cm to 5 cm and has dosimetry based on fission counters, scintillation counters and the proton current.</p> <p>A new development on Target Station Two is in the design and construction phase and should provide both a collimated (~10 cm × 16 cm) and flood area (~100 cm diameter) beam matching atmospheric spectrum up to 800 MeV both with variable collimation. Design fluxes are 1 × 10⁶ neutron.cm⁻².s⁻¹ to 1 × 10⁷ neutron.cm⁻².s⁻¹ (>10 MeV) for the collimated beam and 1 × 10⁴ neutron.cm⁻².s⁻¹ to 1 × 10⁵ neutron.cm⁻².s⁻¹ for the flood beam. A highly flexible large experimental area is envisaged with remote sample positioning and the ability for in-situ dosimetry being developed.</p>	<p>Academic (and therefore published) access is via peer review.</p> <p>See http://www.isis.stfc.ac.uk/about-isis/aboutisis.html</p> <p>Currently non-academic access and proprietary research is negotiated.</p> <p>Contact: Christopher Frost christopher.frost@stfc.ac.uk</p>

Facility	Description	Availability
<p>CYClotron of LOuvain-la-NEuve, Cyclotron Research Centre (CRC) at Catholic University of Louvain-la-Neuve (UCL), Belgium</p>	<p>CYCLONE has a mono-energetic neutron beam line that provides quasi mono-energetic neutrons at energies in the range of 25 MeV to 70 MeV. The neutrons are generated by accelerating a mono-energetic proton beam into a lithium target, with roughly half the resulting neutrons having a pseudo peak within 1 MeV to 2 MeV of the proton energy, and the remaining neutrons approximately evenly distributed over energy down to a few MeV (the low energy "tail"). The peak neutron flux is 1×10^6 neutron·cm⁻²·s⁻¹ (3 mm thick target) over a beam spot of 4 cm in diameter.</p>	<p>Beam time has to be scheduled. See "CYCLONE – A Multipurpose Heavy Ion, Proton and Neutron SEE Test Site," Workshop Record, 1997 RADECS Conference Data Workshop, p. 51, 4th European Conference, Palm Beach, Cannes, France; see http://www.cyc.ucl.ac.be</p>
<p>National Physical Laboratory, Teddington, UK</p>	<p>Can provide well-characterized mono-energetic neutron fields covering the energy range 70 keV to 5 MeV and at 17 MeV via a variety of nuclear reactions using beams of protons or deuterons from a 3,5 MV Van de Graaff accelerator. A thermal neutron irradiation facility is also available with a beam fluence of up to 10^4 cm⁻²·s⁻¹ over an area of 30 cm diameter or an isotropic field with fluences up to 10^7 cm⁻²·s⁻¹ in an access hole of diameter 12 cm.</p>	<p>Prices are estimated primarily in terms of staff time to perform the irradiations. http://www.npl.co.uk/commercial-services/measurement-services/neutron-measurements/</p>
<p>Atomic Weapons Establishment (AWE) Aldermaston, Berkshire, UK</p>	<p>The ASP Accelerator produces 14 MeV neutrons via the D+T reaction. The maximum 14 MeV neutron flux is 2×10^{10} neutron·cm⁻²·s⁻¹ at 1 cm from the target. In addition, deuterium loaded targets can be used to produce 3 MeV neutrons using the d+d reaction, giving a maximum flux of 2×10^8 neutron·cm⁻²·s⁻¹. The accelerator has the capability of being operated in either continuous or pulsed mode. The minimum pulse width is 5 μs.</p>	<p>Beam time has to be scheduled in advance. For further information contact Shaun Hughes on 01189 824122 or email aspaccelerator@awe.co.uk</p>

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C.2.2 Proton facilities

Facility	Description	Availability
Proton Irradiation Facility (PIF) at the Paul Scherrer Institute (PSI) Villigen, Switzerland	<p>Within PSI there are now two proton irradiation facilities, the high energy (HE) PIF and the low energy (LE) PIF. The design of the two PIF areas is very similar with regard to set-up and operation (beam dosimetry, flux calibration, energy degrader and data acquisition). At the high energy PIF (also called the NA3 PIF) the initial proton beam has an energy of 590 MeV, but at the irradiation area the energy is reduced to 254 MeV (range of 30 MeV to 254 MeV). At 254 MeV, the maximum flux is $2,5 \times 10^8$ proton·cm⁻²·s⁻¹ and the maximum diameter of the beam spot is 9 cm. Degraders are used to achieve lower energies, but the uniformity of the beam is reduced, which varies with the distance from the degrader. Because part of the beam line is used for biomedical therapy, electronics are exposed only during weekends. The LE PIF (also called NEB PIF) is located near another biomedical beam line called OPTIS, however the operation of the two beams is more directly coordinated. The energy range for the LE PIF is 6 MeV to 71 MeV, the maximum proton flux is 5×10^8 proton·cm⁻²·s⁻¹, the largest beam spot is 5 cm diameter, and the beam uniformity is > 90 %. Electronic components are exposed at the LE PIF mainly at night and during weekends. These exposures are performed during OPTIS treatment weeks (once a month) beginning at 17:00 after patient therapy has ended, and also on "free weekends".</p>	<p>Beam time has to be scheduled in order to coordinate with the biomedical treatment operation. See "Radiation Effects Testing Facilities in PSI during Implementation of the Proscan Project," W. Hajdas <i>et al.</i>, <u>Workshop Record</u>, 2002 IEEE Radiation Effects Data Workshop, p. 160 and "Radiation Effects Testing Facility in PSI Low Energy OPTIS Area," W. Hajdas <i>et al.</i>, <u>Workshop Record</u>, 1998 IEEE Radiation Effects Data Workshop, p. 152.</p>
The Svedberg Laboratory (TSL) at Uppsala University, Uppsala, Sweden	<p>The PAULA facility (Proton fAcility in Uppsala), upgraded in 2011, provides mono-energetic protons with energy in the range ~10 MeV to ~180 MeV, controllable by selection of the acceleration mode and of degrader slabs. Two modes of operation are available, with scattered and unscattered beams.</p> <p>(1) Scattered beams have the spot diameter (after collimation) between 0,5 cm and 40 cm, selectable by the user. The highest flux amounts to $\approx 3 \times 10^9$ cm⁻²·s⁻¹ for the proton energy of ~180 MeV. The lowest achievable flux corresponds to single protons per cm² per s. The flux within the beam spot is uniform to ±10 %. The flux is monitored by TFBCs and by scintillator telescopes.</p> <p>(2) Unscattered beams have the highest intensity of 3×10^{11} s⁻¹ to 2×10^{12} s⁻¹ for the highest and the lowest energy, respectively. The lowest achievable intensity is $\sim 10^2$ s⁻¹. The typical beam spot shape is a circle with the diameter of 0,7 cm to 2 cm. The beam profile shape is approximately Gaussian. The intensity is measured with a Faraday cup and monitored by scintillator telescopes.</p>	<p>Availability: ~9 months/year. The beam time request form is available at http://www.tsl.uu.se .</p> <p>Cost (2015): EUR 550/h. See pricing policy at http://www.tsl.uu.se .</p> <p>Contact: beams@tsl.uu.se , or http://www.tsl.uu.se/About_TSL/Contact/ .</p> <p>Facility description: http://www.tsl.uu.se/irradiation-facilities-tsl/PAULA-proton-beam-facility/</p>
CYClotron of LOuvain-la-NEuve, Cyclotron Research Centre (CRC) at Catholic University of Louvain-la-Neuve (UCL), Belgium	<p>One of the CYCLONE proton beam lines called the Light Ion irradiation Facility (LIF) has been modified for testing electronics. The proton energy can be varied between 10 MeV to 70 MeV, by adjusting the cyclotron or using plastic degraders. The beam spot is 10 cm in diameter. Beam flux can be modified between a few proton·cm⁻²·s⁻¹ and 5×10^8 proton·cm⁻²·s⁻¹.</p>	<p>Beam time has to be scheduled. See "CYCLONE – A Multipurpose Heavy Ion, Proton and Neutron SEE Test Site," Workshop Record, 1997 RADECS Conference Data Workshop, p. 51, 4th European Conference, Palm Beach, Cannes, France; see http://www.cyc.ucl.ac.be</p>

C.2.3 Laser facilities

Facility	Description	Availability
<p>Single Event Radiation Effects in Electronics Laser (SEREEL2) at MBDA in Bristol, UK</p>	<p>SEREEL incorporates a 1 ps pulsed laser with a computer controlled parametric amplifier system for generating wavelengths in the range 450 nm to 2 600 nm (covering the entire laser SEE range including both single-photon absorption and two-photon absorption). Pulse energies up to 1,5 mJ (dependent upon wavelength). Standard magnification of the focussing objective is $\times 100$ with a 10 mm working distance relative to the microchip under test. Features: In GaAs camera technology for viewing chips through their polished backsides; piezo-electric scanning and positioning technology for fast delivery of large arrays of laser pulses (e.g. 3D SEE sensitivity mapping); selectable laser pulse repetition rate from single shot to 1 kHz. Standard types of memories can be interrogated during testing using MBDA's FPGA-based STREAM system (pin assignment in software for rapid adaptation to many pinout configurations).</p>	<p>Normally contracts need to be for > £ 2 000</p>
<p>Radiation Analysis Laser Facility at Airbus Group Innovations, Suresnes, France</p>	<p>Airbus Group Innovations Radiation Analysis Laser Facility is designed for industrial purpose. It is based on a pulsed (600 ps) laser source operating at a wavelength of 1 064 nm, optimized to perform tests from the electronic device backside with no need for substrate thinning. The laser source is highly stable and the energy can be varied over a wide range. Working distance between the focusing objective and the device under test is 1 cm. The whole laser facility is fully automated thanks to motorized actuators on X Y and Z directions (50 nm minimum step resolution), an automated system for the laser energy adjustment and a camera allowing to view the front side of the chip through the device substrate. Power supply and various acquisition systems may be connected and synchronized to the system as well, which makes parameterized tests easier.</p>	<p>Standard rates include calibration and mandatory staff support</p>
<p>ATLAS (Analysis and Test with Lasers) platform at IMS Laboratory, University of Bordeaux, in Talence, France</p>	<p>ATLAS is an academic laser facility offering SEE test services using three pulsed laser sources, giving access to pulse durations of 150 fs, 1 ps or 30 ps with wavelength tunable from 400 nm to 2 500 nm, pulse repetition rate from single-shot to 10 MHz, and pulse energies higher than 1 μJ on the full range of wavelengths (up to 1 mJ at 800 nm). Standard wavelengths for single-photon absorption SEE testing include 800 nm, 980 nm and 1 064 nm. Two-photon absorption at 1 300 nm is used for 3D SEE mapping. Laser focusing and real-time imaging of the laser impact location is achieved by 100X front-side or backside infrared microscopes.</p> <p>Other features: standard scanning resolution of 100 nm, down to 10 nm using piezo-electric stages; sample preparation (package opening and substrate thinning) available on-site; flexible mechanical fixture compatible with most PCB geometries; wafer probing station with inverted microscope compatible with naked dies or wafer-level laser testing; software controlled scanning, triggering, data acquisition and analysis; customizable IC tester/software interface; digital tester with customizable daughter-board; standard electronic instruments (oscilloscopes, precision power supplies, delay and pattern generators, spectrum analyzer, lock-in amplifier); remote (internet based) testing capability.</p>	<p>Rates are dependent on test details and laser parameters including the support of an ATLAS engineer.</p> <p>Availability: 4 weeks minimum notice.</p> <p>Contact: atlas@ims-bordeaux.fr</p>

Annex D (informative)

Tabular description of variation of atmospheric neutron flux with altitude and latitude

The source is the Simplified Boeing Model in [9], in which the 1 MeV to 10 MeV neutron flux is normalized to a value of $0,85 \text{ neutron}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ at 39 000 ft (11 860 m) altitude and 45° latitude. Even though the fluxes in Table D.1 and D.2 are for neutrons with energies between 1 MeV to 10 MeV, [9] has shown that the same altitude and latitude variation applies to neutrons for all $E > 1 \text{ MeV}$.

**Table D.1 – Variation of 1 MeV to 10 MeV neutron flux in
the atmosphere with altitude**

Altitude ft (m)	1 MeV to 10 MeV neutron flux, $\text{neutron}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$
5 000 (1 520)	0,01
10 000 (3 050)	0,04
15 000 (4 570)	0,08
20 000 (6 100)	0,13
25 000 (7 620)	0,24
30 000 (9 140)	0,38
35 000 (10 670)	0,60
40 000 (12 190)	0,88
45 000 (13 720)	1,02
50 000 (15 240)	1,16
55 000 (16 760)	1,24
60 000 (18 290)	1,25
65 000 (19 810)	1,24
70 000 (21 340)	1,22
75 000 (22 860)	1,20
80 000 (24 380)	1,18

Table D.2 – Variation of 1 MeV to 10 MeV neutron flux in the atmosphere with latitude

Latitude °	1 MeV to 10 MeV neutron flux, neutron·cm ⁻² ·s ⁻¹
90	1,26
76	1,25
69	1,23
62,5	1,21
55	1,13
49	0,99
45	0,85
42	0,74
39	0,63
33	0,46
27	0,35
21	0,29
12	0,23
0	0,23

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Annex E (informative)

Consideration of effects at higher altitudes

As altitude increases both protons and heavy ions provide increasingly important contributions to SEE rates and these should certainly be included for applications above about 60 000 ft. For protons the main interaction is non-elastic nuclear interactions and these are similar to neutron interactions at high energies (> 20 MeV). However small feature size components (65 nm and below) are becoming sensitive to direct ionization effects from protons as they reach maximum linear energy transfer (LET) towards the end of their track (the Bragg peak effect). General techniques for dealing with stopping protons have yet to be developed and proper Monte Carlo simulations will be required. However, SEU from direct proton ionization has only been seen in laboratory experiments with collimated beams. For electronic devices used in large fielded systems such as aircraft, the greater the mass surrounding the electronics, the less likely it is that the electronics within will be sensitive to SEU from direct ionization. This is because the “end of track” distance within which the highest proton LET is achieved in silicon (required to produce an SEU) is $1\ \mu\text{m}$ to $2\ \mu\text{m}$ ($\sim 4\text{--}8 \times 10^{-5}$ in), compared to the centimetres of material that surround the electronic devices, making energy deposition from the protons within the $1\ \mu\text{m}$ to $2\ \mu\text{m}$ very unlikely. However the electronic devices will be sensitive to higher energy protons which will lose energy due to the mass surrounding the electronics and then will be in the low energy domain. Additionally, the electronic devices will also be sensitive to secondary protons generated locally in materials surrounding the device.

Significant heavy ion fragments penetrate down to about 60 000 ft and their higher charge means that many electronic devices are sensitive to SEE by direct ionization.

Direct ionization by energetic heavy ions, for which the range is much greater than electronic device dimensions so that LET is constant across the device, can be dealt with using the integral linear energy transfer spectra as applied to space systems in CREME96 [36] and other codes. However it is necessary to generate such spectra as a function of depth within the atmosphere. This has been done for an updated version of the QARM model (QARM2) using the cosmic ray heavy ion spectra from the Badhwar-ONEILL model [101] and the FLUKA radiation transport code [38, 102]. This model propagates all secondary ion fragments and updates the early methods of Tsao, Silberberg and Letaw [28], who employed semi-empirical spallation cross-sections and followed only the larger spalled nuclei and not the other secondary products. Examples of integral LET spectra in silicon are given in Figure E.1 to Figure E.3 for solar maximum while Figure E.4 and Figure E.5 show the influence of solar modulation.

Readers not involved in aerospace vehicles operating at greater than 60 000 ft (18,3 km) can skip to Figures E.6 and E.7 and can ignore Annex F. Figures E.6 and E.7 show the SEU contribution from three particles within the atmosphere, neutrons, secondary protons and the heavy ions within the primary cosmic rays, all as a function of altitude. These are for two different rigidity cut-offs (see Figure 3), i.e. $R = 0$ (in polar regions) and $R = 8$ ($\sim 20^\circ$ N to 40° N latitude). Figures E.6 and E.7 show that at altitudes of up to 60 000 ft, the neutron contribution to the SEU rate dominates, at $\sim 70\%$, but at higher altitudes the neutron SEU rate diminishes and at 100 000 ft, it is less than 50% . The SEU rates in Figures E.6 and E.7 are based on three separate sets of SEU cross-section data (neutrons, protons and heavy ions) on one specific SRAM, but very similar behaviour has also been seen for a second SRAM [103], thus the overall behaviour in these figures can be considered as typical of how other electronic devices respond to SEU from these three particles as a function of altitude.

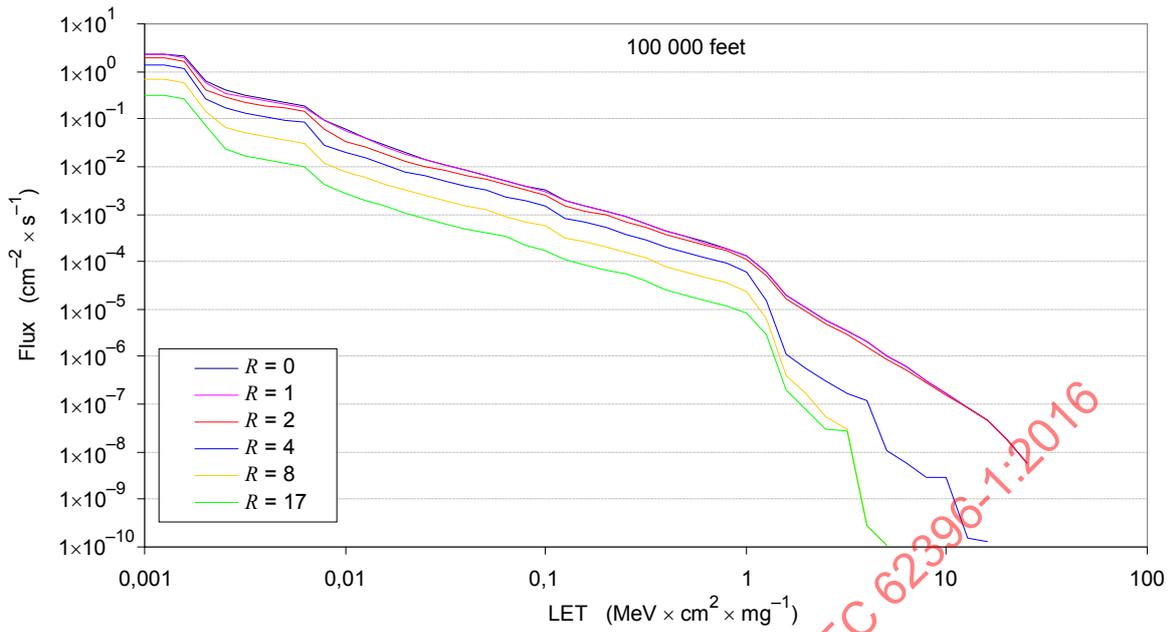


Figure E.1 – Integral linear energy transfer spectra in silicon at 100 000 ft (30 480 m) for cut-off rigidities (R) from 0 GV to 17 GV

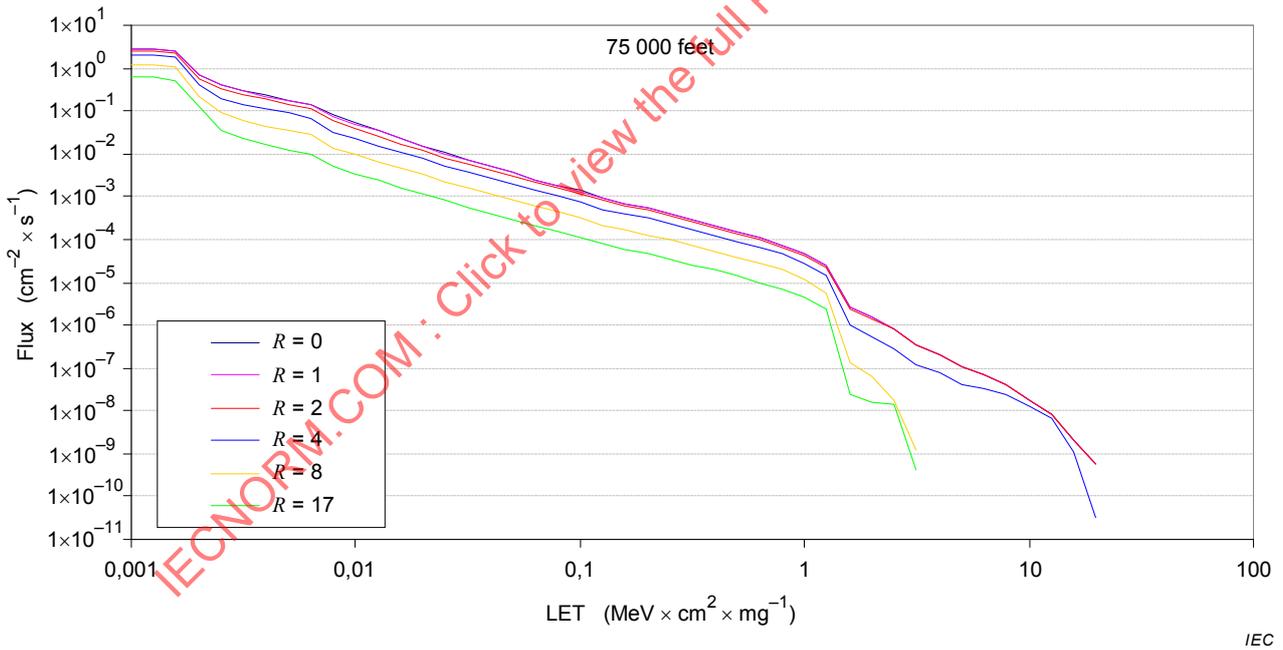


Figure E.2 – Integral linear energy transfer spectra in silicon at 75 000 ft (22 860 m) for cut-off rigidities (R) from 0 to 17 GV

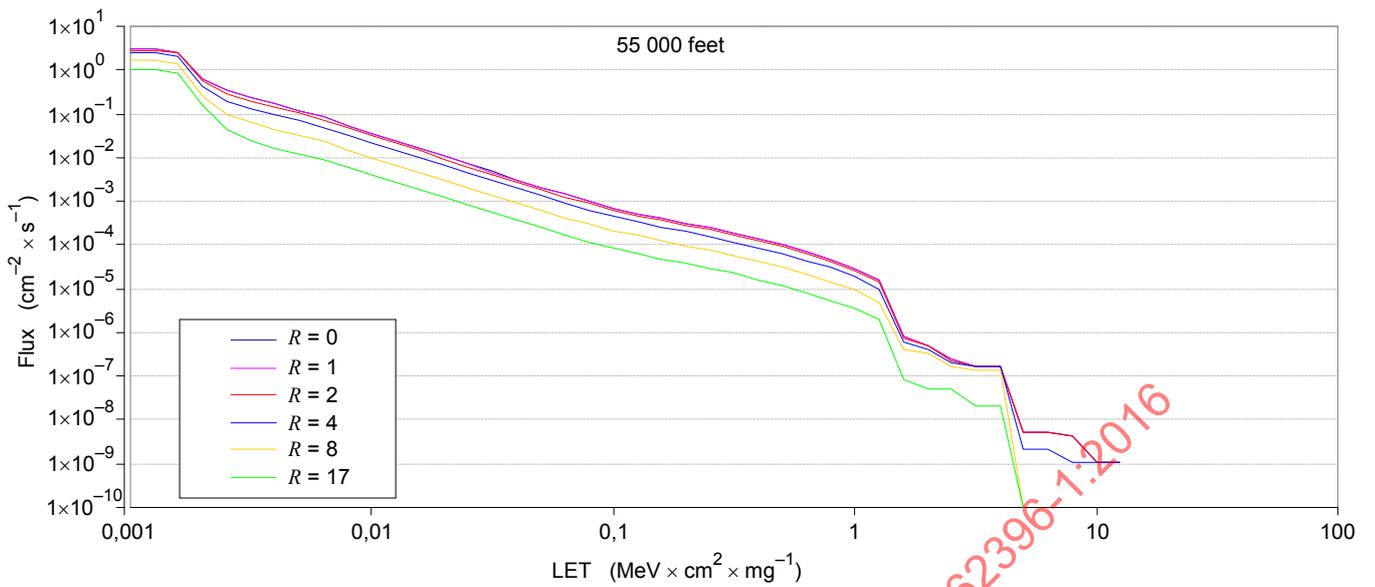


Figure E.3 – Integral linear energy transfer spectra in silicon at 55 000 ft (16 760 m) for cut-off rigidities (R) from 0 GV to 17 GV

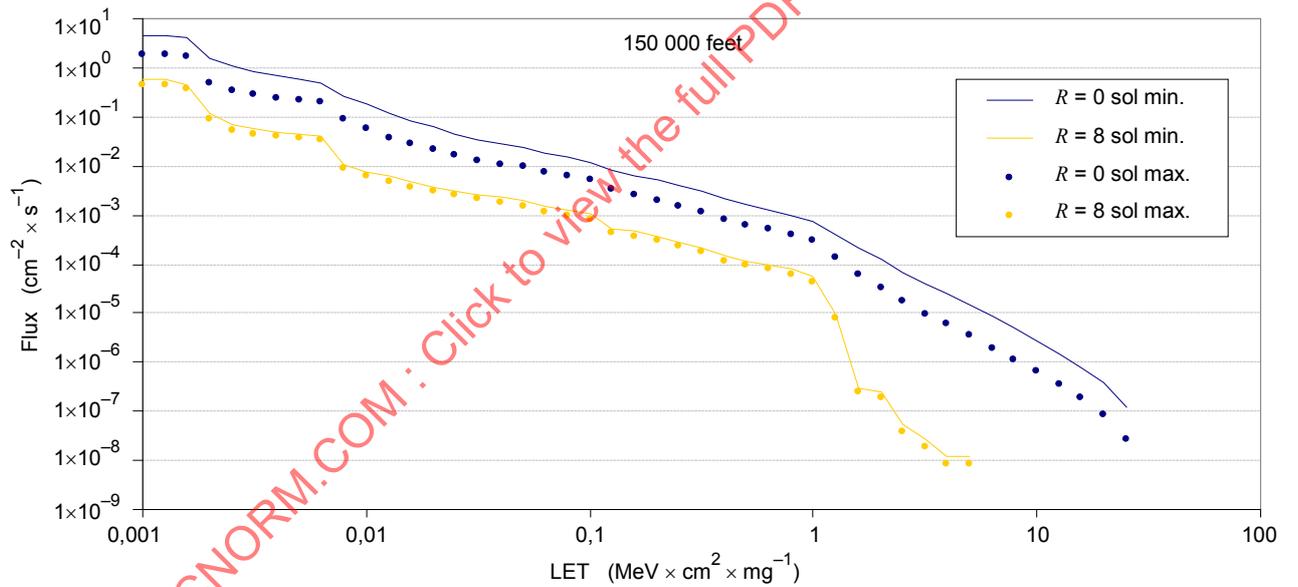


Figure E.4 – Influence of solar modulation on integral linear energy transfer spectra in silicon at 150 000 ft (45 720 m) for cut-off rigidities (R) of 0 GV and 8 GV

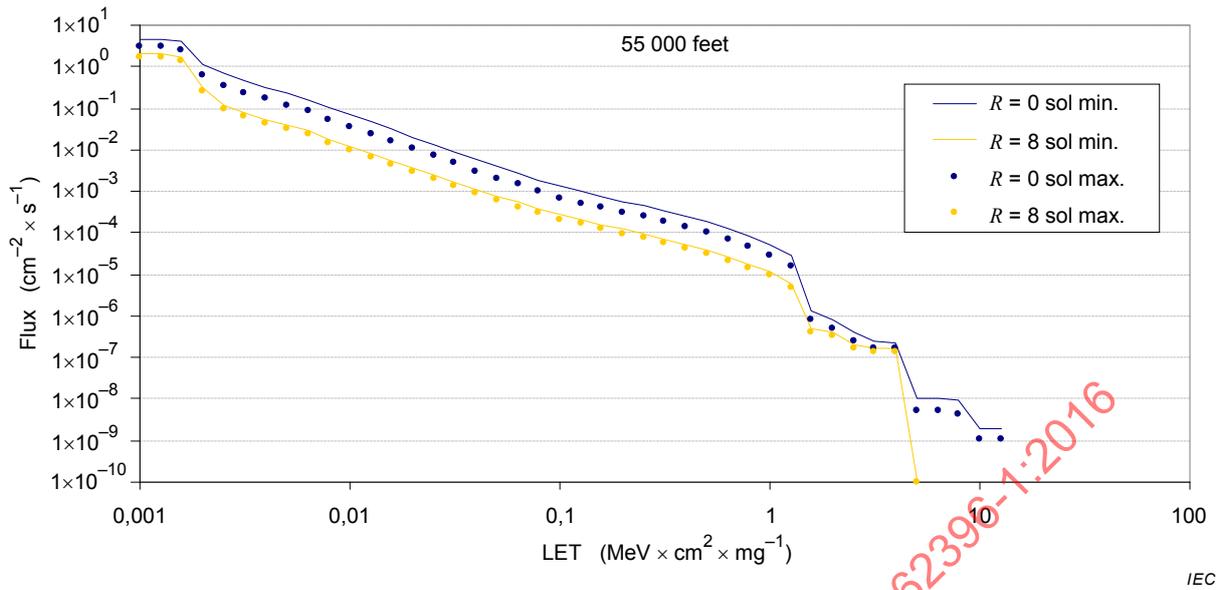


Figure E.5 – Influence of solar modulation on integral linear energy transfer spectra in silicon at 55 000 ft (16 760 m) for cut-off rigidities (*R*) of 0 GV and 8 GV

The integral LET spectra are combined with a path length distribution through a parallelepiped representation of an electronic device sensitive volume to give SEE rates. A commonly used method is the integral rectangular parallelepiped (IRPP) approach as discussed in Petersen et al. [104, 105]. The methods and equations used for the prediction of SEE rates for ions are fully discussed in the ECSS standard (ECSS-E-10-12) [106] and the appropriate section is reproduced below. An essential input is the SEE cross-section as a function of LET measured at ion accelerators and this is often fitted using a Weibull function. Such data is required for space applications and is widely published, for example in the IEEE Radiation Effects Data Workshop.

Using this technique, example SEU rates as a function of altitude are given for the Hitachi-A 4-Mbit SRAM in Figures E.6 and E.7 for two different cut-off rigidities at solar maximum. This electronic device has been fully characterised using heavy ion, proton and neutron beams [21, 47, 107]. SEU rates are normalised to 1 Gbit of memory. It can be seen that while the neutron contribution peaks at around 60 000 ft, the contributions of protons and ions both increase with altitude. For this particular electronic device the SEU rates are enhanced by factors of about 1.4, 2.0 and 3.0 at 40 000 ft, 85 000 ft and 100 000 ft respectively when considering all radiation compared with considering neutrons alone. Investigations are being made into other components to ascertain how typical such factors are.

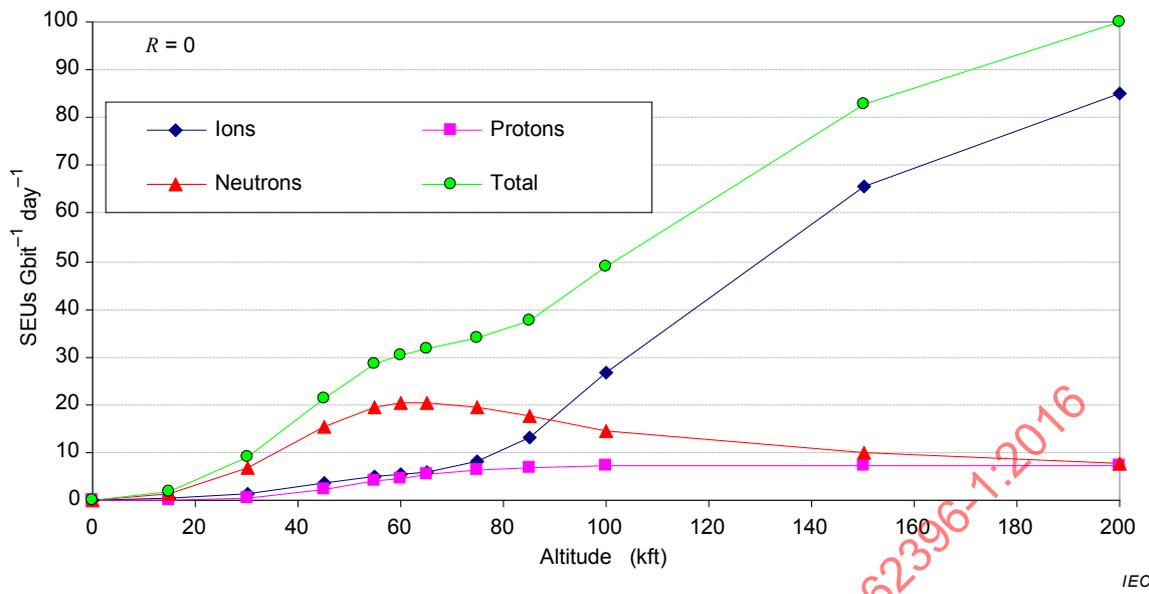


Figure E.6 – Calculated contributions from neutrons, protons and heavy ions to the SEU rates of the Hitachi-A 4 Mbit SRAM as a function of altitude at a cut-off rigidity (*R*) of 0 GV

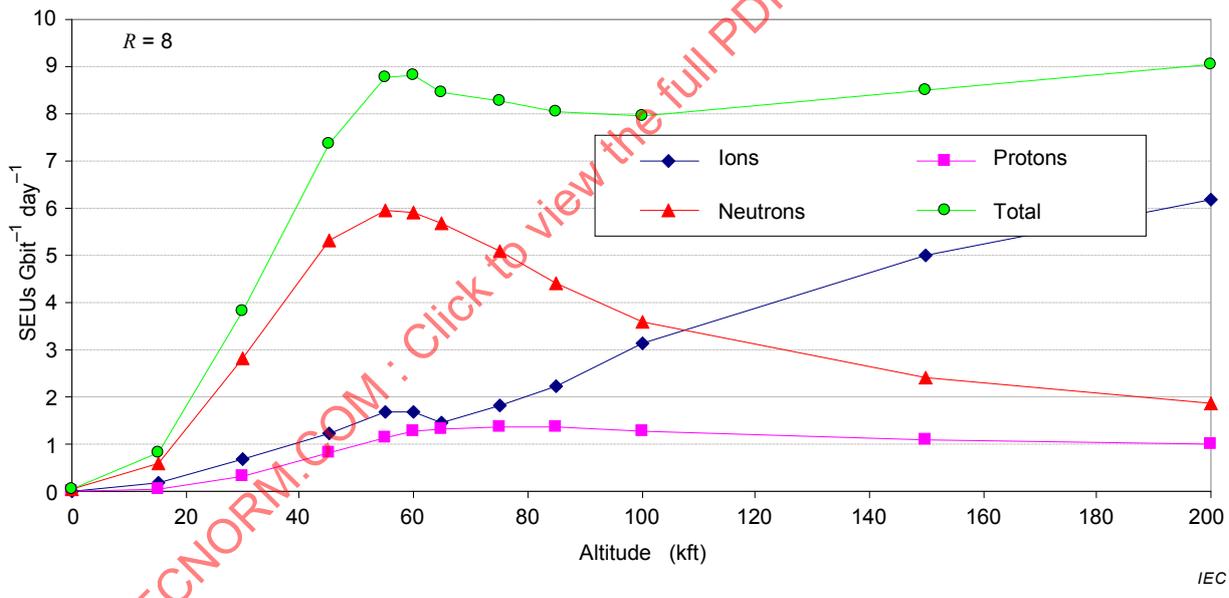


Figure E.7 – Calculated contributions from neutrons, protons and heavy ions to the SEU rates of the Hitachi-A 4 Mbit SRAM as a function of altitude at a cut-off rigidity (*R*) of 8 GV

Annex F (informative)

Prediction of SEE rates for ions³

When an ion crosses an electronic device, it leaves a dense plasma of electron hole pairs along its path. When the charges are generated close to a sensitive node of a circuit, a p-n junction of a transistor for example, these charges are collected and, if of sufficient magnitude, are able to generate soft errors.

The upset rate calculation depends on the paths available in the charge collection region (the sensitive volume). Ordinarily, this region is assumed to be a rectangular parallelepiped (RPP). It leads to two different SEE rate calculations: the RPP model and integral RPP (IRPP) model.

The principle for the RPP model is very simple: the energy deposited (E_{dep}) by an incident ion in the sensitive volume is estimated and if E_{dep} is greater than the threshold energy, the upset occurs. As incident ions are very energetic, they have very long ranges compared with typical electronic device feature sizes and one can assume that their slowing down is continuous and linear. In that case, the deposited energy E_{dep} , can be expressed simply as:

$$E_{\text{dep}} = \rho \cdot LET \cdot d \quad (\text{F.1})$$

The ion is characterised by its LET. An upset occurs when the incident ion has a LET greater than the threshold LET (LET_{th}). To calculate the upset rate, one needs to evaluate the LET spectrum of the incident particles. It leads to a very simple formula due to Bradford where the upset rate is expressed as a function of the incident LET spectrum and the path length distribution (such as the examples shown in Figures F.1 and F.2):

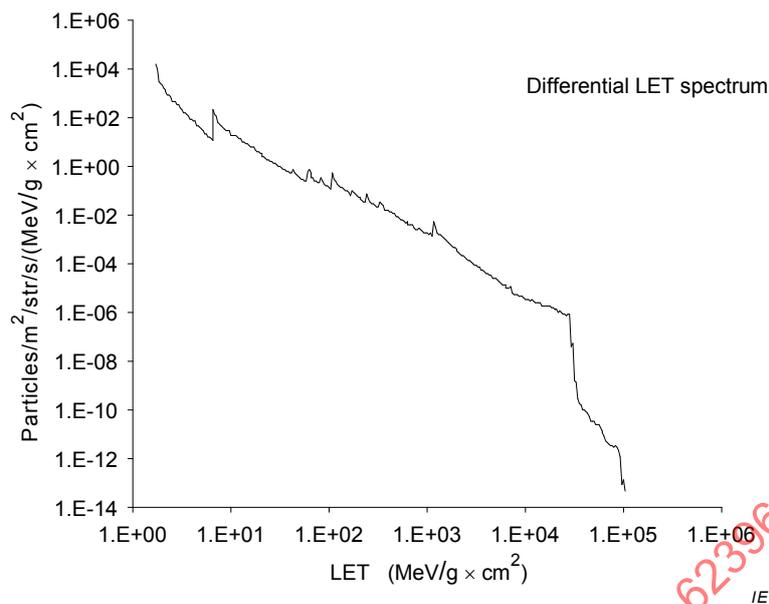
$$N = \frac{A}{4} \int_{LET_{\text{Min}}}^{LET_{\text{Max}}} \frac{d\Phi}{d(LET)}(LET) \cdot P_{\text{CL}}(> D(LET)) \cdot d(LET) \quad \text{Bradford formula for RPP} \quad (\text{F.2})$$

$$A = 2 \cdot (lw + lh + hw) \quad (\text{F.3})$$

where

- A is the total surface area of the SV (sensitive volume);
- l, w and h are the length, width and height of the SV;
- $d\Phi/d(LET)$ is the differential ion flux spectrum expressed as a function of LET (shortened to “differential LET spectrum”);
- $P_{\text{CL}}(>D(LET))$ is the integral chord length distribution, i.e. the probability of particles travelling through the sensitive region with a path length greater than D ;
- LET_{Min} is the minimum LET to upset the cell (also referred to as the LET threshold);
- LET_{Max} is the maximum LET of the incident distribution ($\sim 10^5 \text{ MeV}\cdot\text{cm}^2\cdot\text{g}^{-1}$).

³ Annex F is taken from ECSS-E-HB-10-12A standard [106]. Reproduced by permission from ECSS-E-10-12.



NOTE This graph is from the ECSS-E-HB-10-12A standard [106] and uses the scientific notation for numbers, for example 1.E+02 is 10^2 .

Figure F.1 – Example differential LET spectrum

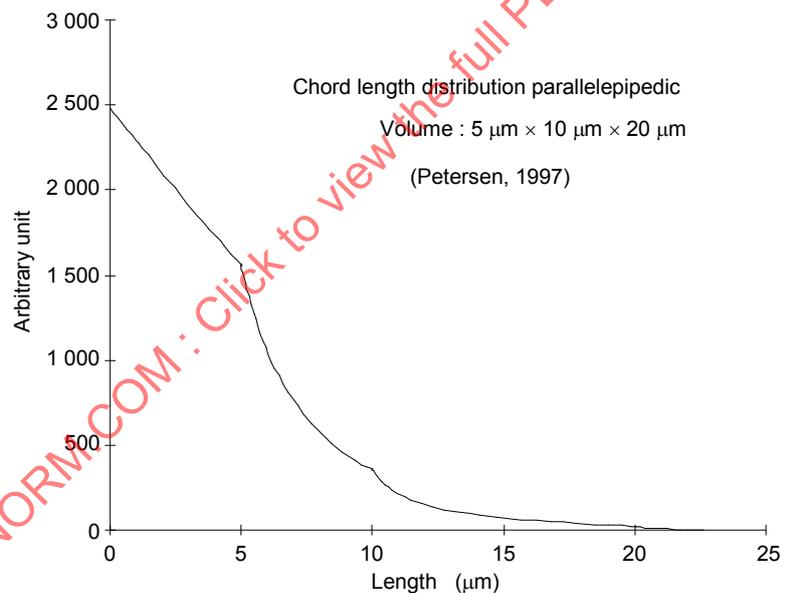


Figure F.2 – Example integral chord length distribution for isotropic particle environment

Equation (F.2) is the Bradford formula [108] used in the CREME model [36]. Some other similar expressions exist that use the differential chord length distribution and the integral LET spectrum as in Equation (F.4) and Equation (F.5) respectively, due to Pickel and Blandford, and Adams [109, 110].

$$N = \frac{A}{4} \int_{D_{\text{Min}}}^{D_{\text{Max}}} \Phi(> \text{LET}(D)) \cdot \frac{dP_{\text{CL}}(D)}{dD} \cdot dD \quad (\text{F.4})$$

$$N = \frac{A}{4} \frac{E_C}{\rho} \int_{LET_{Min}}^{LET_{Max}} \frac{1}{LET^2} \cdot \Phi(> LET) \cdot \frac{dP_{CL}}{d(D(LET))} \cdot D(LET) \cdot d(LET) \quad (F.5)$$

But all these RPP model expressions make the same assumption. The LET threshold of each SV is considered equal to a unique value. Petersen pointed out that it is necessary to fold the LET spectrum with the experimental cross-section curves to properly account for sensitivity variations across the electronic device [104].

In reality the critical LETs of the sensitive nodes are not the same but form a distribution that can be fitted by a Weibull function. To take into account the variation of sensitivity by integrating over a distribution of upset rates corresponding to the variation of cross-section versus LET, the integral RPP approach (IRPP) is used.

$$N = \frac{A}{4S} \int_{LET_{i,Min}}^{LET_{i,Max}} \left\{ \frac{d\sigma_{ion}}{d(LET)}(LET_i) \int_{\frac{h}{D_{Max}}-LET_i}^{LET_{Max}} \frac{d\Phi}{d(LET)}(LET) \cdot P_{CL}(> D(LET)) d(LET) \right\} d(LET_i)$$

integral rectangular parallelepiped (IRPP) equation (F.6)

$$S = l \cdot w \quad (F.7)$$

where

- $d\Phi/d(LET)$ is the differential LET spectrum;
- $P_{CL}(>D(LET))$ is the integral chord length distribution;
- $d\sigma_{ion}/d(LET)$ is the differential upset cross-section;
- A is the total surface area of the sensitive volume;
- S is the surface area of the sensitive volume in the plane of the semiconductor die;
- l, w and h are the length, width and height of the sensitive volume;
- D_{Max} is the maximum length that can be encountered in the SV;
- LET_{Max} is the maximum LET of the LET spectrum;
- $LET_{i,Min}$ is the lower bin limit in the differential upset cross-section $d\sigma_{ion}/d(LET)$;
- $LET_{i,Max}$ is the upper bin limit in the differential upset cross-section $d\sigma_{ion}/d(LET)$.

Annex G (informative)

Late news as of 2014 on SEE cross-sections applicable to the atmospheric neutron environment

G.1 SEE cross-sections key to SEE rate calculations

SEE cross-sections are required to calculate the SEE rate at aircraft altitude, and the best SEE cross-sections are those based on actual measurements from SEE testing. The SEE neutron cross-section is the parameter that quantifies the probability that an electronic device will interact with the atmospheric neutrons and cause a specific SEE effect. In accordance with JESD 89A, during SEE testing individual electronic devices or an entire board were exposed to high energy particle beams and the induced SEE events were recorded. The SEE cross-section is defined as the number of measured effects divided by the absorbed particle fluence. The closer the beam spectrum is to that of the atmospheric neutrons, the more representative are those SEE cross-sections for avionics SEE rate applications. Thus, the best SEE cross-sections come from testing with a spallation neutron source (e.g. WNR/ICE House at Los Alamos or TRIUMF). Other beam sources, are, in order of preference, a high energy mono-energetic proton source, a quasi mono-energetic neutron source (e.g., TSL) or a mono-energetic neutron source (e.g., 14 MeV neutron generator). These beam sources are more fully discussed in 6.2.3 of IEC 62396-2:2012.

For SEU and MCU the cross-section units are generally those of “ $\text{cm}^2\cdot\text{bit}^{-1}$ ”. For all other effects (SEL, SEFI, SET, SEB) the effect is based on the response of the entire electronic device and so the units are “ $\text{cm}^2\cdot\text{device}^{-1}$ ” per device effect.

Annex G compiles SEE cross-sections for various SEE effects in different electronic device types, plotting them as a function of the IC feature size. The cross-sections were measured in specific electronic devices, although the specific part numbers were not always given. To utilise the SEE cross-section data in Annex G in a conservative manner for calculating SEE rates, some assumptions may be required to obtain the final cross-section used to calculate the SEE rates.

Often the exact electronic device, or the same part number, as used in an avionics LRU, may have never been tested previously, but closely related electronic devices were tested. Thus estimates may have to be made by utilising SEE data that is based on the testing of similar electronic devices, and the basis for the similarity between the exact electronic device and the electronic device with test data has to be justified (e.g., same manufacturing process by same IC vendor, same feature size, etc.). Guidance for these assumptions can be utilised (see Annex B and IEC 62396-2) as well as reviews of published data.

G.2 Limitations in compiling SEE cross-section data

The data available to the user when determining SEE cross-section data is limited due to the following.

- a) The graphs and tables of the SEE cross-sections published in the available literature vary greatly in the degree of specific data provided, which is based primarily on the availability of the SEE data. Microelectronics manufacturers and other organizations possess a great deal of proprietary SEE data which is not accessible and so could not be incorporated into Annex G.
- b) Many reports in publicly available literature with SEE data tend to “hide” the name of the specific electronic devices that have been tested or the actual SEE response.
- c) SEE response data in many publicly available sources, especially from testing for terrestrial applications, can be utilised, but it may be disguised by being expressed in SER (soft error rate) units of FIT or FIT/Mbit. According to standard JESD 89A, upset data

expressed as FIT/Mbit can be converted to a cross-section in units of $\text{cm}^2 \cdot \text{bit}^{-1}$ by using the conversion factor $7,7 \times 10^{-17} \text{ Mbit} \cdot \text{cm}^2 / (\text{FIT} \cdot \text{bit})$, and to a cross-section in units of $\text{cm}^2 \cdot \text{device}^{-1}$ by using $7,7 \times 10^{-11} \text{ cm}^2 / \text{FIT} \cdot \text{device}$, both of which are based on a neutron flux ($E > 10 \text{ MeV}$) of $13 \text{ neutron} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$ in New York City.

G.3 Cross-section measurements (figures with data from public literature)

For each SEE effect listed below, the main objective of Annex G is to present the relevant SEE data which is contained in the figures that are included below.

- a) SEU (single event upset)
 - Provide upper bound estimates based on updated figures analogous to Figure 10 and Figure 11 of this standard.
 - Provide guidance based on memory element type (SRAM bit, DRAM bit, flash memory bit, register (flip-flop, latch, digital buffer, etc.)).
- b) MCU (multiple cell upset)
 - Provide estimates for MCU in SRAMs (may be extrapolated to other electronic devices).
- c) SEFI (single event functional interrupt)
 - Provide estimates of SEFI cross-section for microprocessors, FPGAs and DRAMs.
- d) SEL (single event latch-up)
 - Applicable only to CMOS devices, but similar types of high current type conditions (due to contention) have also been seen in microprocessors and FPGAs.
 - Some CMOS technology variations are immune to latch-up: (silicon on insulator (SOI)).
 - SEL cross-section increases with increasing temperature, so the effect of electronic device temperature within the LRU is important.
 - Provide figure showing SEL cross-section in electronic devices in which SEL has been measured.
 - Data in figure that can be used to obtain an upper bound estimate on the SEL rate.
- e) SET (single event transient)
 - Provide guidance on which electronic devices are sensitive.
 - Provide guidance on nature of worst case transient (duration, amplitude of transient).
 - Encourage use of filters in LRU design to preclude SET transients impacting LRU.
 - SET is dependent on the operating frequency and will have higher impact at frequencies above 100 MHz; transients will have more relative impact when electronic devices are running at higher frequencies compared to lower frequencies.
- f) SEB (single event burnout)
 - Applies only to high voltage electronic devices operated at $> 200 \text{ V}$.
 - If power electronic devices are operated at $> 300 \text{ V}$, data indicates that it is reasonable to assume that if the device use conditions are at less than half of rated voltage, i.e. a derating percentage $> 50 \%$, then SEB is precluded.
 - If SEB is not precluded in power electronic devices (voltage $> 300 \text{ V}$, inadequate derating) then provide upper bound estimate of SEB rate.

G.4 Conservative estimates of SEE cross-section data

G.4.1 General

Subclauses G.4.2 to G.4.7 provide guidance regarding the SEE cross-sections for specific effects in specific types of electronic devices. The variation of SEE cross-section with the