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Process management for avionics – Atmospheric radiation effects – Part 2: Guidelines for single event effects testing for avionics systems

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 2: Guidelines for single event effects testing for avionics systems

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International Standard IEC 62396-2 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) improvements and changes to test facilities have been added in Clause 7, which includes new facilities at TSL, TRIUMF and ChipIr,
b) links with IEC 60749-38 and IEC 60749-44 are made in 7.1.

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
107/316/FDIS	107/318/RVD

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

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

A list of all 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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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INTRODUCTION

This industry-wide international standard provides additional guidance to avionics systems designers, electronic equipment manufacturers and their customers for determining the susceptibility of electronic components to single event effects. It expands on the information and guidance provided in IEC 62396-1:2016.

Guidance is provided on the use of existing single event effects (SEE) data, sources of data and the types of accelerated radiation sources used. Where SEE data is not available considerations for testing are introduced, including suitable radiation sources for providing avionics SEE data. The conversion of data obtained from differing radiation sources into avionics SEE rates is detailed.

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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 2: Guidelines for single event effects testing for avionics systems

1 Scope

This part of IEC 62396 aims to provide guidance related to the testing of electronic components for purposes of measuring their susceptibility to single event effects (SEE) induced by neutrons generated by cosmic ray interactions in the Earth's atmosphere (atmospheric neutrons). Since the testing can be performed in a number of different ways, using different kinds of radiation sources, it also shows how the test data can be used to estimate the SEE rate of electronic components and boards due to atmospheric neutrons at aircraft altitudes.

Although developed for the avionics industry, this process can be applied by other industrial sectors.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62396-1:2016, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62396-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Abbreviated terms

ANITA	Atmospheric-like Neutrons from thIck TArget (TSL, Sweden)
BL1A, BL1B, BL2C	beam line designations at the TRIUMF facility (Canada)
BPSG	borophosphosilicate glass
ChipIr	beam line at the ISIS neutron source facility (Rutherford Appleton Laboratory, UK)
CIAE	China Institute of Atomic Energy
CMOS	complementary metal oxide semiconductor
COTS	commercial off-the-shelf

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CUP	close user position, neutron beam facility (TSL, Sweden)
CYRIC	CYclotron and Radio Isotope Center (Tohoku University, Japan)
D-D	deuterium-deuterium
DRAM	dynamic random access memory
D-T	deuterium-tritium
DUT	device under test
E	energy
EEPROM	electrically erasable programmable read only memory
EMC	electromagnetic compatibility
EPROM	electrically programmable read only memory
ESA	European Space Agency
eV	electron volt
FinFET	fin field effect transistor
FIT	failures in time (failures in 10^9 h)
FPGA	field programmable gate array
GeV	giga electron volt
GNEIS	Gatchina Neutron Spectrometer (Russia)
GSFC	Goddard Space Flight Center
GV	giga volt (rigidity unit)
IBM	International Business Machines
IC	integrated circuit
ICE	Irradiation of Chips and Electronics
IEEE Trans. Nucl. Sci.	IEEE Transactions on Nuclear Science
ISIS	neutron beam source (Rutherford Appleton Laboratory, UK)
IUCF	Indiana University Cyclotron Facility (USA)
JEDEC	JEDEC Solid State Technology Association
JESD	JEDEC standard
JPL	Jet Propulsion Laboratory
LANSCE	Los Alamos Neutron Science Center (USA)
LET	linear energy transfer
LETth	linear energy transfer threshold
MBU	multiple bit upset (in the same word)
MCU	multiple cell upset
MeV	mega electron volt
NASA	National Aeronautical and Space Agency
PCN	product change notification
PIF	Proton Irradiation Facility (TRIUMF, Canada)
PNPI	Petersburg Nuclear Physics Institute (Russia)
PSG	phosphosilicate glass
QMN	quasi-monoenergetic neutron
RADECS	RADiations, Effects on Components and Systems
RAL	Rutherford Appleton Laboratory (UK)
RAM	random access memory

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RCNP	Research Center of Nuclear Physics (Osaka, Japan)
SBU	single bit upset
SDRAM	synchronous dynamic random access memory
SEB	single event burn-out
SEE	single event effect
SEFI	single event functional interrupt
SEGR	single event gate rupture
SEL	single event latchup
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
SW	software
TID	total ionizing dose
TNF	TRIUMF neutron facility (TRIUMF, Canada)
TRIUMF	neutron beam source (Vancouver, Canada)
TSL	Theodor Svedberg Laboratory (Uppsala, Sweden)
WNR	Weapons Nuclear Research (Los Alamos, USA)

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5 Obtaining SEE data

5.1 Types of SEE data

The type of SEE data available can be viewed from many different perspectives. As indicated, the SEE testing can be performed using a variety of radiation sources, all of which can induce single event effects in electronic components. In addition, many tests are performed on individual electronic components, but some tests expose an entire single board computer to radiation fields that can induce SEE. However, a key discriminator is deciding on whether existing SEE data that may be used is available, or whether there really is no existing data and therefore a SEE test on the electronic component or board of interest has to be carried out.

5.2 Use of existing SEE data

5.2.1 General

The simplest solution is to find previous SEE data on a specific electronic component. Data may be available on SEE caused by heavy ions, protons, high energy neutrons, or thermal neutrons. Heavy ion data is normally only applicable to space applications, where direct ionization by the primary cosmic ray flux is of concern. However, heavy ion data can be useful for screening purposes, as described in 5.2.2. Proton data is usually also gathered for space applications, where primary cosmic rays and trapped particles are of concern. However, high energy protons provide a good proxy for neutrons in SEE measurements, as they undergo very similar nuclear interactions with electronic component materials. Therefore, both existing neutron data and existing proton data may be applicable to the evaluation of SEE rates in a device of interest, as described in 5.2.3. Low-energy ("thermal") neutrons can also cause SEE in some electronic components but such data is only available on a very small number of electronic components (see 5.2.4) and it involves neutron interactions with boron-10 rather than silicon.

Electronic components are constantly changing. In some cases, electronic components which had been tested become obsolete and are replaced by new electronic components which have not been tested. The fact that an electronic component is made by the same vendor and is of the same type as the one it replaced does not mean that the SEE data measured in the first electronic component applies directly to the newer electronic component. In some cases, small changes in the electronic component design or manufacturing process can have a large effect in altering its SEE response. In addition, electronic component manufacturers typically follow JESD46 [1][1] for product change notices (PCNs) to inform customers of component design changes. JESD46 [1] recommends a part number change when a die shrink or die foundry or die process change occurs but not when the die metallisation layout is altered, which can also lead to different SEE results. All SEE test data published therefore should refer to the specific manufacturer, the specific die geometry and full component part number.

5.2.2 Heavy ion data

An important resource that can be utilized to eliminate electronic components are the results from heavy ion SEE testing carried out to support space programs (~80 % of the electronic components tested for space applications are tested only with heavy ions). This heavy ion SEE data can be used to calculate SEE data from high energy neutrons and protons by utilizing a number of different calculation methods, but this requires the active involvement of a radiation effects expert in the process. Heavy ion testing is characterized by the LET (linear energy transfer) of the ions to which the ICs are exposed. The LET is the energy that can be deposited per unit path length, divided by the density (units of MeV·cm^2/mg). With neutron SEE, secondary particles or recoils created by the neutron interactions act as heavy ions, and the highest possible LET of neutron-induced recoils in silicon is ~15 MeV·cm^2/mg [1, 2]. Thus, any electronic component tested with heavy ions that has a LET threshold > 15 MeV·cm^2/mg will be immune from neutron-induced SEE. In a recent paper summarizing SEE testing at NASA-GSFC [3], twenty-one ICs of various types were tested with only heavy ions and eight of them (~40 %) had LET thresholds > 15 MeV·cm^2/mg for diverse SEE effects.

However, for the rare commercial SRAMs that are susceptible to SEL from heavy ions [4], this susceptibility can be increased due to the presence of small amounts of high Z materials within the IC, for example tungsten plugs, because higher Z recoils are created which can cause SEE reactions due to their higher values of LET. The high Z materials also lead to higher proton and neutron SEL cross-sections due to the neutron/proton reactions producing these recoils with higher LET and energy. Therefore heavy ion SEL cross-sections need to be examined carefully for applicability to proton-neutron SEL susceptibility caused by embedded high Z materials in the SRAMs. A suggested conservative value of LET threshold above which an electronic component can be considered immune from SEL induced by neutrons is 40 MeV·cm^2/mg [4]. However, this caution does not apply to the primary rationale given above for eliminating some electronic components from consideration for neutron SEE sensitivity based on heavy ion SEE testing, since only some electronic components incorporate these higher Z materials and the limitation applies to SEL.

Heavy ion SEE data should not be used for application to the atmospheric neutron environment for calculation of neutron cross-section, except by scientists and engineers who have extensive experience in using this kind of data. Unless otherwise stated explicitly, when SEE data is discussed in the remainder of this document, it refers only to single event testing using a neutron or proton source, not to the results from testing with heavy ions.

NOTE IEC 62396-1:2016, B.3.2, provides an approach to transforming heavy ions data into proton/neutron SEE cross-sections.

5.2.3 High energy neutron and proton data

If SEE data on an electronic component of interest is found from SEE tests using high energy neutrons (for example ground level testing as per JESD89A [10]) or protons, it will still require expertise regarding how the data is to be utilized in order to calculate a SEE rate at aircraft

[1] Numbers in square brackets refer to the Bibliography.

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altitudes. Data obtained by electronic component vendors for their standard application to ground level systems is often expressed in totally different units, FIT units, where one FIT is one error in 10^9 electronic components hours, which is taken to apply at ground level.

5.2.4 Thermal neutron data

There is little data on thermal neutron cross-section. However a number of the spallation neutron sources including TRIUMF, TSL and ISIS (Vesuvio) contain a substantial percentage of thermal neutrons within the high energy beam. Using thermal neutron filters or time of flight it is possible at such sources to determine thermal neutron cross-section. In addition there are a number of dedicated thermal neutron sources and these are listed in IEC 62396-1.

A continuing problem with the existing SEE data is that there is no single database that contains all of the neutron or proton SEE data. Instead, portions of this kind of SEE data can be found published in many diverse sources. The SEE data in the larger databases is mainly on much older electronic components, dating from the 1990s and even 1980s, and is primarily from heavy ion tests that were performed for space applications and not from testing with protons and neutrons.

5.3 Deciding to perform dedicated SEE tests

If existing SEE data is not available, for any one of the many reasons discussed above and which will be further expanded upon below, then one should refer to IEC 62396-1 for the other alternatives; in case there is no real alternative, SEE testing can be considered. The advantage of such a test is that it pertains to the specific electronic component or board that is of interest, but the disadvantage is that it entails making a number of important decisions on how the testing is to be carried out. These pertain to selecting the most useful test article (single chip or entire board), the nature of the test (static or dynamic (mainly applicable to board testing)), assembling a test team, choosing the facility that provides the best source of neutrons or protons for testing, scheduling and performing the test, coping with uncertainties that appear during the test and, finally, using the test results to calculate the desired SEE rate for avionics. Many of these issues will be discussed in Clauses 6 and 7.

6 Availability of existing SEE data for avionics applications

6.1 Variability of SEE data

Because of the diverse ways that SEE testing is carried out, and the multitude of venues for how and where such data is published, the availability of SEE data for avionics applications is not a simple matter.

6.2 Types of existing SEE data that may be used

6.2.1 General

SEE data can be derived from a number of different kinds of tests, and all of the differences between these tests need to be understood in order to make comparisons meaningful. Although there are many different types of single event effects, for the purposes of this document, the focus is on three of them: single event upset (SEU), single event functional interrupt (SEFI) and single event latchup (SEL). SEU pertains to the energy deposited by an energetic particle leading to a single bit being flipped in its logic state. The main types of electronic components that are susceptible to SEU are random access memories (RAMs, both SRAMs and DRAMs), field programmable gate arrays (FPGAs, especially those using SRAM-based configuration) and microprocessors (the cache memory and register portions). A SEFI refers to a bit flip in a complex electronic component that results in the electronic component itself or the board on which it is operating not functioning properly. A typical example is an SEU in a control register, which can affect the electronic component itself, but can also be propagated to another electronic component on the board, leading to board malfunction. SEL refers to the energy deposited in a CMOS device that leads to the turning on of a parasitic p-n-p-n structure, which usually results in a high current in the device and a non-functioning

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state. High energy neutrons in the atmosphere can induce all of these effects: SEU, SEFI and SEL. Where electronic components are operated at high voltage stress (200 V and above) they can be subject to single event burn-out, SEB, or single event gate rupture, SEGR; these effects are covered in detail in IEC 62396-4.

One of the important simplifying assumptions to be used in this document is that, for single event effects, including SEU, SEFI and SEL, the response from high energy protons, i.e., those with $E > 100$ MeV, is the same as that from high energy neutrons of the same energy. The SEE response is generally measured in terms of a cross-section (cm^2), which is the number of errors of a given type divided by the fluence of particles to which the electronic component was exposed. Therefore, for the SEU, SEFI and SEL, cross-sections determined by measurements made with high energy protons can be used as the cross-sections for high energy atmospheric neutrons so long as the proton beam test uses the same energy range. This is far more than an assumption, since it has been demonstrated by direct measurement in many different electronic components, see [5, 6, 7, 8, 9] and IEC 62396-1. In these references, SEU was measured in the same electronic components using monoenergetic proton beams and using the neutron beam from the ICE facility at WNR, Los Alamos National Laboratory. The energy spectrum of the neutrons in the ICE facility is almost identical to the spectrum of neutrons in the atmosphere. An estimate of the SEE rate at aircraft altitudes in an electronic component can be obtained by the simplified formula:

$$\text{SEE rate per electronic component} = 6\,000\ [\text{neutron/cm}^2{\cdot}\text{h}] \times \text{avionics SEE cross-section}\ [\text{cm}^2\ /\text{electronic component}] \quad (1)$$

Here, the integral neutron flux in the atmosphere, $E > 10$ MeV, is taken to be 6 000 neutron/$cm^2 \cdot h$, the approximate flux at 40 000 ft (12,2 km) and 45° latitude as in IEC 62396-1; this approximation is suitable for electronic components with feature size above 150 nm. This shows the importance of the SEE cross-section. As indicated above, the avionics SEE cross-section is taken to be the SEE cross-section obtained from SEE tests with a spallation neutron source such as the WNR, and also with a proton or neutron beam at energies > 100 MeV. The simplified approach of Formula (1) is used in IEC 62396-1 and is the nominal flux under the above conditions. For electronic components with feature size below 150 nm the relevant neutron flux will be higher than 6 000 neutron/$cm^2 \cdot h$ because the threshold energy will be lower than 10 MeV, therefore the threshold energy (and flux) used for estimation should be clearly shown and validation demonstrated (see IEC 62396-1). The failure rate is the integral over all energies of the neutron flux multiplied by the SEE cross-section: $\int \Phi(E)\sigma(E)dE$. Here the integral is replaced by an average flux multiplied by an average SEE cross-section with assumed limits of integration.

A more elaborate approach for calculating the SEE rate is to utilize a number of measurements of the SEE cross-section as a function of neutron or proton energy, and integrate the curve of the SEE cross-section over energy with the differential neutron flux. The details for this approach are given in the standard JESD89A [10], although the neutron flux given in this standard is at ground level and would have to be multiplied by approximately a factor of 300 to make it relevant to avionics applications (see 6.2.3).

Thus the data that is most valuable for estimating the SEE rate in avionics is from SEE cross-section measurements made with: a) a spallation neutron source such as the WNR, b) a monoenergetic proton beam and c) a quasi-monoenergetic neutron (QMN) beam. Other SEE data that is also valuable are SEU cross-sections made with a monoenergetic 14 MeV neutron beam. Based on comparisons of SEU cross-section measurements with a 14 MeV neutron beam and the WNR, the WNR SEU cross-section is approximately a factor of 1,5 to 2 higher than the 14 MeV SEU cross-section for relatively recent electronic components [7], (feature size < 0,5 μm), and a factor of 4 times higher for older electronic components [8]. For some of the very latest electronic components, the factor is close to 1. In general, there are a number of spallation neutron facilities around the world for neutron soft error rate testing; the accuracy of these is considered in references [11, 12]. Calculation of soft error rate depends largely on the combination of the electronic component and the facility to be used. There does need to be some kind of practical threshold energy to determine the neutron flux, but the

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threshold cannot be a fixed value and generally decreases as the scaling of the device proceeds. The value of “10MeV” threshold has been used for electronic components with geometry above 100 nm, however the threshold energy used for neutron flux determination should be clearly shown and should be validated with reference to the electronic component technology.

6.2.2 Sources of data, proprietary versus published data

As indicated above, SEE cross-section measurements that are relevant to avionics SEE rates are being made by a variety of different groups. These include:

a) space organizations that use only monoenergetic proton beams for their SEE testing as in space where there are few neutrons but many protons;
b) electronic component vendors who use neutron sources to measure the upset rate at ground level (which they refer to as the soft error rate (SER), rather than the SEU rate, although the terms have the same meaning);
c) avionics vendors who use neutron sources to measure the upset rate at aircraft levels.

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Generally, SEE data taken and reported by government agencies contains most if not all of the relevant information, including identifying the specific electronic components tested and providing the measured SEU cross-sections in unambiguous units. This applies to most of the proton data taken and reported by NASA in the open literature by the NASA centres at GSFC and JPL. GSFC and JPL invariably publish almost all of the proton SEE data that they take. However, even though they disseminate essentially all of the results from the proton SEE testing that they carry out, this is data that is usually reported in the open literature in an inclusive compilation that contains results from SEE testing with both heavy ions and protons, thus the proton SEE data has to be carefully sought out. Examples of NASA-GSFC compilations of SEE testing containing proton SEE test results are given in [13, 14, 15, 16], and examples of JPL reports of SEE testing containing proton SEE test results are given in [17, 18, 19]. Other governmental agencies do not necessarily publish the results from all of the proton SEE tests that they perform.

Data from the other sources, primarily private companies, is not nearly as accessible. Electronic component vendors perform a large number of tests. Such testing is performed in accordance with industry standard JESD89 [10] and its addendum JESD89-3 [105], or to IEC 60749-38 and IEC 60749-44. Much of this data remains proprietary and is not published openly. Where such data is available it is important to note that it is specific to the manufacturer, design geometry, and full part number. Unfortunately, when SEE data from electronic component vendors is published, the results are often disguised, so that the identity of the electronic components tested is hidden by using an arbitrary designation and the results are expressed in units that are of little use quantitatively.

Where the data is expressed in FIT units, which means errors per 10^9 electronic component hours, this can be converted into a SEE cross-section by using the FIT definition and dividing by 13 (13 neutron/cm^2·h is the flux of high energy neutrons ($E > 10$ MeV) at ground level in New York City, which is the value recommended by the JESD89A standard [10] and so most often used.) Thus, FIT $\times$ 10^{-9}/13 gives the SEE cross-section in cm^2/electronic component.

Some reports give the SER rate in units of FIT/Mbit, which allows the SEE cross-section per bit to be calculated by multiplying as follows: (FIT/Mbit) $\times$ 10^{-15}/13 to obtain the SEE cross-section in cm^2/bit. Other papers report the FIT value in arbitrary units which allows the authors to show how the FIT rate varies with a particular parameter (for example, applied voltage), but it allows no quantitative assessment to be made of the SEE cross-section. Examples of such reports using FIT rates are given in [6], [20, 21, 22, 23].

Most of the SEE data that has been discussed comes from the SEE testing of individual electronic components, placing those electronic components in a beam of neutrons or protons and monitoring changes in the status of the electronic component for errors. A typical procedure is to fill a portion of memory in a RAM with a specified bit pattern and monitor that memory for bit flips in one or more addresses. However, some tests are done using an entire board to monitor when an error has occurred. In this case, the malfunction of the board is an indication that an error has occurred, and such an error is referred to as a SEFI, but the functional interruption is in the board rather than the actual electronic component being irradiated. If the beam is collimated such that only one or two electronic components are exposed to the particles in the beam during each test, the likely source of error is a SEE in those electronic components. However, this is a dynamic type of test and it can be that the electronic component in the beam experienced the initial error which was propagated to another electronic component on the board, and faulty performance of the latter electronic component is what led to the board malfunctioning.

There are some reports of such board level tests in the open literature, but they are less common. NASA-JSC has a requirement to perform such testing on all electronic boards that will be used on manned space missions. This testing is carried out with a beam of protons representative of space environment, and while it is recorded in NASA-JSC reports, these reports are not widely available; examples are given in [24, 25, 26]. The main purpose of the test is to screen all of the electronic components for the potential of a hard error induced by the protons, such as a single event latchup, so recoverable errors are not analysed in great detail in these reports. Other government agency groups also perform such board level SEE testing, and the results of these tests are often reported in the literature, but are not included in any organized database. In addition, private companies carry out such board level testing, often for the benefit of specific programs for avionics applications (neutron tests for avionics vendors) or space applications (proton tests for low earth orbit spacecraft contractors), and this data is rarely reported in the open literature. By 2005 the number of user groups had grown to more than 25, but the ratio of test groups that published their results had not changed much.

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6.2.3 Data based on the use of different sources

6.2.3.1 Obtaining SEE data using radiation sources

In general, all SEE testing is carried out using an accelerator-based source of neutrons or protons, meaning that the electronic component or board to be tested will receive a larger fluence of particles over a given period of time in the test environment compared to the fluence it would receive during that same time period in the intended vehicle in the atmosphere or space. In the past, testing was usually carried out with only one type of source, but in recent times, some engineering groups have been exposing electronic components to more than one type of particle environment and comparing the SEE responses. Two main types of sources have been used for this SEE testing for avionics applications, neutrons and protons, although there are a variety of different kinds of neutron sources that have been used, as will be discussed in 6.2.3.2 and 6.2.3.3.

6.2.3.2 Data obtained using neutron sources

Single event effects, in particular single event upset, can be induced by neutrons in two distinct energy ranges, at high energies (> 1 MeV) and at very low energies (thermal or epi-thermal neutron energy, > 0,025 eV). High energy neutrons cause SEU by nuclear reactions with device materials, causing energetic ions to be emitted. It is the energy from these ions which causes ionization in the semiconductor lattice, leading to the upset. Neutrons with energies above about 10 MeV are of the greatest concern. This is because many of the interactions which lead to SEE have threshold energies in the region between 2 MeV and 10 MeV in silicon, oxygen and other typical device materials [27, 28, 29] and because elastic interactions (which have no threshold energy) are more effective at higher energies [30, 31, 32, 33]. Nonetheless, neutrons with lower energies (for example 3 MeV or below) can cause SEE [28, 34], albeit with much reduced probability. Estimates of the SEU contribution by neutrons below 10 MeV in electronics technologies with geometry greater than 0,2 μm are below 10 %, but for lower feature sizes this fraction increases [28, 35]. This is consistent with measurements made with monoenergetic neutrons on electronic components of the mid-1990s (feature sizes above 0,5 μm), showing that the SEU cross-section at 3 MeV for these older electronic components was about a factor of 100 lower than that at 14 MeV for most of the SRAMs tested [36]. However, for more recent electronic components, especially those with feature sizes less than 0,2 µm and even down to 45 nm, the contribution of neutrons with energies below 10 MeV is expected to be in the range 8 % to 10 % [28].

For high energy neutrons, there are four different types of sources:

a) a spallation neutron source which has neutrons with energies over a wide energy spectrum similar to that of the atmospheric neutrons;
b) a quasi-monoenergetic neutron (QMN) source that has a peculiar energy spectrum, roughly half of the neutrons are at a peak energy and the other half are evenly distributed between close to the peak and ~1 MeV;
c) a 14 MeV neutron generator, the only source that is close to being truly monoenergetic; and
d) Van de Graaf accelerators that can produce relatively monoenergetic neutrons in the energy range for about 4 MeV to 12 MeV using d+d reaction.

The WNR at Los Alamos which was mentioned previously is the best-known example of a spallation neutron source, although the neutron irradiation facility at TRIUMF (Vancouver, Canada), RCNP (Research Center for Nuclear Physics, Osaka Univ., Osaka, Japan), and ISIS (Rutherford Appleton Laboratory, UK) are other such sources. Since the WNR facility was upgraded around the year 2000, it is sometimes referred to by its new name, the ICE (Irradiation of Chips and Electronics) House [37]. Figure 1 compares the neutron spectra from Los Alamos (the ICE House), the neutron facility at TRIUMF [38], ANITA at TSL [39], Vesuvio at ISIS [46], RCNP [44] and the atmospheric neutron spectrum at ground level [30, 31] with the avionics neutron spectrum (IEC 62396-1).

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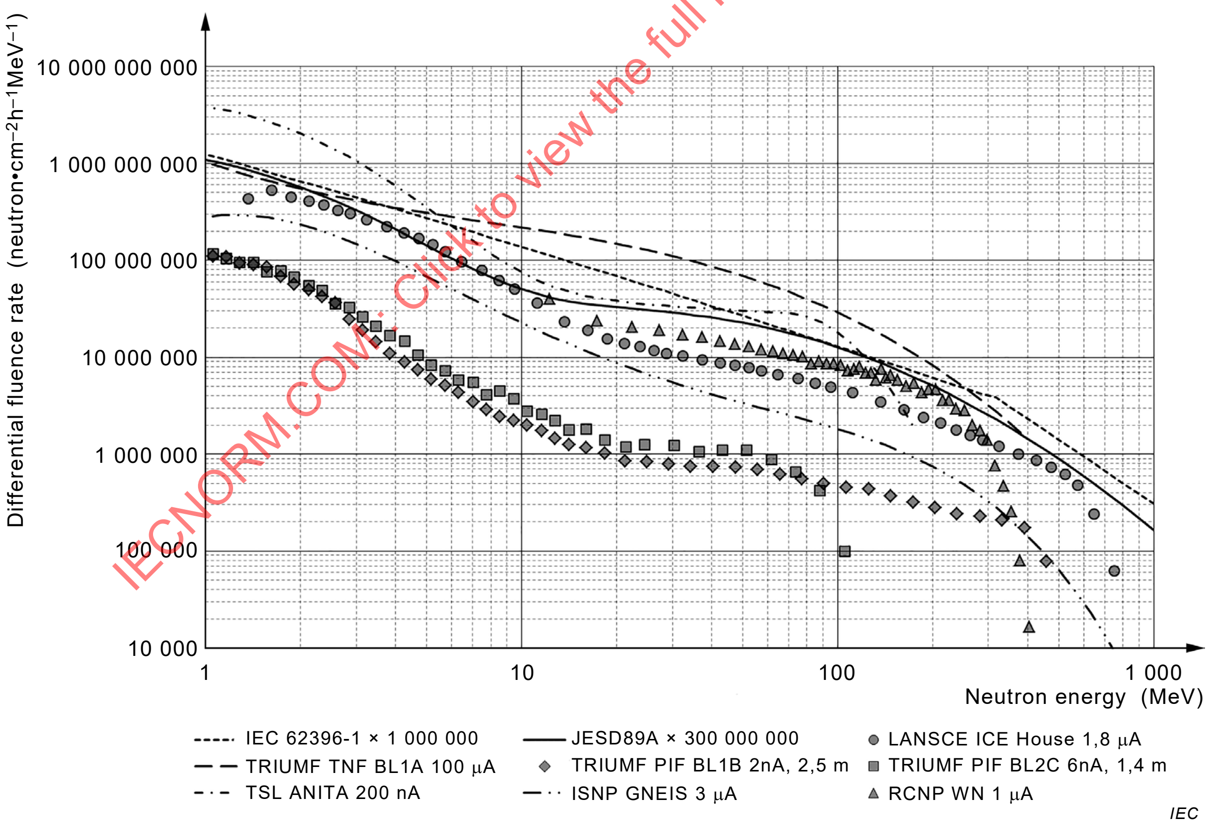

Figure 1 – Comparison of Los Alamos, TRIUMF and ANITA neutron spectra with terrestrial/avionics neutron spectra (JESD89A and IEC 62396-1)

SEU data on electronic components that were exposed to the ICE House neutron beam has been published in a number of papers [6, 7, 8], [40, 41], however, many more electronic components have been tested at Los Alamos and those results are considered to be proprietary. These results have not been published, nor are they expected to be published.

Reference [42] indicates that in the year 2001, at least eight different groups carried out SEE testing, and of these, it is estimated that only two of the testing groups published some of their results, an American national laboratory and a university. The six private companies, both IC manufacturers and avionics vendors, kept their test results proprietary.

The TRIUMF facility in Canada, called the TNF (TRIUMF Neutron Facility) also provides a spallation neutron source. Until 2004, it had not been used very much, but since that time, a number of papers on SEU results from the testing of electronic components at the TNF have been published [38].

A spallation neutron facility, PNPI (Petersburg Nuclear Physics Institute), has been set up in St Petersburg, Russia, to study the effect of high energy neutrons on electronic components. The high energy neutrons are produced by a 1 000 MeV synchrotron. The GNEIS spectrometer is used to provide a neutron beam that matches that of the atmospheric radiation [43,111].

At TSL in Uppsala, Sweden, the facility has been developed to produce a pseudo white neutron source called ANITA (Atmospheric-like Neutrons from thIck TArget) [39]. The high energy (about 200 MeV) protons interact with a tungsten target to produce spallation neutrons. The facility was built in 2007 and provides neutrons with atmospheric-like spectrum up to the highest energy of ~180 MeV (see Figure 1). The neutron flux above 10 MeV is ~10^6 times the atmospheric one at 39 000 feet [39]. A correlation has been established between the SEE data obtained at ANITA and LANSCE [39], which has enabled the wide use of the ANITA facility for SEU testing of modern DUTs (SRAMs, microprocessors, high-voltage electronic components, entire servers, etc.) The beam has a lower fraction of high energy neutrons (above 100 MeV) than the LANSCE neutron field. As a consequence, a correction may be required, especially in case of testing for SEL or other SHE phenomena (see 8.5). Correction factors may be difficult because the correction factors are most likely electronic component dependent and would require full-energy neutron measurement on the electronic component.

The RCNP (Research Center of Nuclear Physics) in Osaka, Japan, provides a spallation neutron beam with energy up to 420 MeV and maximum proton beam energy of 420 MeV that can be used for electronic component test [44]. The neutron beam is produced by bombarding a proton beam with a typical energy of 392 MeV on to the tungsten target (50 mm (height) x 50 mm (width) x 65 mm (depth)) and collimated into a 108 mm diameter beam. The irradiation space is very wide and a large sample with around 1 m x 1 m x 1 m can be placed in the beam line. Beam time for industries is provided twice a year with about one week span.

The ISIS facility at Harwell, UK, can provide high energy neutrons up to 800 MeV, and there are two target stations. The Vesuvio (Target station 1) beam line [45] is currently available but the high energy neutron flux content is lower than in atmospheric radiation. A new facility, ChipIR at ISIS Target station 2, will produce neutrons that have a good correlation with the atmospheric radiation spectrum and will be able to produce a collimated beam for electronic component test and a flood beam for equipment test [46].

There are a number of quasi-monoenergetic neutron (QMN) sources around the world, including some in the United States, but until recently they had not been used for testing microelectronics for SEE. The site with the most experience with such tests is the Theodor Svedberg Laboratory (TSL) at Uppsala University, Uppsala, Sweden [47]. A few papers have been published reporting on the results of electronic components being exposed to the TSL neutron beam [9], [48, 49]. Methodologies have been developed for extracting SEU cross-section data at the pseudo-peak energy [48, 49]. In addition, a similar facility, CYRIC (Cyclotron and Radio Isotope Center), has been operating in Japan at Tohoku University [50] which also has been used to make some SEU measurements. A different methodology from that of the Swedish researchers has been developed for extracting SEU cross-section data at the pseudo-peak energy [51, 52].

The facilities at TRIUMF PIF and TSL ANITA are capable of producing high energy neutron beams with a large area; these beams are suitable for the accelerated SEE testing of complete equipment and systems.

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In Figure 2, SEU measurements made by several different groups at these various facilities are combined to illustrate how the high energy SEU cross-section per bit for SRAMs has varied with feature size over the last five or more years. The trend that is illustrated in Figure 2 shows a consistency within an approximate plateau region of 10 to 30 times between maximum and minimum values, however it cannot predict how this might change in the future, as feature sizes continue to decline below 100 nm.

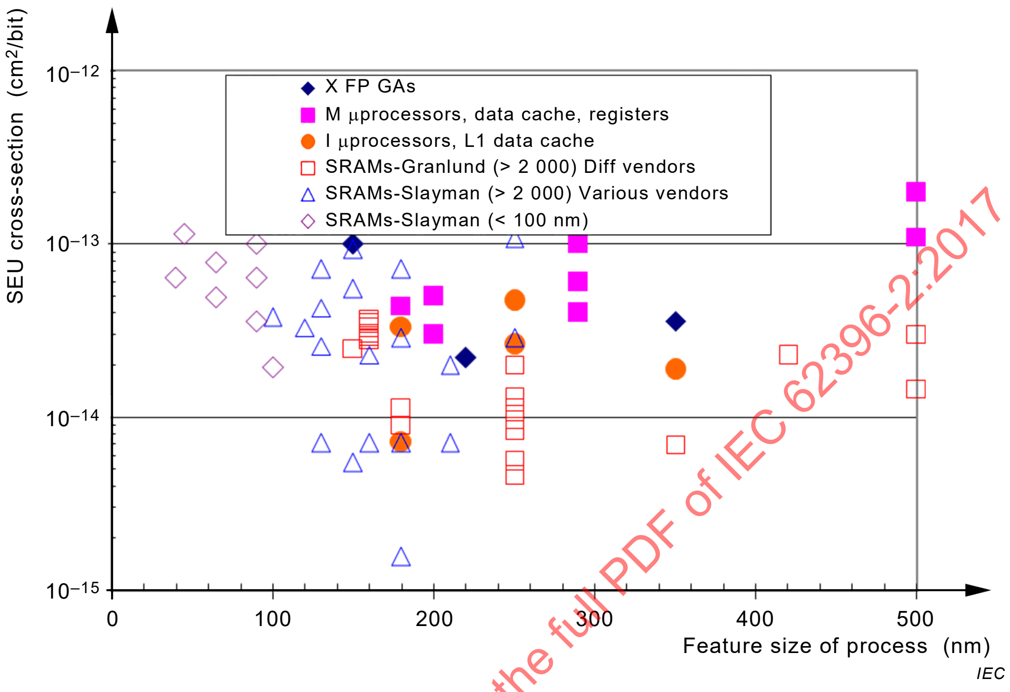

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Figure 2 – Variation of high energy neutron SEU cross-section per bit as a function of electronic component feature size for SRAM and SRAM arrays in FPGA and microprocessors

The third kind of high energy neutron facility is one that provides essentially monoenergetic neutrons at 14 MeV, from the D-T reaction. It is the highest energy of such a monoenergetic neutron beam. A number of facilities in the United States and abroad have such neutron generators. Tests on SRAM devices fabricated in the mid-1990s indicated that the SEU response per bit from a spallation neutron source was 3 to 5 times higher than from a 14 MeV neutron source [8]. Tests on more recent electronic components have shown a closer agreement in the SEU response between a spallation neutron source and 14 MeV neutron sources [7], [9]. This indicates that for current, low voltage electronic components, 14 MeV neutrons provide a fairly good simulation of the atmospheric neutrons with respect to inducing SEUs. However, 14 MeV neutrons do not provide a good simulation with respect to inducing single event latchup (SEL) and multiple bit upset (MBU) [53]; the ratios may be electronic component dependent.

In 2006 and 2007, it was shown [54, 28] that for electronic components with feature sizes smaller than 0,25 µm [39] the SEU susceptibilities to neutrons with lower energies, between 3 MeV to 10 MeV, were much greater than was the case in older technology electronic components (see Figure 3). Previously, the contribution of such lower energy neutrons had been largely ignored, since it was very small. For future electronic components with even smaller feature sizes (< 90 nm), the contribution to the SEU rate from these lower energy neutrons or protons is likely to grow, and so SEU testing of such electronic components using neutron sources covering this energy range [53, 54] may be needed to accurately assess the SEU rate (additional references are [35], [55, 56]).

Furthermore, the extrapolation of data points in curves that display trends in SEE susceptibility, such as in Figure 2, to future reduced feature sizes needs to be updated over time with data on newer electronic components to be assured of bounding the SEE susceptibilities of future electronic components. The situation of the higher SEU susceptibility to neutrons in the 3 MeV to 10 MeV range is one such example of how SEE susceptibility trends change with decreasing feature size and a second is the increase in the susceptibility to MCU with decreasing feature size (see IEC 62396-1:2016, Figure G.4).

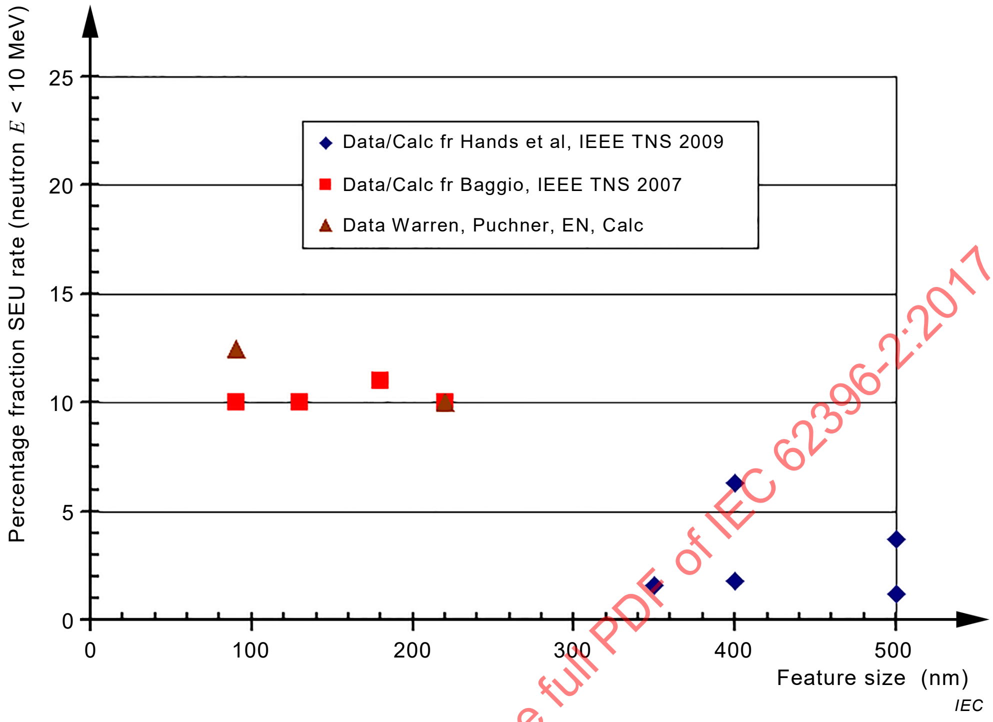

Figure 3 – Percentage fraction of SEU rate from atmospheric neutrons contributed by neutrons with $E < 10$ MeV

There is a fourth type of neutron facility that should be considered for testing electronic components for inducing SEUs, that of thermal neutrons. Thermal neutrons cause SEUs through neutron reactions with the isotope ^{10}B, boron-10, which can be present in high enough concentrations to be of concern mainly as a constituent of the glassivation layer above an IC, i.e., in BPSG (borophosphosilicate glass) (see IEC 62396-5). Many electronic components use a different type of glassivation (for example, PSG) and in some cases, the boron in the BPSG is ^{11}B, boron-11, so there are no ^{10}B reactions leading to SEU from the reaction products (alpha particle and ^{7}Li) of the ^{10}B interaction. A limited amount of data has been published on the SEU cross-section induced by thermal neutrons [9], [22], [57, 58, 59]. Boron can also be used as a dopant in the semiconductor material or used in tungsten plug layer, and as feature sizes of state of the art electronic components continue to shrink below 100 nm thermal upset from the use of boron as a dopant can become significant. Thermal neutrons come from high energy neutrons whose energy is reduced by multiple collisions (thermalized). This makes determining the thermal flux difficult because it depends on the local environment and changes with the local environment. For example, the thermal neutron flux in an airplane depends on how much fuel there is in the airplane. These considerations are detailed in IEC 62396-5.

On the other hand, it is noted in the Fang and Oates paper [100] that both thermal neutron and package alpha SER will be negligible for FinFET electronic components compared to comparable size planar devices; due to the reduction of boron-10 in tungsten plug layers as a result of technology scaling, thermal neutron SER declines at a faster rate than package alpha SER and does not present a serious concern for FinFET devices. Nevertheless these conclusions are at electronic component sensitivity level and one needs to be aware that the environment, for example the aircraft mechanical structure, can lead to increases of the thermal neutron flux in some aircraft areas.

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6.2.3.3 Data obtained using proton sources

It was demonstrated over 30 years ago [60] that high energy protons cause SEUs in microelectronics. It was also recognized that at high energies, the protons, even though they are charged particles, cause the upsets by the same mechanism as the high energy neutrons, i.e. by nuclear reactions with the silicon, rather than by direct ionization in the silicon. However for the smaller geometries below 100 nm there is evidence of direct ionization by low energy protons [61]. Proton SEU cross-sections have therefore been published over the years, but the effectiveness of the low energy protons in causing upsets has increased over time, as the applied voltage to the ICs has decreased below 5 V and feature size has reduced. For more recent electronic components, the SEU cross-section has generally not decreased very much with energy, the cross-section due to 50 MeV protons being only about a factor of 2 higher than the cross-section due to 14 MeV neutrons [7]. A very useful compendium of SEU cross-sections in more than 120 different SRAMs and DRAMs was compiled by ESA in 1997 [64], mostly on 5 V electronic components, but a few at 3,3 V. However, few if any, of these electronic components are used today. In contrast, many other papers in the open literature today contain measured proton SEU response data, for example Coy Kouba, [65] where many electronic components were tested with 200 MeV protons at IUCF for NASA JPL. There are many references on proton testing and there is a summary each year from NASA GSFC with some proton test results.

6.2.4 Ground level versus avionics applications

At ground level two SEE mechanisms are significant and both of these are considered by JESD89A and IEC 60749-38. In addition to SEE caused by atmospheric neutrons, traces of radioactive materials contaminating semiconductor devices and their packaging lead to a source of alpha particles which can cause SEE by direct ionization. This leads to a residual SEE rate which is independent of the level of atmospheric radiation.

SEE due to radioactive contamination is not significant for avionics applications, and need not be tested for or considered in analysis unless otherwise suggested. Considering neutrons above 10 MeV in energy, the atmospheric neutron flux at 40 000 ft (12,2 km) is nominally 6 000 neutron/cm^2·h, a factor of approximately 450 times greater than that at ground level, which is nominally 13 neutron/cm^2·h (at the same latitude). The SEE rate due to atmospheric neutrons is correspondingly two orders of magnitude greater at 40 000 ft (12,2 km) than at ground level. The relative contribution of SEE due to alpha particles from radioactive contamination is two orders of magnitude lower at altitude than at ground level. Extensive field tests with sample electronic components at sea level, at high altitude terrestrial laboratories, and at underground laboratories [106, 107. 108, 109] demonstrate that SEE rates due to alpha particles from radioactive contaminants are typically at a similar order of magnitude to SEE rates due to atmospheric neutrons at ground level. Accordingly, at altitude, the fraction of SEE due to alpha particles is negligible compared to uncertainties in measuring and predicting SEE rates due to atmospheric neutrons.

Where ground-based SEE rates due to atmospheric neutrons above 10 MeV are available, for example determined according to JESD89A, estimates for rates at 40 000 ft (12,2 km) can be made by multiplying by the factor 450.

6.3 Sources of existing data

Subclauses 6.2.1, 6.2.2, 6.2.3 and 6.2.4 referred to diverse references in the open literature that contain SEU cross-section information from tests carried out with neutron and proton sources. In Table 1, descriptions of the SEU information contained in some of these references are compiled, in particular those with the largest amount of data.

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Table 1 – Sources of existing data (published after 2000)

Electronic component tested or listed	Particle type, energy	Data contained	Reference	Publication year	Comments
a) SEU: 18 SRAMs, 6 FPGAs, 7 micro-processors b) SEFI: 6 FPGAs, 2 micro-processors c) SEL 3 SRAMs	WNR neutrons, 14 MeV neutrons, quasi-monoenergetic neutrons and high energy protons	a) SEU cross-section, cm^2/bit b) SEFI cross-section, cm^2/electronic component c) SEL cross-section, cm^2/electronic component	[76]	2010	Compilation of measured data from twenty-two separate references; most of electronic components identified by part number; includes measured cross-sections for electronic components using different sources (neutron, protons)
a) SEU, MCU and SEFI in 15 DRAMS b) SEU various SRAMs (0,1 µm to 0,25 µm)	WNR neutrons	SEU, MCU cross-section, units of FIT/bit, SEFI, units of FIT/electronic component	[77]	2007	Plots of SEU and SEFI (>1 000 cell upsets) in DRAMs and SEU in SRAMs based on data provided by others
a) SEU in 14 SRAMs b) SEL in 2 SRAMs	Neutrons: WNR, TRIUMF, IUCF (LENS), thermal, protons high energy	SEU cross-section, cm^2/bit, SEL cross-section, cm^2/electronic component	[78]	2006	Plots of cross-sections for six older identified SRAMs and eight newer (unidentified) SRAMs
SEU in 14 SRAMs	TRIUMF neutrons (includes thermal)	SEU cross-section, cm^2/bit (atmospheric neutron spectrum, thermal)	[59]	2006	Electronic components and details identified
SEU in 9 SRAMS	WNR, quasi-monoenergetic neutrons, high energy protons	SEU cross-section, units of FIT/Mbit	[79]	2006	Electronic components and details identified
9 SRAMs, 1 flash memory	14 MeV neutrons, 250 MeV protons	SEU and SEL (proton) in cm^2/electronic component	[80]	2006	All electronic components had SEU, four SRAMs exhibited SEL
SEL in 5 SRAMs	High energy protons	SEL cross-section in units of cm^2/electronic component	[4]	2005	Electronic component details but not part numbers, effect of temperature
SEU in FPGAs	High energy protons	SEU in configuration bits and block RAM, cm^2/bit, SEFI: cm^2/electronic component	[81]	2004	Two different Virtex II FPGAs tested
8 SRAMs (0,5 µm to 0,14 µm feature size)	High energy protons and WNR neutrons	SEU cross-section, cm^2/bit	[7]	2004	Electronic components not identified; SEU cross-sections from WNR and from proton data

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Electronic component tested or listed	Particle type, energy	Data contained	Reference	Publication year	Comments
6 SRAMs	High energy proton and neutron 14 MeV and thermal neutron	SEU cross-section, cm^2/bit	[9]	2004	Electronic components identified; SEU cross-sections from high energy proton and neutron 14 MeV and thermal neutron data
6 SRAMs (0,18 µm, 0,13 µm, 0,09 µm feature size)	150 MeV protons	SEU cross-section, arbitrary units	[21]	2004	Test electronic components, vendor not identified, SOI and bulk
10 SRAMs	WNR, quasi-monoenergetic neutrons	SEU cross-section, cm^2/bit (quasi-monoenergetic neutron), SER (arbitrary units) compare WNR with quasi-monoenergetic neutron	[49]	2004	Electronic components and details identified monoenergetic SEU cross-sections derived from measurements
FPGA, 4 sections tested	High energy protons	SEU cross-section (cm^2/bit), SEFI cross-section (cm^2/ electronic component)	[74]	2004	Electronic component and portions of electronic component (configuration memory block, memory power-on-reset and external ports) identified
6 SRAMs (0,25 µm, 0,13 µm, 0,09 µm feature size)	WNR neutrons	SER rate, FIT/Mbit	[20]	2003	Test electronic component, SOI and bulk, from two vendors
24 SRAMs, 6 feature sizes	WNR neutrons	SER, error/bit•h at 40 000 ft (12,2 km)	[41]	2003	Electronic components and four vendors not identified
SEL in 4 SRAMs	WNR	SEL in units of FIT/Mbit,	[82]	2003	Electronic component details but not part numbers, effect of temperature
9 SRAMs (0,5 µm to 0,14 µm feature size)	High energy protons and WNR neutrons	SEU cross-section in SER units, FIT/Mbit	[6]	2002	Electronic components not identified; SER rates from WNR and from proton measurements
SRAMs, DRAMs, other electronic component	High energy protons	Asymptotic SEU cross-section, cm^2/bit or per electronic component	[18]	2001	Electronic components identified; SEU cross-sections from high energy proton measurements

A number of original reference sources published before 2000 appear in Annex A.

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7 Considerations for SEE testing

7.1 General

Testing for single event effects for avionics purposes involves the consideration of a variety of factors. These factors include the type of hardware to be tested (individual electronic component or entire board), the type of test used (static or dynamic), and the type of facility providing the neutron or proton beam. These are discussed in greater detail in 7.2 to 7.4.

In addition, a number of standards are available that provide guidance on how to conduct SEE testing and discuss proper procedures. Existing standards are available for SEE testing with heavy ions [83, 84], and although these do not strictly apply to neutron and proton SEE testing, many but not all of the procedures that are described also apply to SEE tests with neutrons and protons. Three other standards apply specifically to SEE testing with neutrons and protons. These include IEC 62396-1 which directly applies to avionics. Reference [10] is a JEDEC standard that is also directed at SEE testing with neutrons, but its focus is testing for purposes of SEE effects on the ground; nevertheless, it is directly applicable to SEE testing for avionics purposes. There are details of the real-time soft error test (terrestrial) in IEC 60749-38 and details of accelerated SEE testing with neutron beams in IEC 60749-44. Reference [85] is a standard that is also under development which applies to SEE testing with protons.

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7.2 Selection of hardware to be tested

It is easier and more direct to test one electronic component type at a time, such as a RAM or a microprocessor. However, if the actual avionics board contains many electronic components that are potentially susceptible to SEE from high energy neutrons, this approach could involve a large number of tests. When testing individual electronic components for single event effects, the testing is usually performed on a specially designed test board, one test board for each type of electronic component. To achieve the test goals more quickly, some organizations have been favouring the testing of entire boards. With this kind of testing, either the entire board or each of the potentially susceptible electronic components on the board are exposed to a neutron or proton beam.

If a device-by-device SEE test approach is being considered, it can be narrowed down to three main types of electronic components that are likely to have SEE effects induced by the atmospheric neutrons: RAM devices, microprocessors and FPGAs are the most susceptible electronic components.

One of the advantages of testing individual electronic components is the ability to distinguish between different types of single event effects. In most cases, single event upset is the dominant effect, but this may not always be true. As described in 5.2.3 single event latchup (SEL) and single event functional interrupt (SEFI) can also be induced by the atmospheric neutrons, in which case, their occurrence in the device under test (DUT) can confuse a proper counting of the upsets errors during the irradiation. Thus, the need to distinguish the various modes of SEE effects is important. However, one of the advantages of testing an entire board is that SEFI effects in one of the other electronic components on a board can lead to improper functioning of the entire board as an error is propagated from device to device. Such an effect cannot be detected by testing individual electronic components. Conversely, it can be that the cross-section for such an effect can be smaller than the SEE cross-sections in the three main types of electronic components referred to above as most susceptible to SEE effects.

7.3 Selection of test method

Selection of the software is generally tied to the selection of the type of electronic components to be tested and the test vehicle, either a test board with a single electronic component or some version of the actual avionics board. If a RAM, microprocessor or FPGA is to be tested, then the test board containing the DUT has to be interrogated in such a way as to distinguish the different types of SEE that can occur. To guard against SEL, the current is always monitored, since in most cases a latchup state results in an increase in the current.

SEL also results in a loss of functionality in the DUT. With an electronic component like a SRAM, in which SEU and SEL are the only expected effects, the software would generally be written to load in a test pattern of words into a specified portion of the SRAM memory cells, usually with a checkerboard pattern of alternating 1s and 0s. The number of bit flips after exposure is the number of upsets, and the current is monitored to detect a possible SEL. Multiple cell upset (MCU) (more than one upset induced by a high energy neutron or proton) is a possibility which increases as feature size reduces (see IEC 62396-1:2016, Figure G.4). At feature sizes of about 180 nm an MCU rate of about 2 % to 3 % of the SEU rate can be expected; at about 100 nm the figure rises to about 30 % and at sizes approaching 25 nm the rate will reach 100 %. There are ways of examining the test pattern words to distinguish which words experienced more than a single bit flip as a result of a single radiation event; where more than one bit is upset in a single word then the effect is termed multiple bit upset (MBU).

With electronic components like DRAMs, microprocessors and FPGAs, the possibility of burst errors or a SEFI makes the testing more difficult. The combination of test procedures and the accompanying software via the various programs and/or diagnostics that are run by the device or the evaluation board should be designed to detect an error that is more than a single bit flip. The goal is to detect SEFI events which are often referred to by another name, such as a “hang” or “hang-up”. These are errors that cause the device to not function properly, such as when a control register would receive an upset.

To design a test that includes the possibility of a SEFI requires a more detailed understanding of the operation of the electronic component. It often involves the use of an evaluation board for an electronic component like a microprocessor or FPGA in order to exercise it in its various modes of operation and to distinguish the various kinds of errors. A better understanding of the design of SEE tests to measure SEFI can be obtained from papers that report on the results from SEFI events during SEE testing. For the testing in microprocessors, these include [86, 87] in which “hangs” or other types of errors that caused a disruption in the program flow are measured. The emphasis in these two papers is on SEFIs induced during SEE testing with heavy ions, but SEFIs have also been induced by protons in similar microprocessors [88, 89]. SEFIs have also been induced in DRAMs [90], and also in SRAMs in rare cases, but this has been seen mainly in testing with heavy ions and not with protons, although upper bound proton SEFI cross-sections have been calculated.

The SEE testing of entire boards or subsystems is much more complex since the electronic components experiencing SEE will interact with one another. The board or system level effects testing should be performed only after careful expert analysis has been carried out to understand the combined SEE mechanisms. However, testing in this way gives greater realism since all electronic components on the board are being exposed at the same time; one needs to care about simultaneous errors which can occur if too high fluxes are used. With this kind of testing, it is the malfunctioning of the board that signals the functional interrupt to the system, the functional interrupt being to the entire board and not to any specific device. This testing is dynamic, so that an error in one electronic component can propagate to other electronic components, ultimately leading to the board no longer being able to function. Examples of reports on the results of this kind of systems level testing are given in [91], which used a heavy ion beam, in [92] which used a proton beam and in [93] which used a neutron beam.

7.4 Selection of facility providing energetic particles

7.4.1 Radiation sources

In order to expose electronic components and even entire boards to a particle environment that simulates the atmospheric neutrons, there are two main types of sources that can be used, proton beams and neutron beams. Even within these two overall groups, there are a number of different kinds of sources and these are discussed in 7.4.2 to 7.4.5. In IEC 62396-1:2016, Annex C, are listed the main facilities that have these kinds of high energy beams available. Users should still check directly with the facilities for the current costs and availabilities.

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7.4.2 Spallation neutron sources

The spallation type of neutron source is created by the interaction of a high energy proton beam with a large, dense target, producing secondary neutrons. This is exactly the same way in which the atmospheric neutrons are created in the atmosphere; hence this type of neutron source is closest to the neutrons in the atmosphere with respect to the energy spectrum of the neutrons. There are currently four main neutron spallation sources that have been used for exposing ICs and boards for purposes of SEE testing. These are the WNR, discussed in 6.2.1, the TRIUMF Neutron Facility (TNF) at TRIUMF [10], the ANITA facility at TSL [39, 102] and ChipIr at the Rutherford Appleton Laboratory.

The WNR has been much more widely used for SEE testing as discussed in 5.2. At present, with the new ICE House configuration it is very convenient to use, and it has currently an acceleration factor of over six orders of magnitude, so that 1 h in the beam exposes a device to the same neutron fluence as about 10^6 h in an airplane nominally at 40 000 ft (12,2 km). Recently a second flight path called ICE-II has been commissioned and has been operational for over two years. Following upgrades to the accelerator, the intensity has been increased 2,5 times. In addition, because ICE-II is closer to the neutron production target, its intensity is approximately two times greater than the original ICE House.

The TNF at the TRIUMF (Tri University Meson Facility in Vancouver, Canada) provides a neutron spectrum that is quite similar to that of the atmospheric neutrons, and the flux available (for $E > 10$ MeV) is about a factor 2 to 2,5 higher than that at the WNR; at TRIUMF this is about 10^6 times the neutron flux at an altitude of 39 000 ft (11,9 km). Figure 1 compares the neutron spectra from Los Alamos (the ICE House), the TNF at TRIUMF and the atmospheric neutron spectrum at ground level. Access to the horizontal neutron beam (~5 cm x 12 cm) is via a vertical track through 5 m of steel shielding which limits the test card size to about 5 cm thickness by 20 cm width. This makes the TNF most convenient for electronic component testing.

The TNF has a significant advantage in that the neutron field also contains thermal neutrons as the neutrons pass through a water moderator near the production target. Thus, by conducting a test on an electronic component twice to measure the number of upsets, with and without an effective thermal neutron shield such as a thin sheet of cadmium metal, two SEU cross-sections can be obtained. These are the standard SEU cross-section due to high energy neutrons ($>$ 10 MeV) and the SEU cross-section due to thermal neutrons.

TRIUMF also has larger area, lower flux neutron beams at the PIF facility for large system testing as described in 7.4.5.

The RCNP was established in 1976 and has been widely utilized by Japanese groups since 2001. The RCNP has a spallation neutron spectrum with the peak energy of 400 MeV and a flux of 5 x 10^5 n/cm^2/s. The RCNP will be reinforced for higher neutron flux, and better utilities after a one-year-outage from late 2018.

The ANITA neutron beam facility (Atmospheric-like Neutrons from thIck TArget) [39, 102], is briefly described in 6.2.3.2. The features of the ANITA facility are: a high LANSCE equivalent flux, user flux control, spacious user area (from 2,5 m to 15 m from the source), possibility to vary the beam size (from pencil-shape to greater than 1 m in diameter), low thermal neutron flux, low ionizing dose rate in the beam, on-line neutron dosimetry, and the possibility to use both white and QMN beams during the same test campaign and at the same beam line. TSL/ANITA will be decommissioned after 2018 due to operating costs. In 2017, experiments from researchers /engineers have not been accepted. The following information regarding TSL and ANITA is for information only.

Due to the options to promptly change the ANITA beam size (from 1 cm to 120 cm) and the neutron flux (from 10^7 neutron/cm^2·s down to $5 \cdot 10^0$ neutron/cm^2·s, above 10 MeV), testing of both electronic components and larger systems can be combined in the same campaign.

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The ANITA facility has recently been upgraded by adding a new irradiation position called close user position (CUP) [102]. The energy-integrated neutron flux above 10 MeV at the ANITA-CUP facility, amounting to more than 10^7 neutron/cm^2·s^1, is the highest among the facilities with atmospheric-like spectra. The beam size is ≈ 20 cm × 20 cm. The ANITA-CUP neutron field, reported in [102], includes a significant thermal-neutron component with the flux amounting to ~20 % of the integrated flux above 10 MeV. The dose rate from prompt γ-rays at the CUP does not exceed 17 rad/h. A user may perform irradiations at the CUP simultaneously with the ones at the conventional user area.

The ISIS neutron source facility has completed the dedicated ChipIr neutron SEE beam line following feasibility testing on the ISIS spallation source using the existing Vesuvio beam line that began in 2007. These tests demonstrated that a fast neutron SEE beam line could be incorporated into a generalised neutron scattering facility by modification to the target/reflector assembly and having a careful fast neutron transport design. The resulting ChipIr beam line incorporates several features designed to make SEE testing highly effective; the primary feature is the high flux, atmospheric like spectrum of neutrons in the fast regime delivered to a large experimental area. In-situ cabling of various types, an EMC experimental room, automated positioning of large and small DUTs, automated beam logging and monitoring and optional and automated filters for the incident beam are incorporated into the beam line design. The beam line can also operate in collimated 'pencil' like beam down to mm^2 beam size up to approximately 1 m^2 'flood' area beam, again completely automated, to allow simple rapid change between electronic component and system testing.

A large scale spallation neutron facility, CSNS (China Spallation Neutron Source), is being constructed in Dongguan (near Hong Kong in China). The energy of primary proton is as high as 1,6 GeV. The first neutron beam will be observed in October 2017, with operation for users expected in 2018.

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7.4.3 Monoenergetic and quasi-monoenergetic beam sources

As noted in 6.2.3.2, both monoenergetic and quasi-monoenergetic neutron (QMN) sources have been used for testing electronic components to measure their SEE response from neutrons. The monoenergetic sources produce relatively low energy neutrons, E < 14 MeV, and utilize the interaction of a charged particle with a target. The main source of this type that has been regularly utilized is the 14 MeV neutron generator which produces neutrons with energies in the range of ~13,5 MeV to 14,5 MeV. These neutrons are produced by accelerating a deuteron beam into a tritium target, and so result from the (D, T) reaction. The exact energy of the neutrons depends on the exact energy of the initiating deuteron, which is usually about 200 keV. Similar neutron generators are also available that accelerate deuterons into a deuterium target, but in this case, the energy of the neutrons produced is much lower, ~ 3 MeV. For purposes of SEE testing, this energy is too low to be very useful for avionics purposes, since, based on electronic components of the mid-1990s (feature size above 0,5 μm), the SEU cross-section at 3 MeV is approximately 100 times lower than the cross-section at 14 MeV (based on about five different electronic components, [36]). Low-energy neutrons can cause failures but it is difficult to use this failure rate to predict the failure rate in a real situation. For more recent electronic components, especially those with feature size below 0,2 μm and even down to 45 nm, the contribution of neutrons with energies below 10 MeV is expected to be in the 8 % to 10 % range. As indicated with regard to the high energy neutron SEU cross-section variation with the feature size shown in Figure 2, without test data it cannot be predicted how the SEU response to neutrons of both high and low energies might change in the future as feature sizes continue to decline below 0,1 μm.

Quasi-monoenergetic neutrons (QMN) are also produced by a similar mechanism, but in this case, it is a beam of protons that is accelerated into a target that is usually a lithium plate several millimeters thick. The neutrons produced have a usual energy distribution that is essentially a two-part energy distribution. Approximately half of the neutrons have high energies, within a few MeV of the energy of the protons in the initiating beam, and these constitute an apparent peak or a pseudo peak. The other half of the neutrons is approximately evenly distributed over energy from the high energy pseudo peak down to a few MeV. Thus, there is a peak of neutrons with the same high energy, but there is also a sizable number of neutrons in what is referred to as the “low energy tail”. The higher the energy of the initiating proton, the longer the tail extends over energy and the smaller the percentage of all of the neutrons that lie within the pseudo peak.

In the past, the difficulty of using a quasi-monoenergetic neutron (QMN) source consisted in separating out the SEE contribution from the neutrons within the peak, which have a very specific energy, from the contribution of the SEE events from the neutrons within the “tail”. As indicated in 6.2.3.2, two different groups have developed procedures for how to process their SEE data to obtain the SEE cross-section at the peak energy, i.e., a way of subtracting the contribution of the lower energy neutrons in the tail. These are given in [48, 49, 50, 51].

This can be a useful neutron source, but the user has the responsibility of assuring that the SEU data obtained truly applies at each peak energy, and that the overall collection of SEU data obtained, including all of the various peak energies, is self-consistent. It has been observed that some SEU data from this kind of neutron source appeared to exhibit larger variations over energy than has usually been seen in monoenergetic proton SEU data. It is unclear whether these larger variations are due to the calculation procedure, the facility, too small a number of upsets during some of the runs, or other causes.

7.4.4 Thermal neutron sources

Thermal neutrons are available at a number of different kinds of facilities. The most widely available type of facility is a nuclear reactor, and in particular, research or test reactors. These reactors usually have an area of high thermal neutrons, called a thermal column, and this would be the best location for exposing electronics to thermal neutrons and measuring the resulting SEU events. A number of such facilities are available and are listed in IEC 62396-1:2016, Annex C. One of the problems with a thermal column is the gamma radiation that usually accompanies the neutrons in a thermal column. If the gamma flux is too high, there could be an effect of the total ionizing dose (TID) absorbed by the electronic components being tested from the gamma radiation while the electronic component is also receiving the neutrons. For most commercial off the shelf (COTS) electronic components, a TID dose of under 10 000 rad should not have any deleterious effect in the response of the electronic components. TID doses in excess of 20 000 rad to 50 000 rad very likely will have an effect on the response of the electronic components and should be avoided, unless previous TID testing of the electronic components have demonstrated that they are immune from such TID effects. When electronic components are exposed to such a thermal neutron beam as the thermal column, the number of SEU events measured is due to the thermal neutrons only.

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The second type of facility that has been used is a high energy neutron facility that has both high energy neutrons ($E > 10$ MeV) as well as thermal neutrons. Both TRIUMF and WNR have such facilities, having both thermal neutrons along with spallation neutrons. The actual atmospheric neutrons are a second source, but to make it practical, the neutron flux has to be increased, and this can be done at high altitude laboratories. Thus TRIUMF, WNR and high altitude laboratories both offer a mixed neutron environment, with both high energy neutrons ($E > 10$ MeV) along with thermal neutrons. To separate out the SEU events due to thermal neutrons from those due to the $E > 10$ MeV neutrons, two sets of tests are needed, with one in which the electronic components are covered with an efficient thermal neutron shield. Suitable materials such as cadmium and boron (borated materials) have very high efficiencies in absorbing all of the thermal neutrons even with a thin covering of suitable material (between 0,1 mm and 1 mm).

Thus, two sets of SEU measurements are made, one with the electronic components open to all of the neutrons and the second with the electronic components fully shielded from the thermal neutrons. By subtracting the two sets of SEU events (and accounting for differences in the neutron fluences) from the thermal neutrons and from the $E > 10$ MeV neutrons, the thermal neutron SEU cross-section can be determined.

The third type of facility is more specialized, one that is generally called a “cold neutron” facility. These are generally used by materials scientists for examining the internal structure of materials, and since this application is in great demand, there are few opportunities to obtain neutron exposure time at such a facility. However, one such facility at NIST (National Institute of Standards and Technology) is available and may be used. Care should be exercised in using such a facility because the cold neutrons are more efficient than the thermal neutrons in interacting with the boron-10 and causing SEU events. Thus, the number of SEUs from a cold neutron source has to be adjusted down to obtain the equivalent number of SEU events from true thermal neutrons. A procedure for carrying this out is found in [94].

7.4.5 Whole system and equipment testing

7.4.5.1 General

The above facilities are suitable in general for testing electronic components and small modules due to restricted beam size, however some are capable of testing larger samples. After the individual electronic components and modules have been radiation assessed it is useful to verify the final electronic unit or system design (see IEC 62396-3) by testing at the higher level. The neutron radiation source for such testing is required to be approximately uniform over a substantial area for example 0,5 m^2 to 1 m^2, so that the whole equipment can be exposed to the radiation. In general such equipment would be tested by "in the loop" testing, for example the equipment is fed parameters from an external computer test system and its function is in some way closed loop with the parameters so that the response of the equipment under test can be monitored during the trial. Because the response when performing equipment or system test is more complex (because of many SEE sensitive electronic components present) the beam flux should be much lower than for individual component tests, typically 1 000 to 10 000 times the nominal flux. A small number of facilities have been used for test of whole units or systems in the beam and these include the following.

7.4.5.2 TRIUMF Proton Irradiation Facility (PIF)

At the PIF facility a large area neutron beam [95] has been developed by stopping energetic protons from either BL2C (116 MeV) or BL1B (500 MeV) [103] in a lead absorber that completely stops the protons and then by using the neutrons generated in the forward direction after the absorber. These neutrons have a spectrum similar to the atmospheric neutrons as the production mechanism is similar. The maximum neutron flux of 10 MeV or greater is about a factor of 10^7 higher than the sea level flux. The neutron beam is uniform to about 80 % over transverse dimensions of 80 cm by 80 cm at a distance of 200 cm to 300 cm from the lead absorber. This beam is ideal for testing large electronic systems for effects from terrestrial or aircraft altitude neutrons. The maximum neutron rate is about a factor of 8 less than at the TRIUMF neutron facility (TNF) location using the recently upgraded BL1B. It can also be varied from more than 400 000 neutron/cm^2·s to less than 1 000 neutron/cm^2·s by changing the proton current or the distance to the test point.

A summary of the beam rates, beam size and corresponding years of ground level and aircraft level operation is provided in reference [95]. The variation of neutron rates has proven essential to satisfy testing requirements which range from assessing avionics components for long term regulatory compliance to complex ground level network systems with significant memory, processing and data transmission capabilities. BL2C with a proton energy of 116 MeV stopping in a 20 mm lead absorber has been more frequently scheduled for neutron use so there is more operating experience and calibrations for this beam line at different geometries. Since its intensity upgrade, BL1B operating at 500 MeV with protons stopping in a 23 cm lead absorber is now able to be scheduled more frequently.

7.4.5.3 ANITA facility at TSL

The ANITA neutron beam facility (Atmospheric-like Neutrons from thIck TArget) [39, 102], briefly described in 6.2.3.2 and 7.4.2, is widely used for system testing, due to the availability of large neutron fields (up to 120 cm in diameter) and the user control of the neutron flux in the range from $1 \cdot 10^7$ down to $5 \cdot 10^0$ of the flux at 39 000 ft (11,9 km) altitude. A user can switch between testing of an entire system (unit, board) and testing of single electronic components, or vice versa, at any time during the testing campaign, due to the flexibility in the beam size, which is achieved by a flexible collimator opening as well as by the possibility to

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vary the distance from the neutron source and the DUT from 2,5 m to 15 m. The possibility to switch between the testing modes for systems and components (without any significant rearrangements in the user's equipment) is widely used by testing groups as a means to search for the component which is originally responsible for malfunction of the entire system.

7.4.5.4 ChipIr Beam line at the ISIS neutron source facility, Rutherford Appleton Laboratory

The ChipIr beam line at the ISIS neutron source facility has been designed with an operational mode that produces a large area beam (1 m^2). This provides a uniform, atmospheric neutron field suitable for the testing of entire systems. Switching between this ‘flood’ area beam and a collimated ‘pencil’ beam is easy and quick using the beam line’s automated collimator which provides a highly flexible and variable choice of beam size. Coupled with the beam line’s automated positioning of large (and small) DUTs, ChipIr provides an efficient and flexible means to switch between individual electronic components and whole system testing during a campaign. The beam line is also designed to enable lowering of the flux both through user control of the beam line and by varying the distance of the DUT within the large experimental blockhouse.

7.4.5.5 Spallation neutron source in the Research Center for Nuclear Physics (RCNP) at Osaka University

The RCNP at Osaka University provides a spallation neutron source with a maximum energy of 392 MeV and with a maximum flux of 5 x 10^5 neutron/$cm^2 \cdot s$. The beam line is collimated to 108 mm in diameter. The irradiation room is very wide so that a target with a size larger than 1 m x 1 m x 1 m can be placed in the beam line. The distance of the target from the beam outlet can be adjusted in a range of several meters. Equipment for measurements including computers can be placed either in the target room where neutron flux is low enough or in the remote control room. A remotely controlled camera can be placed to observe the equipment under test from the control room.

7.4.5.6 14 MeV and 2,5 MeV neutron source in the Physics department of China Institute of Atom Energy's (CIAE) neutron generator

The CIAE provides a 14 MeV neutron generator, capable of producing fluxes as high as 1 x 10^8 neutron/$cm^2 \cdot s$ at close to 10 cm of the target. The irradiation room is very wide so that a target with a size larger than 1 m x 1 m x 1 m can be placed in the beam line. Equipment for measurements including computers can be placed either in the target room where neutron flux is low enough or in the remote control room.

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8 Converting test results to avionics SEE rates

8.1 General

The goal of any SEE testing for avionics applications is to determine the SEE rates in electronic components and/or in entire boards that would be expected based on the results of the SEE testing. This is relatively easily done when using a spallation neutron source, but can be more complicated when using other types of neutron sources. Ultimately the results from the testing of the individual SEE sensitive elements will be combined to determine the effect on the equipment or system.

8.2 Use of spallation neutron source

When testing with a spallation neutron source, the SEUs recorded are all due to the high energy neutrons, except if there are also thermal neutrons within the source. If in fact there are thermal neutrons which could be contributing to upsets, such as with the TRIUMF neutron source or actually from using the atmospheric neutrons, at high altitudes or even at sea level, the contribution of the thermal neutrons needs to be accounted for and subtracted. The remaining SEUs are due to the high energy neutrons.

The SEU rate for avionics applications can be calculated in two different ways. The first way is to calculate the SEU cross-section and then apply Formula (1) and the second way is to use the ratio between the high energy (for example electronic components with threshold $E > 10$ MeV) neutron flux in the beam and that in the atmosphere (6 000 neutron/cm^2·h). Both methods yield the same SEU rate for avionics applications which can best be shown by an example.

In the example, the WNR or ICE House facility at Los Alamos is used to provide the neutrons such that no thermal neutrons are present. During the testing of a board in the Los Alamos beam, 250 SEUs were recorded in 1 h on a given board (or in a specific electronic component on the board) and during this time the board received a total neutron fluence of $4,5 \times 10^9$ neutron/cm^2. In addition, Los Alamos indicate that the neutron flux ($E > 10$ MeV) in their beam is $7,5 \times 10^5$ times more intense than the nominal aircraft neutron flux of 6 000 neutron/cm^2·h. Normally the electronic component or in this case the board is exposed to a known total neutron fluence and during the exposure the total number of events measured from the cross-section is calculated, but each method below is acceptable and provides the same result. The neutron cross-section is then given by Formula (2) and the event rate in any environment is given by Formula (1).

Event cross-section (cm^2) = total number events / total neutron fluence (neutron/cm^2) (2)

Using the example, the upset cross-section for the board is 250 / 4,5 x 10^9 = $5,55 \times 10^{-8}$ cm^2/board from Formula (2). The upset rate from Formula (1) in the atmospheric radiation environment is 6 000 x 5,56 x 10^{-8} = $3,34 \times 10^{-4}$ upset/board·h.

Assuming the accelerator beam is constant in intensity with time, the SEU cross-section is $250/(7,5 \times 10^5 \times 6\,000)$ or $5,56 \times 10^{-8}$cm^2/board. Thus, the SEU rate for avionics applications (at 40 000 ft (12,2 km) and 45° latitude) is $5,56 \times 10^{-8} \times 6\,000$ or $3,34 \times 10^{-4}$ upset/board·h.

Alternatively if the accelerator beam is constant in intensity with time, it is known that the 250 upsets were in a neutron flux that was $7,5 \times 10^5$ more intense for 1 h than that in an aircraft at 40 000 ft (12,2 km), hence, for an aircraft, the hourly rate would be $250/7,5 \times 10^5$/h or $3,33 \times 10^{-4}$ upset/board·h.

8.3 Use of SEU cross-section curve over energy

If a different kind of neutron or proton source is used, one that provides a beam of either monoenergetic protons or quasi-monoenergetic neutrons (QMNs), then several different approaches may be taken. The simplest method is to use the SEU cross-section taken at the highest particle energy used (for example approximately 200 MeV) and apply it as the SEU cross-section from the atmospheric neutron spectrum. This will generally be conservative since neutrons with lower energies within the atmospheric neutron spectrum have low SEU cross-sections.

The more complicated, but more accurate, method is to use the SEU cross-sections taken at a number of different particle energies to create an SEU cross-section curve that varies with energy, and integrate this curve with the differential neutron flux in the atmosphere. This gives more accurately the spectrum-averaged SEU cross-section. Formula (3) is a simplified formula for the variation of the differential neutron flux with energy, E, taken from IEC 62396-1, which applies at 40 000 ft (12,2 km).

$$dN/dE = \begin{cases} 0,346 \times E^{-0,922} \times \exp[-0,0152(\ln E)^2] & E < 300 \text{ MeV} \\ 340 \times E^{-2,2} & E > 300 \text{ MeV} \end{cases} \quad \text{neutron/cm}^2\cdot\text{s}\cdot\text{MeV} \qquad (3)$$

The spectrum-averaged cross-section is expected to be very similar to the SEU cross-section from the actual atmospheric neutrons or to that when measured using a spallation neutron source.

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The difficulty with this method lies in developing an accurate SEU cross-section curve as a function of neutron energy. First, if a quasi-monoenergetic neutron (QMN) beam has been used, the effect of the “tail” of low energy neutrons has to be determined and subtracted off to enable the SEU cross-section due to just the neutrons within the peak energy to be calculated. As indicated in 6.2.3.2 and 7.4.3, there are a number of different methods available for removing the effect of the neutrons in the low energy tail to determine the SEU cross-section at the peak energy. With monoenergetic proton beams, this is not a problem because each beam contains protons of a single energy. However, it is known that at low energies, for example, < 50 MeV, there can be differences between the SEU cross-section due to protons and due to neutrons, so using a 14 MeV source for the lowest energy point would be a good idea. In JESD89A [10], one suggested method uses protons at 50 MeV, 100 MeV and 150 MeV, and neutrons at 14 MeV. However, a recent paper suggests that the 150 MeV point should be replaced by a data point at 200 MeV or higher [7].

In addition, a number of other specifics related to the use of proton SEU data that are generally not discussed in the literature will be reviewed. There should be a minimum number of errors measured at each data point that each SEU cross-section is based upon, but the number of errors is rarely stated in the open literature. Using the minimum number of errors as 30 can serve as a good starting point. The reason for this is that a simplified statistical measure of the variation in the measured number of errors is the square root of the number of errors, and for 30 errors, the variation is about 18 % of the measured number. At present, there are more statistically rigorous methods for accounting for the variation, such as in JESD89A:2006, Annex C, which could also be used; these methods are based on confidence levels. Therefore, it would be helpful if curves of the SEU cross-section also included error bars on the measured SEU cross-section, however this is rarely done in open literature papers and reports. In addition, the actual number of errors that each SEU cross-section value is based upon is very rarely specified. It is recommended that where curves are drawn, error bars be included and that the actual number of single events be reported together with the cross-sections.

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Additional complications are involved in generating the SEU cross-section curve. When proton SEU cross-sections were first reported in the early 1980s, the first model that was developed, the Bendel model, had only one parameter. It was recognized that this was inadequate, so a two-parameter Bendel model was derived, which was much better. These and all subsequent models have the SEU cross-section increasing monotonically with the neutron or proton energy. Other two-parameter models were later developed, but while they may have given a better fit, it was at the expense of more complex functions of energy. More recently, the four-parameter Weibull fit model has been used for proton SEU data as a natural extension of the Weibull fit that is applied to describe the variation of the heavy ion SEU cross-section induced by the cosmic rays. Once a distribution like the Weibull was established as being extremely useful for the variation of heavy ion SEU cross-sections with the LET of the ions, it was evident that it could easily be applied to proton SEU cross-sections, in this case, as a function of the energy of the particles. Thus, the Weibull distribution is often used for proton and neutron SEU cross-sections. The Weibull distribution at a proton/neutron E is given as

$$\text{SEU cross-section, } \sigma(E) = \sigma_{\text{P/N-L}} \left(1-\exp\{-[(E - E_0)/W]^S\}\right) \tag{4}$$

where

$\sigma_{\text{P/N-L}}$ is the limiting or asymptotic proton/neutron cross-section (high energy);

E_0 is the threshold energy below which there is no SEU cross-section;

W is the “width” parameter;

S is the “fitting” parameter.

Nevertheless, one of the difficulties with measured SEU cross-sections is that the variation of the cross-section with energy is often not smooth, even though all of the fits, the Weibull, the Bendel, etc., are predicated on the fact that the cross-section increases smoothly with energy. Therefore, if a piece-wise linear fit were to be used along with a smooth fit like the Weibull, the results could be different by up to 25 % or more. If test results show irregular variation of the SEU cross-section as a function of energy, using a linear fit to this kind of SEU data to calculate the SEU cross-section from the atmospheric neutrons could lead to low results. An example of this is shown in Figure 4, in which SEU cross-section data from three different SRAMs is shown (Baggio [7], Dyer [9] and Granlund [49]). In each case, the Weibull fit of Formula (4) and a linear fit from each energy point, point to point, were integrated with the differential neutron flux given by Formula (2) to obtain the actual SEU cross-section from the atmospheric neutrons, as in Formula (5). As shown in Figure 4, there can be large enough variations over energy with the result that the average SEU cross-section using the two different fitting approaches, that is, a smoothed fit versus a linear fit, could differ by more than 25 %.

$$\text{Spectrum averaged SEU } \sigma = \int_{1}^{1000} \sigma(E)(dN/dE)dE \Big/ \int_{1}^{1000} (dN/dE)dE \qquad (5)$$

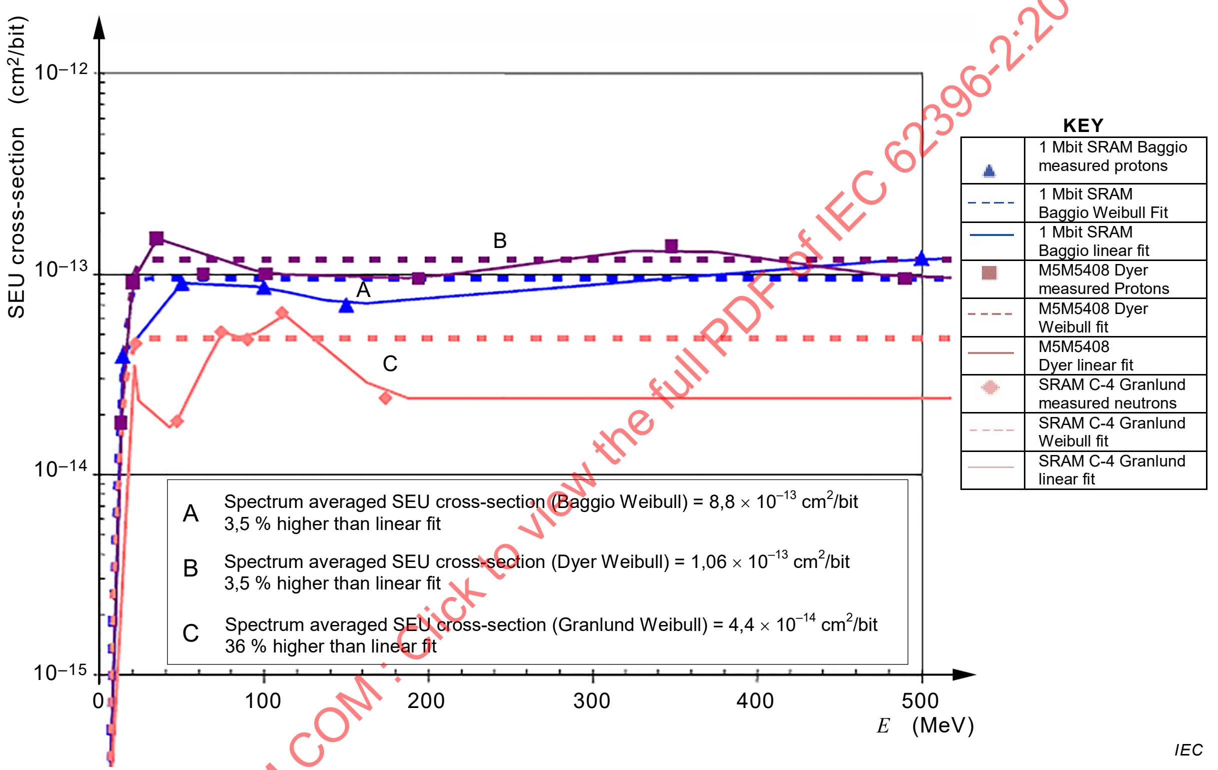

Figure 4 – Comparison of monoenergetic SEU cross-sections with Weibull and piece-wise linear fits

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Generally, the Weibull fit is preferred for a number of reasons. It is based on a least-squares type of approach, so it averages out all of the variations over energy. It can be based on data from several different samples of the same part and in that sense it can more effectively "average" out the behaviour of different samples, which can often exhibit significant variations between them. It usually gives a higher value "averaged" value of the spectrum-averaged SEU cross-section over the atmospheric neutron spectrum, and so from the perspective of providing conservative values, it is the preferred approach.

Having data from several samples of the same part, a single Weibull fit applies to all of the data and so Formula (5) has to be applied only once to obtain the spectrum-averaged SEU cross-section. However, for the piece-wise linear fit approach, the spectrum-averaged SEU cross-section would have to be calculated for the SEU data from each sample, applying Formula (5) to each set of data. The final spectrum-averaged SEU cross-section would be obtained by averaging the individual spectrum-averaged SEU cross-sections for each sample. By calculating the spectrum-averaged SEU cross-section for a set of SEU cross-section data using the two approaches, a consistency check can be applied to the accuracy of the data. If the variation between the spectrum-averaged SEU cross-section is larger than a given percentage, for example 15 %, then perhaps more data points are necessary, or data points based on a larger number of errors are needed in order to improve the internal consistency of the data. In all cases, it should be remembered that good statistics are needed for each and every data point taken at all of the various proton/neutron energies used in the testing.

8.4 Measured SEU rates for different accelerator-based neutron sources

The characterization of the different accelerator-based neutron sources used by Slayman [96] with three energy ranges, 1 MeV to 10 MeV, 10 MeV to 100 MeV and > 100 MeV is represented in Table 2. The numbers for the two lower fluence facilities at TRIUMF BL1B and BL2C have been added.

As the production method is similar, the distribution for the BL1B spectrum is similar to that for WNR. Comparison measurements for SEU rates between LANSCE WNR and TRIUMF TNF as reported by Sandia and QinetiQ [97] and others (unpublished) indicate the rates are 20 % to 30 % higher at WNR than at TRIUMF using the > 10 MeV fluence for normalization.

Table 2 – Spectral distribution of neutron energies

Source	1 MeV to 10 MeV	10 MeV to 100 MeV	> 100 MeV
IEC 62396-1	35	35	29
JESD89A	35	35	30
QARM (model)	40	36	24
LANSCE WNR	52	26	22
TRIUMF TNF	24	54	21
TRIUMF BL1B	52	29	19
TRIUMF BL2C	69	30	1
TSL ANITA	65	28	7

8.5 Influence of upper neutron energy on the accuracy of calculated SEE rates – Verification and compensation

The energy of the primary proton beam incident on the spallation target is an important factor in determining the fidelity of the synthetic spallation neutron spectrum with regard to the spectrum of atmospheric neutrons. In this respect the LANSCE ICE House [98] is currently the best, as the primary proton energy there is the highest (800 MeV). At TRIUMF [38, 95], the neutron sources at the TNF/NIF (BL1A) and PIF (BL1B) derive from 500 MeV protons; those at the PIF (BL2C) derive from 116 MeV protons. At TSL ANITA [39], the primary proton source is at 180 MeV. These limited upper energies correspond to a reduction in spectral fidelity to the natural atmospheric neutron spectrum produced by cosmic rays.

Platt et al. [99] have shown that errors in SEE rate estimates derived from measurements in neutron spectra with relatively low upper energy limits can be appreciable for some current electronic components but negligible for other electronic components. They also developed a new method for adjusting the measured response from a relatively low upper energy spectrum by combining this measurement with a second, independent SEE measurement made with higher energy particles (neutron or proton). This was achieved through an analysis that utilized a wide range of cross-section functions available in the literature, leading to an adjustment factor that allowed errors in the SEE rate (derived from the lower energy spectrum) to be reduced.

This adjustment methodology is new and has not be formally endorsed, but it appears to be useful if sources with higher energy neutron spectra are not available but only facilities with lower energy spectra are accessible. This concept of utilizing more than one set of SEE data to adjust and improve one of the data sets is novel, but also has some practical and philosophical limitations. This method works for SEE effects in which the energy dependence

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is weak at the limiting neutron energy of the facility neutron beam, which is satisfied for SEU in modern COTS electronic components. In other cases, for example SEL or other SHE phenomena in some electronic components, the influence of the upper energy appears to be appreciable and so much more caution needs to be taken in trying to use this method.

In other cases, for example SEL or other SHE phenomena in some electronic components, the influence of the upper energy might not be negligible. If such a case is suspected, a collocated primary proton beam [38] or a derived QMN source [47] can be used to determine whether there is a sensitivity of the studied cross-section to neutron energy at or near the upper energy limit. Reference [99] also shows how cross-section measurements in a spallation beam can be combined with cross-section measurements in collocated QMN (or proton) beam to compensate for the effects of a limited upper energy in the spallation beam. Such an approach enables the SEE rate equivalent to the LANSCE beam to be determined when LANSCE is unavailable or unsuitable, for example because of the size of the DUT.

The method of Platt et al. [99] is expected to be applicable for SEU in modern electronic components. On the other hand, as soon as SEL or other SHE phenomena are concerned, it is recommended that the method be used with caution and proper analysis. More extensive use of the method in practical testing is needed, including validating comparisons between SEE data from different facilities and the natural atmospheric spectrum.

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Annex A
(informative)

Sources of SEE data published before the year 2000

Table A.1 – Sources of existing SEE data published before the year 2000

Electronic component tested or listed	Particle type, energy	Data contained	Reference	Publication year	Comments
6 SRAMs, 2 micro-processors, 2 FPGAs	High energy proton, WNR neutron, 14 MeV neutron	SEU cross-section, cm^2/bit	[8]	1998	Electronic components identified; SEU cross-sections from WNR, 14 MeV and from proton data
5 SRAMs	QMN	SEU cross-section, cm^2/bit	[48]	1998	Electronic components identified; monoenergetic SEU cross-sections derived from measurements
20 SRAMs and 26 DRAMs	High energy proton and WNR neutron	SEU cross-section, cm^2/bit	[5]	1997	Electronic components not identified; SEU cross-sections mixture of neutron and proton data
5 SRAMs	3 MeV and 14 MeV neutrons	SEU cross-section, cm^2/bit	[36]	1997	Electronic components identified; SEU cross-sections from neutron data
87 SRAMs, 48 DRAMs, 10 EEPROMs, 8 Flash EPROMs, 8 UV EPROMs	High energy protons (20 MeV, 30 MeV, 50 MeV, 60 MeV, 100 MeV, 200 MeV, 300 MeV and 500 MeV)	SEU cross-section, cm^2/bit	[64]	1997	All electronic components identified; electronic components tested between 1989 to 1996

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