

BS IEC 62396-1:2016



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Process management for avionics — Atmospheric radiation effects

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

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National foreword

This British Standard is the UK implementation of IEC 62396-1:2016. It supersedes BS IEC 62396-1:2012 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/107, Process management for avionics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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INTERNATIONAL STANDARD



**Process management for avionics – Atmospheric radiation effects –
Part 1: Accommodation of atmospheric radiation effects via single event effects
within avionics electronic equipment**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 03.100.50; 31.020; 49.060

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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)).

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 should 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****SECEDED**

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)
LANSCÉ	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
SECDDED	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].

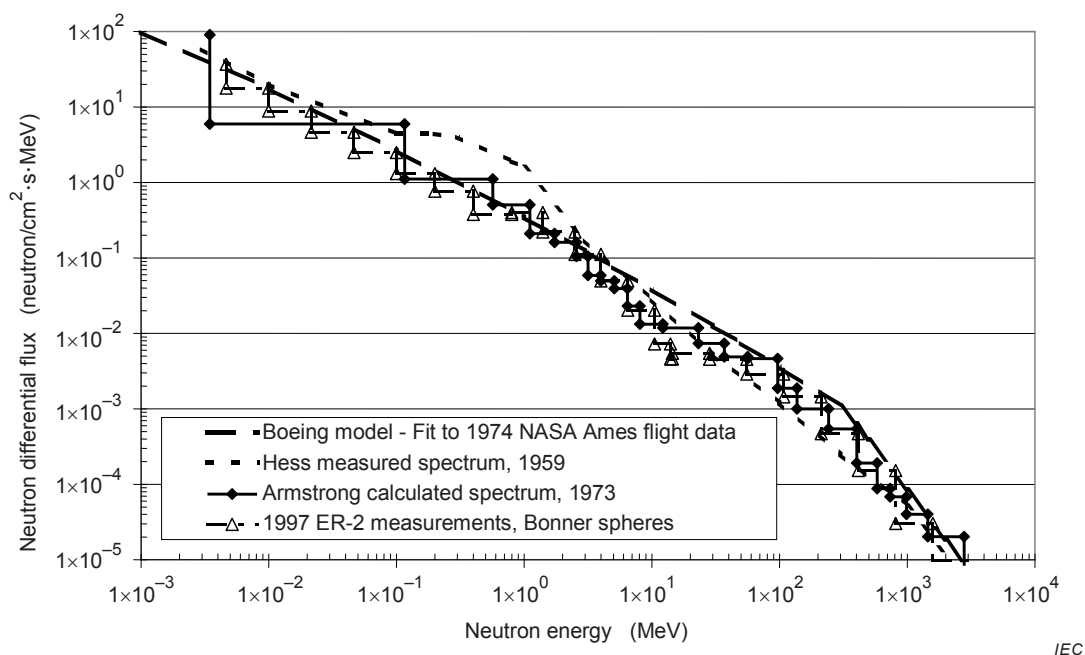


Figure 1 – Energy spectrum of atmospheric neutrons at 40 000 ft (12 160 m), latitude 45°

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

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

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 Pfotzer 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].

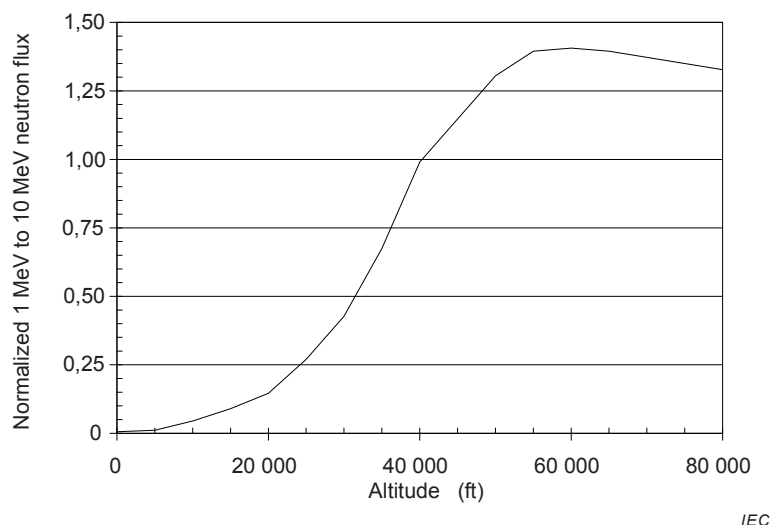


Figure 2 – Model of the atmospheric neutron flux variation with altitude (see Annex D)

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 ~ 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 of 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.

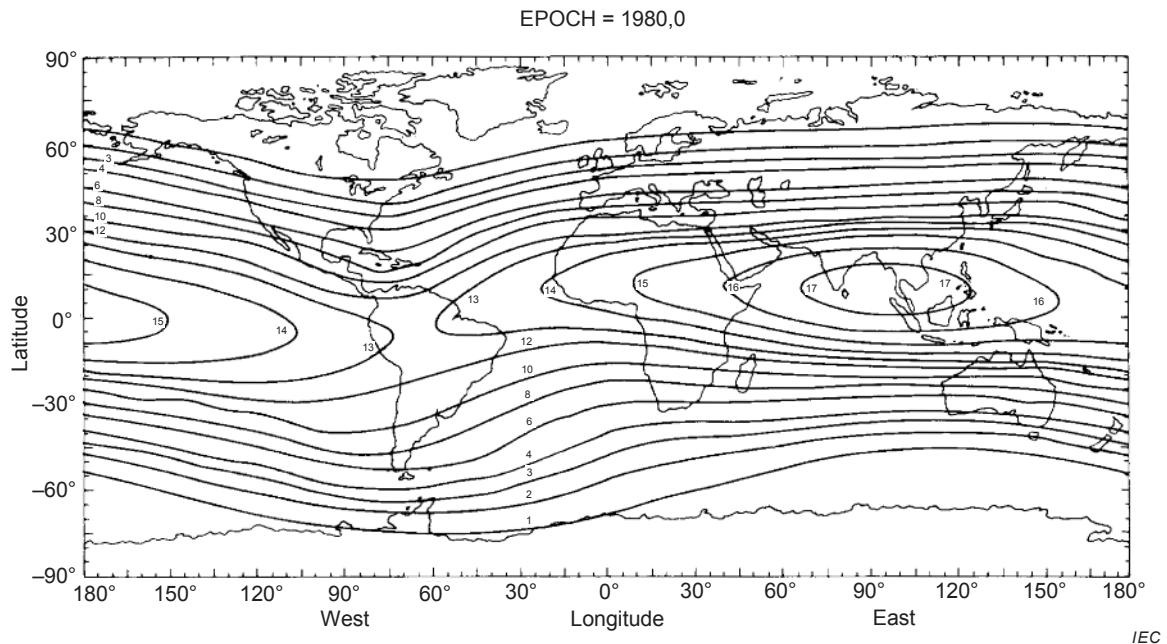


Figure 3 – Distribution of vertical rigidity cut-offs around the world

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.

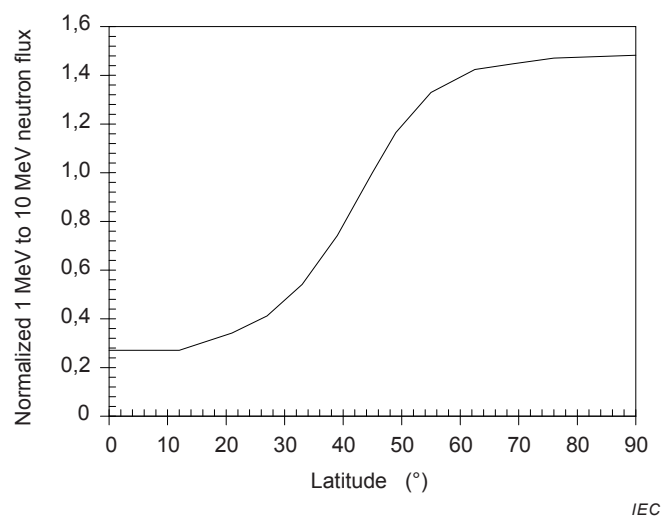


Figure 4 – Model of atmospheric neutron flux variation with latitude

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 Pfotzer maximum. With respect to the latitude variation there is a slight decrease in the total atmospheric proton flux of about a factor of 2 in traversing from the polar to equatorial regions, which is less pronounced than the latitude variation with neutrons. Therefore, for purposes of calculating SEE rates in the atmosphere, since the neutron flux dominates and the suggested flux of $6\,000\text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ ($E > 10\text{ MeV}$) is conservative, the contribution of the protons to the SEE rate can be considered as being included within the neutron-induced

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.

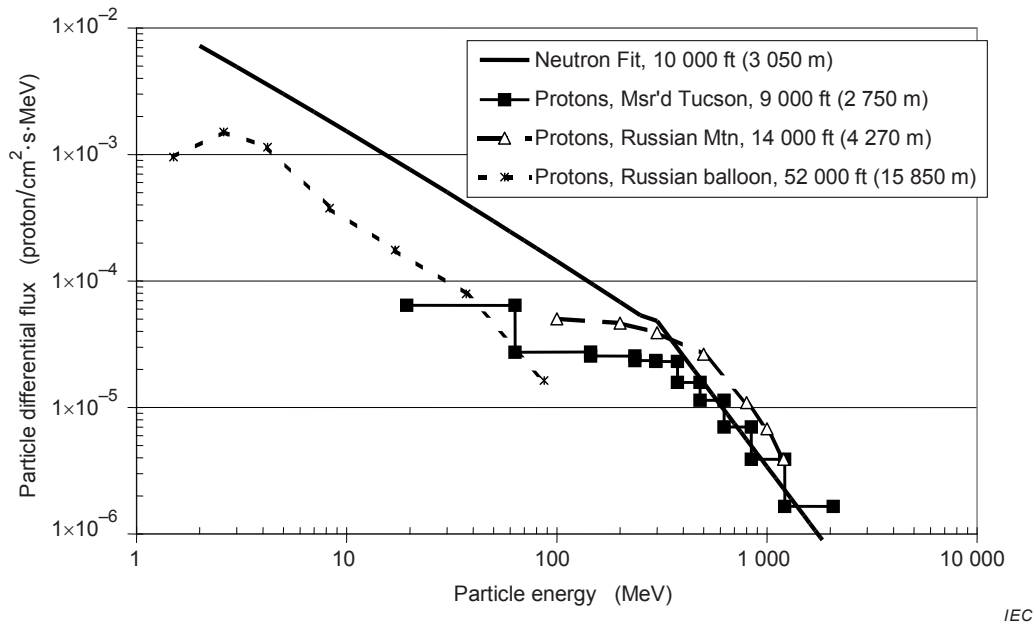


Figure 5 – Energy spectrum of protons within the atmosphere

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 g·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 g·cm⁻² of atmosphere. However their flux is very low. Therefore, heavy ions in the atmosphere can be generally ignored as a potential threat to electronics, although for the case of very high altitudes it is possible that some heavy ions may be encountered. Only for altitudes greater than 60 000 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 $6\,000\text{ neutron}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ 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 1940s 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