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INTERNATIONAL STANDARD

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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

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

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

FOREWORD

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International Standard IEC 62396-2 has been prepared by IEC technical committee 107: Process management for avionics.

This standard cancels and replaces IEC/TS 62396-2 published in 2008. This first edition constitutes a technical revision.

This first edition includes the following significant technical changes with respect to the technical specification IEC/TS 62396-2.

a) Clause 5 information expanded including additional information in sections on heavy ion data, neutron and proton data and thermal neutron data.
b) The neutron sources Clause 6 has been updated, Figure 1 now contains data on additional radiation simulators, and Figure 2 contains more recent data with results for feature sizes below 100 nm. A new Figure 3 contains data on low energy neutron (< 10 MeV) SEU percentage fraction.

c) The sources of existing data (radiation SEE data) table has been split in to two tables: one for post 2000 sources and the other for pre 2000 sources which is now in Annex A.

d) The Anita spallation neutron source has been added to Clause 7.

e) A new subclause, 7.4.5, has been added on whole system and equipment testing.

f) A new subclause, 8.4, provides a comparison between accelerator based neutron sources.

g) A new subclause, 8.5, compares the influence of upper neutron energy for neutron sources.

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

FDIS	Report on voting
107/186/FDIS	107/192/RVD

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

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

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

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

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- withdrawn,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

A bilingual edition of this document may be issued at a later date.

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

INTRODUCTION

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

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.

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 microelectronic devices for purposes of measuring their susceptibility to single event effects (SEE) induced by 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 devices and boards due to atmospheric neutrons at aircraft altitudes.

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

2 Normative references

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

IEC 62396-1:2012, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

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

IEC/TS 62396-4, *Process management for avionics – Atmospheric radiation effects – Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects*

IEC/TS 62396-5, *Process management for avionics – Atmospheric radiation effects – Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems*

3 Terms and definitions

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

4 Abbreviations used in the document

ANITA	Atmospheric-like Neutrons from thIck TArget (TSL, Sweden)
BL1A, BL1B, BL2C	Beam line designations at the TRIUMF facility (Canada)
BPSG	Borophosphosilicate glass
CMOS	Complementary metal oxide semiconductor
COTS	Commercial off-the-shelf
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
EPROM	Electrically programmable read only memory
ESA	European Space Agency
eV	Electron volt
FIT	Failures in time (failures in 10^9 hours)
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
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
PIF	Proton Irradiation Facility (TRIUMF, Canada)
PNPI	Petersburg Nuclear Physics Institute (Russia)
PSG	Phosphosilicate glass
QMN	Quasi-monoenergetic neutrons
RADECS	Radiations, effets sur les composants et systèmes.
RAM	Random access memory
RCNP	Research Center of Nuclear Physics (Osaka, Japan)
RVC	Result of voting (IEC)
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	Tri-University Meson Facility (Canada)
TSL	Theodor Svedberg Laboratory (Sweden)
WNR	Weapons Nuclear Research (Los Alamos USA)

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 ICs. In addition, many tests are performed on individual devices, 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 device 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 IC device. 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 device 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 section 5.2.3. Low-energy ("thermal") neutrons can also cause SEE in some devices but such data is only available on a very small number of devices (see section 5.2.4) and it involves neutron interactions with boron-10 rather than silicon.

5.2.2 Heavy ion data

An important resource that can be utilized to eliminate devices is the results from heavy ion SEE testing carried out to support space programs (~80 % of the devices 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][1]. Thus, any device 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], 21 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

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

within the IC, e.g., 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 a device 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 devices from consideration for neutron SEE sensitivity based on heavy ion SEE testing, since only some devices 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 international standard, it refers only to single event testing using a neutron or proton source, not to the results from testing with heavy ions.

5.2.3 Neutron and proton data

If SEE data on a device of interest is found from SEE tests using high energy neutrons or protons, it will still require expertise regarding how the data is to be utilized in order to calculate a SEE rate at aircraft altitudes. Data obtained by IC vendors for their standard application to ground level systems are often expressed in totally different units, FIT units, where one FIT is one error in 10^9 device hours, which is taken to apply at ground level.

IC devices are constantly changing. In some cases, devices which had been tested, become obsolete and are replaced by new devices which have not been tested. The fact that a device is made by the same IC vendor and is of the same type as the one it replaced does not mean that the SEE data measured in the first device applies directly to the newer device. In some cases, small changes in the IC design or manufacturing process can have a large effect in altering the SEE response, but in other cases, the effect on the SEE response may be minimal.

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 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 62396-1:2012.

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 devices, 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 there is no real alternative but to carry out one's own SEE testing. The advantage of such a test is that it pertains to the specific device 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), 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 the following clauses.

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 international standard, 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 devices 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 device that results in the device 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 device itself, but can also be propagated to another device 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 state. High energy neutrons in the atmosphere can induce all of these effects: SEU, SEFI and SEL. Where semiconductor devices are operated at high voltage stress (200 V and above) they may be subject to single event burn-out, SEB or single event gate rupture, SEGR; these effects are covered in detail in IEC/TS 62396-4.

One of the important simplifying assumptions to be used in this international standard 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/dev), which is the number of errors of a given type divided by the fluence of particles to which the device 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. This is far more than an assumption, since it has been demonstrated by direct measurement in many different devices see [5, 6, 7, 8, 9] and IEC 62396-1. In these references, SEU was measured in the same devices using monoenergetic proton beams and using the neutron beam from the Weapons Neutron Research (WNR) facility at the Los Alamos National Laboratory. The energy spectrum of the neutrons in the WNR is almost identical to the spectrum of neutrons in the atmosphere. An estimate of the SEE rate at aircraft altitudes in a device can be obtained by the simplified equation:

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

Here, the integral neutron flux in the atmosphere, $E > 10$ MeV, is taken to be 6 000 n/cm^2·h, the approximate flux at 40 000 ft (12,2 km) and 45° latitude as in IEC 62396-1, this flux is suitable for devices 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 Equation (1) is used in IEC 62396-1 and is the nominal flux under the above conditions. For