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PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

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

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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Email: csc@iec.ch
Tel.: +41 22 919 02 11
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**Process management for avionics – Atmospheric radiation effects –
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CONTENTS

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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

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

FOREWORD

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This PAS shall remain valid for an initial maximum period of three years starting from 2007-09. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

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

- Part 2: Guidelines for single event effects testing for avionics systems
- Part 3: Optimising system design to accommodate the Single Event Effects (SEE) of atmospheric radiation
- Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects
- Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

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

1 General

The purpose of this PAS is to provide guidance related to the testing of microelectronic devices for purposes of measuring their susceptibility to single event effects (SEE) induced by the 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 the atmospheric neutrons in the atmosphere at aircraft altitudes.

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 effects. However, a key discriminator is deciding on whether existing SEE data is available that may be used, 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.

1.1 Use of existing SEE data

The simplest solution is to find previous SEE data on a specific IC device. This is not nearly as simple as it appears. First, the largest interest lies in SEE data that is directly usable for purposes of estimating the SEE rate in avionics. Thus, SEE tests that have been carried out on devices using heavy ions, data which is directly applicable for space missions, is data that is not directly applicable for avionics purposes. 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. Therefore, heavy ion SEE data should not be used for application to the atmospheric neutron environment, except by scientists and engineers who have extensive experience in using this kind of data. For that reason, unless otherwise stated explicitly, when SEE data is discussed in the remainder of this PAS, it refers only to single event testing using a neutron or proton source, not to the results from testing with heavy ions.

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.

A continuing problem with the existing SEE data is that there is no single data base containing 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 data bases are mainly on much older devices, dating from the 1990s and even 1980s, and it is primarily from heavy ion tests that were performed for space applications and not from testing with protons and neutrons.

1.2 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 your 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 sections.

2 Availability of existing SEE data for avionics applications

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.

2.1 Types of existing SEE data that may be used

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 PAS, 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 kinds 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 in 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. The high energy neutrons in the atmosphere can induce all of these effects: SEU, SEFI and SEL.

One of the important simplifying assumptions to be used in this PAS 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 (cm²/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, measurements made with high energy protons can be used as the same cross section from the atmospheric neutrons. This is far more than an assumption, since it has been demonstrated by direct measurement in many different devices [1-6][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:

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

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

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 [2]. 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 the Technical Specification IEC/TS 62396-1 [2] and is the nominal flux under the above conditions.

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 JESD-89A [7], 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 2.1.3).

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 beam. Other SEE data that are 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 devices ([4], feature size < 0,5 µm), and a factor of 4 times higher for older devices [5]. For some of the very latest devices, the factor is close to 1.

2.1.1 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, b) IC 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. Generally, SEE data taken and reported by government agencies contain most if not all of the relevant information, including identifying the specific IC devices tested and the 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 the most recent NASA-GSFC compilations of SEE testing containing proton SEE test results are given in [8-11], and examples of JPL reports of SEE testing containing proton SEE test results are given in [12-14]. 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. IC vendors perform a large number of tests, but only a small fraction of that data is reported upon in the open literature. Furthermore, when the SEE data from IC vendors is published, the results are often disguised so that the identity of the devices tested, or the part number is usually hidden by using an arbitrary designation and the results are expressed in units that are ambiguous at best and often of little use quantitatively. Sometimes, the data is expressed in FIT units, which means errors per 10^9 device hours, however, this does not incorporate information on how many bits are included in the device. If only the FIT value is given, this can be converted into a SEE cross section by using the FIT definition and dividing by 14 [14 n/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 JESD-89A standard and so most often used.] Thus, FIT $\times$ 10^{-9}/14 gives the SEE cross section in cm^2/device.

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) × 10^{-15}/14 to obtain the SEE cross section in cm^2/bit. Other papers report the FIT value in arbitrary units (a.u.) which allows the authors to show how the FIT rate varies with a particular parameter (e.g., 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 [3, 15-18].

Most of the SEE data that we have been discussing comes from the SEE testing of individual components, placing those devices in a beam of neutrons or protons and monitoring changes in the status of the device 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 device being irradiated. If the beam is collimated such that only one or two devices are exposed to the particles in the beam during each test, the likely source of error is a SEE error in those devices. However, this is a dynamic type of test and it may be that the device in the beam experienced the initial error which was propagated to another device on the board, and faulty performance of the latter device is what lead 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 going on the Space Shuttle and related programs. This testing is carried out with a beam of protons, and while it is recorded in a NASA-JSC report, these reports are not widely available, examples are given in [19-21]. Furthermore, the main purpose of the test is to screen all of the devices for the potential of a hard error induced by the protons, such as a single event latchup, so recoverable errors are not analyzed 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 data base. 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.

2.1.2 Data based on the use of different sources

In general, all SEE testing is carried out using an accelerated source of neutrons or protons, meaning that the device 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 devices 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 below.

2.1.2.1 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 and at very low energies, called thermal neutron energy. The high energy neutrons cause the SEU by the nuclear reaction with the silicon in the IC that creates a recoil, and it is the energy from this recoil that is locally deposited in other silicon atoms that directly causes the upset. For the purposes of simplification, neutrons with energies > 10 MeV are of greatest concern, but it is true that neutrons with lower energies, e.g. (2 to 3) MeV, can also cause SEUs. However, since the SEU cross section for E < 10 MeV is considerably lower than the cross section for E > 10 MeV, 10 MeV is used as an effective cut-off. Estimates of the SEU contribution for electronics technology with geometry greater than 0,2 μm by neutrons with E < 10 MeV to the total SEU rate from the entire WNR neutron spectrum is < 10 %, but for lower feature sizes, this fraction is expected