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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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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

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

FOREWORD

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Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will transform it into an International Standard.

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single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.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 (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, 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) $\times$ $10^{-15}/14$ 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

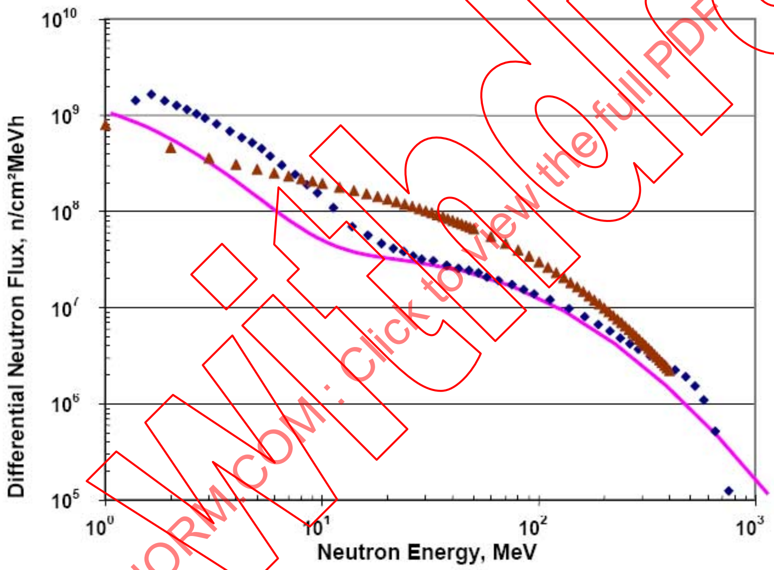
In general, all SEE testing is carried out using an accelerated source of neutrons or protons, meaning that the device or board to be tested will receive a larger fluence of particles over a given period of time in the test environment compared to the fluence it would receive during that same time period 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 to increase. This is roughly consistent with SEU measurements made with monoenergetic neutrons (3 and 14 MeV) on devices of the mid 1990's (feature size greater than 0,5 μm), showing that the SEU cross section at 3 MeV for these older devices was about a factor of 100 lower than that at 14 MeV for most of the SRAMs tested [22]. However, for more recent devices, 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 (8 to 10) % range.

For high energy neutrons, there are three different types of sources: 1) a spallation neutron source which has neutrons with energies over a wide energy spectrum similar to that of the atmospheric neutrons, 2) a quasi-monoenergetic neutron 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, and 3) a 14 MeV neutron generator, the only source that is close to being truly monoenergetic.

The WNR at Los Alamos which was mentioned previously is the best example of a spallation neutron source, although the neutron irradiation facility at TRIUMF (Tri University Meson Facility, in Vancouver, Canada) is another such source. 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 [23]. Figure 1 compares the neutron spectra from Los Alamos (the ICE House), the neutron facility at TRIUMF and the atmospheric neutron spectrum at ground level.



KEY		
	FACILITY	Multiplication Factor
(magenta line)	Ground Spectrum [latitude 45° North]	Line plot is ground level multiplied by 3×10^8
◆	ICE House (WNR) Measured Spectrum 2005	1
▲	TRIUMF at 100 μA	1

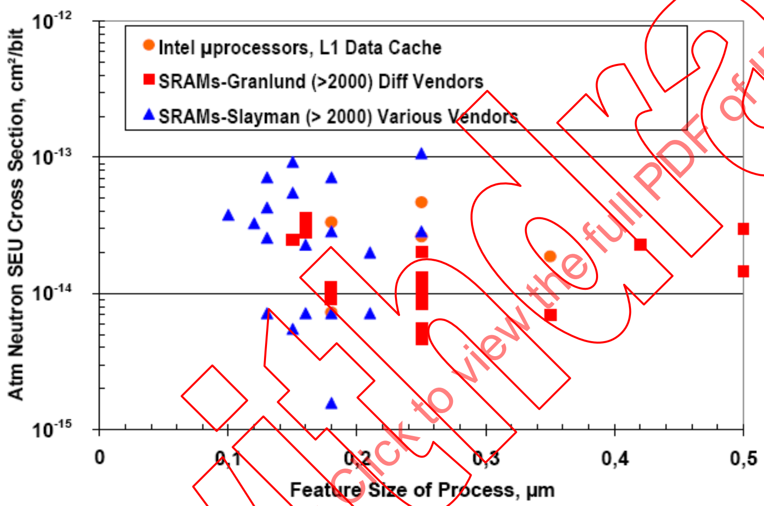
Figure 1 – Comparison of Los Alamos and TRIUMF neutron spectra with terrestrial neutron spectrum

SEU data on devices that were exposed to the WNR neutron beam have been published in a number of papers [3-5, 24-25], however, many more devices 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 [26] indicates that in the year 2001, at least eight different groups carried out SEE testing, and of these, we estimate that maybe two of the testing groups may publish some of their results, an American national laboratory and a university. The six private companies, both IC manufacturers and avionics vendors, will keep 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 received limited use, but since that time, a number of papers on SEU results from the testing of IC devices at the TNF have been published [27].

There are a number of quasi-monoenergetic neutron sources around the world, including some in the United States of America, 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 [28]. A few papers have been published reporting on the results of microelectronics devices being exposed to the TSL neutron beam [Refs 6, 29, 30]. Methodologies have been developed for extracting SEU cross section data at the pseudo-peak energy [29, 30]. In addition, a similar facility has been operating in Japan at Tohoku University [31] 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 [32, 33].

In Figure 2, we combine SEU measurements made by several different groups at these various facilities to illustrate how the high energy SEU cross section per bit for SRAMs has varied with feature size over the last 5 or more years. The trend that is illustrated in Figure 2 shows a consistency within an approximate plateau region of 10 to 30, however we cannot predict how this might change in the future, as feature sizes continue to decline below 0,1 µm.



KEY	
Symbol	**Data**
●	Intel microprocessors, L1 Data Cache
■	SRAMs – Granlund (>2000) Various Vendors
▲	SRAMs – Slayman (>2000) Various Vendors

Figure 2 – Variation of high energy neutron SEU cross section per bit as a function of device feature size

The third kind of high neutron facility is one that provides essentially monoenergetic neutrons, and 14 MeV, from the D-T reaction, 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 [5]. Tests on more recent devices have shown a closer agreement in the SEU response between a spallation neutron source and a 14 MeV neutron sources [4, 6]. This indicates that for current, low voltage devices, 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) [34].

There is a fourth type of neutron facility that should be considered for testing devices for inducing SEUs: with thermal neutrons. Thermal neutrons cause SEUs through the neutron reactions with the isotope ^{10}Boron, 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). Many devices use a different type of glassivation (e.g., PSG) and in some cases, the boron in the BPSG is ^{11}Boron, 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 [6, 17, 35].

2.1.2.2 Data obtained using proton sources

It was demonstrated that high energy protons cause SEUs in microelectronics nearly 25 years ago [36]. 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, by nuclear reactions with the silicon, rather than by direct ionization in the silicon. 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. Thus, for DRAMs made during the 1980s and tested with protons, the SEU cross section decreased by more than an order of magnitude for proton energies < 50 MeV [37, 38]. For more recent devices, 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 [4]. A very useful compendium of SEU cross sections in more than 120 different SRAMs and DRAMs was compiled by ESA in 1997 [39], mostly on 5 V devices, but a few at 3,3 V, however, few if any of these devices are used today. In contrast, most other papers in the open literature contain measured proton SEU response data for fewer devices, roughly 4 to 8 devices.

2.1.3 Ground level versus avionics applications

There are a number of important differences between the SEU considerations for devices in avionics applications and those on the ground. First and foremost, the neutron flux in the atmosphere is much higher than it is on the ground, so the SEU rate is going to be proportionally higher. The nominal difference is taken to be a factor of 300 between the neutron flux at 40 000 ft (12,2 km) and on the ground. As explained in JESD-89A and in various technical papers [40, 41], there are two main sources of upsets in devices on the ground, the atmospheric neutrons and alpha particles from trace amounts of radioactive materials within the IC package. As the nature of IC packaging has evolved over the years, the specific components responsible for most of the alpha particle emissions have changed. Today, the major source is the lead in solder bumps, but because there is a movement to eliminate the use of lead in ICs, this too may change, although the replacement solder material (e.g., tin-silver-copper or tin-silver-bismuth) may also emit low levels of alpha particles, and so the alpha particle problem will not be going away, but changing.

At the ground level, for some devices, the SEU or SER rate due to the alpha particles from the IC package may be similar to that from the atmospheric neutrons. For other devices, the neutrons are the main source of the upsets. However, in avionics, with the neutron flux in the atmosphere being more than 100 times the neutron flux on the ground, the SEU rate from the alphas emitted by the package is very small compared to the rate from the neutrons. Thus, the alpha particles from the IC package can be neglected as a source of upsets for avionics applications.

As discussed in 2.1.1, for most ground level applications, the upset rate is quantified in terms of the FIT rate, number of upsets in a device in 10^9 device hours. The reason for this is that the testing and analysis is being done primarily by IC vendors and not by companies that sell ground level systems. That has been changing over the last five years, especially after the possibility of cosmic ray neutrons causing upsets was publicized in the general press [42]. This occurred with the article in Forbes magazine of November, 2000 that reported that Sun servers were having problems, with dozens of machines crashing due to bit flips in the SRAM used for the L2 cache memory which were caused by cosmic rays or alpha particles. Sun Microsystems received a great deal of adverse publicity and hundreds of thousands of people became aware of the fact the cosmic rays can cause errors in memory chips. In this case, the problem was amplified because Sun initially blamed the vendor of the SRAMs [43].

Sun Microsystems and its competitors in the server market (e.g., Cisco Systems) have become very involved in neutron-induced upsets, testing devices and systems to quantify the rates and designing error correcting schemes to protect their systems against individual errors. The testing they perform is generally considered proprietary and so the results from these tests are not available; this applies to the testing of both individual devices and entire computer boards.

For ground level applications, it is likely that the IC vendors perform more neutron testing than the server vendors, and their testing is almost always on individual devices. Nevertheless, their SEU or SER results invariably remain proprietary. In some cases, they do publish their results, and in that case the upset information is expressed in FIT units, with the identity of the individual devices that were tested hidden by means of generic designations (e.g., part A, part B1, etc.). When the data is published by the IC vendors, it is often presented at a particular annual meeting, the International Reliability Physics Symposium (IRPS). Examples of recent IRPS papers that contain information related to SEUs induced by the atmospheric neutrons, although expressed in units that may not be directly usable, are given in [16-18, 33].

There is one group of IC vendors who are more open about their SEU testing results. These are two microelectronics manufacturers who make FPGAs (field programmable gate arrays). These companies are Xilinx and Actel. Examples of some of the papers that they have published containing relevant SEU information are given in [44-46].

2.2 Sources of existing data

In the previous Subclauses, we have 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 below, we compile descriptions of the SEU information contained in some of these references, in particular those with the largest amount of data.

Table 1 – Sources of existing data

Device tested or listed	Particle type, energy	Data contained	Ref.	Comments
20 SRAMs and 26 DRAMs	Hi E proton and WNR neutron	SEU cross section, cm^2/bit	1	Devices not identified; SEU X-Stns mixture of neutron and proton data
9 SRAMs (0,14 to 0,5 µm)	Hi E proton, 14 MeV neutron and WNR neutron	SER rate, FIT/Mbit	3	Devices not identified; SER rates from WNR and from proton measurements
8 SRAMs (0,14 to 0,5 µm)	Hi E proton and WNR neutron	SEU cross section, cm^2/bit	4	Devices not identified; SEU X-Stns from WNR and from proton data
6 SRAMs, 2 µprocessors, 2 FPGAs	Hi E proton, WNR neutron, 14 MeV neutron	SEU cross section, cm^2/bit	5	Devices identified; SEU X-Stns from WNR, 14 MeV and from proton data
6 SRAMs	Hi E proton and neutron 14 MeV and thermal neutron	SEU cross section, cm^2/bit	6	Devices identified; SEU X-Stns from hi E proton and neutron 14 MeV and thermal neutron data
SRAMs, DRAMs, other devices	High energy protons	Asymptotic SEU cross section, cm^2/ bit or per device	13	Devices identified; SEU X-Sections from high Energy proton measurements
6 SRAMs (0,25, 0,13, 0,09 µm)	WNR neutrons	SER rate, FIT/Mbit	15	Test devices, SOI and bulk, from two vendors.
6 SRAMs (0,18, 0,13, 0,09 µm)	150 MeV protons	SEU cross section, arbitrary units	16	Test devices, vendor not identified, SOI and bulk
5 SRAMs	3 and 14 MeV neutrons	SEU cross section, cm^2/bit	22	Devices identified; SEU X-Sections from neutron data
24 SRAMs, 6 feature sizes	WNR neutrons	SER, error/bit•h at 40 000 ft (12,2 km)	25	Devices and 4 vendors not identified
5 SRAMs	Quasi-mono-energetic neutrons	SEU cross section, cm^2/bit	29	Devices identified; mono-energetic SEU X-Stns derived from measurements
10 SRAMs	Quasi-mono-energetic neutrons	SEU cross section, cm^2/bit	30	Devices identified (10 of the 24 SRAMs of 25); mono-energetic SEU X-Stns derived from measurements
87 SRAMs, 48 DRAMs, 10 EEPROMs, 8 Flash EPROMs, 8 UV EPROMs	High energy protons (20, 30, 50, 60, 100, 200, 300 and 500 MeV)	SEU cross section, cm^2/bit	39	All devices identified; devices tested between 1989 to 1996
FPGA, 4 sections tested	Hi energy protons	SEU cross section (cm^2/bit), SEFI cross section (cm^2/dev)	45	Device and portions of device (configuration memory block memory power-on-reset and external ports) identified

3 Considerations for SEE testing

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 device or entire board), the type of test used (static or dynamic), and the type of the facility providing the neutron or proton beam. These are discussed in greater detail in the following sections.

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 [47, 48], 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/TS 62396-1 [2] which directly applies to avionics. Reference

[7] 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. Reference [49] is a standard that is also under development which applies to SEE testing with protons.

3.1 Selection of hardware to be tested

It is easier and more direct to test one device type at a time, such as a RAM or a microprocessor. However, if the actual avionics board contains many devices that are potentially susceptible to SEE from high energy neutrons, this approach could involve a large number of tests. When testing individual devices for single event effects, the testing is usually performed on a specially designed test board, one test board for each type of device. 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 devices 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 devices that are likely to have SEE effects induced by the atmospheric neutrons: RAM devices, microprocessors and FPGAs as the most susceptible devices.

One of the advantages of testing of individual devices 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 section 2.1 single event latchup (SEL) and single event functional interrupt, 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 devices on a board may 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 devices. Conversely, it may be that the cross section for such an effect may be smaller than the SEE cross sections in the three main types of devices referred to above as most susceptible to SEE effects.

3.2 Selection of test method

Selection of the software is generally tied to the selection of the type of devices to be tested and the test vehicle, either a test board with a single device 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 effects 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 a device 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 bit upset (more than one upset induced by a high energy neutron or proton) is a remote possibility, usually (1 to 2) % of the SEU rate. There are ways of examining the test pattern words to distinguish which words experienced more than a single bit flip.

With devices like DRAMs, microprocessors and FPGAs, the possibility of 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, shall 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 device. It often involves the use of an evaluation board for a device 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 [50, 51] in which "hangs" or other types of errors in 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 [52, 53]. SEFIs have also been induced in DRAMs [54], but also 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 section has been calculated.

The SEE testing of entire boards or subsystems is much more complex since the devices 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 devices on the board are being exposed at the same time. 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 device can propagate to other devices, 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 [55], which used a heavy ion beam, [56] which used a proton beam and [57] which used a neutron beam.

3.3 Selection of facility providing energetic particles

In order to expose devices 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 the following sections. In Annex C of IEC/TS 62396-1 [2] 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.

3.3.1 Spallation neutron source

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 by 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 only two main neutron spallation sources that have been used for exposing ICs and boards for purposes of SEE testing. These are the WNR, discussed in 2.1 and the TRIUMF Neutron Facility (TNF) at TRIUMF [58].

The WNR has been much more widely used for SEE testing as discussed in 2.1. At present, with the new ICE House configuration it is very convenient to use, and it has an acceleration factor of approximately six orders of magnitude, so that one hour in the beam exposes a device to the same neutron fluence as 10^6 hours in an airplane nominally at 40 000 ft (12,2 km). However, in 2004, because of security issues at the Los Alamos National Laboratory, the laboratory was shut down to visits from outside scientists and engineers for a number of months, but it reopened for outside customers again beginning in 2005.

The TNF at the TRIUMF (Tri University Meson Facility in Vancouver, Canada) is much less convenient to use than the WNR. However, it provides a neutron spectrum that is quite similar to that of the atmospheric neutrons and the flux available (for E > 10 MeV) is similar to that at the WNR, 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.

Even though TRIUMF had not been used very much for SEE testing before 2004, with the temporary closing of WNR, it has been in much greater use since 2004. It is not convenient for placing the test board in the beam and it has to be lowered down a channel on a pulley system, but the TNF has a significant advantage in that the neutron field also contains thermal neutrons. Thus, by conducting a test on a device 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.

3.3.2 Monoenergetic and quasi-monoenergetic beam sources

As noted in 2.1.2.1, both monoenergetic and quasi-monoenergetic neutron sources have been used for testing devices 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 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 it 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 devices 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 devices, [22]). For more recent devices, 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 we cannot predict 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 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 lithium. The neutrons produced have a usual energy distribution, 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 are 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 source was to separate 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 section 2.1.2.1, 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 [29, 30, 32, 33].

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. We have seen some SEU data from this kind of neutron source that 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 calculational procedure, the facility, too small a number of upsets during some of the runs, or other causes.

3.3.3 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 the Annex C of IEC/TS 62396-1 [2]. 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 devices being tested from the gamma radiation while the device is also receiving the neutrons. For most commercial off the shelf (COTS) devices, a TID dose of under 10 000 rads should not have any deleterious effect in the response of the parts. TID doses in excess of 20 000 to 50 000 rads very likely will have an effect on the response of the devices and should be avoided, unless previous TID testing of the devices have demonstrated that they are immune from such TID effects. When devices are exposed to such a thermal neutron beam as the thermal column, the number of SEU events measured is due to only the thermal neutrons.

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. TRIUMF is one such facility 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 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, one in which the devices 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 and 1) mm).

Thus, two sets of SEU measurements are made, one the devices open to all of the neutrons and the second with the devices 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 must 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 [59].

4 Converting test results to avionics SEE rates

The ultimate goal of any SEE testing for avionics applications is to determine the SEE rates in devices 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.

4.1 Use of spallation neutron source

When testing with a spallation neutron source, the SEUs recorded are all due to the high energy (> 10 MeV) 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, therefore the contribution of the thermal neutrons needs to be accounted for and subtracted off. 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 Equation (1) and the second way is to use the ratio between the high energy (E > 10 MeV) neutron flux in the beam and that in the atmosphere (6 000 n/cm²·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 one hour on a given board (or in a specific device on the board). In addition, Los Alamos indicates 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 n/cm^2·h.

By the first method, 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 $3,33 \times 10^{-4}$ Upset/board·h. By the second method, we know that the 250 upsets were in a neutron flux that was $7,5 \times 10^5$ more intense than that in an aircraft at 40 000 ft (12,2 km) hence, for an aircraft, the hourly rate would be 250/$7,5 \times 10^5$ per hour or $3,33 \times 10^{-4}$ Upset/board·h.

4.2 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, then several different approaches may be taken. The simplest method is to use the SEU cross section taken at the highest particle energy used (e.g. 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 a SEU cross section curve that varies with energy, and integrate this curve with the differential neutron flux in the atmosphere. This gives more accurate the spectrum averaged SEU cross section. Equation (2) below is a simplified formula for the variation of the differential neutron flux with energy, E, taken from IEC/TS 62396-1[2], which applies at 40 000 ft (12,2 km).

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

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

The difficulty with this method lies is in developing an accurate SEU cross section curve as a function of neutron energy. First, if a quasi-monoenergetic neutron 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 2.1.2.1 and 3.3.2, 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, e.g., < 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 JESD-89A [7], one suggested method uses protons at 50, 100 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 [4].

In addition, we will review a number of other specifics related to the use of proton SEU data that are generally not discussed in the literature. 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. In actuality, there are more statistically rigorous methods for accounting for the variation, such as in Annex C of JESD-89A, which could also be used that 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.

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. Another 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 is being 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

$$\text{SEU Cross Section, } \sigma(E) = \sigma_{P/N\text{-}L}\,(1-\exp\{-[(E-E_0)/W]^S\}) \qquad (3)$$

where

$\sigma_{P/N\text{-}L}$ 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 that 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 3 in which SEU cross section data from three different SRAMs are shown (Baggio [4], Dyer [6] and Granlund [30]. In each case, the Weibull fit of Equation (3) and a linear fit from each energy point, point to point, were integrated with the differential neutron flux given by Equation (2) to obtain the actual SEU cross section from the atmospheric neutrons, as in Equation (4). As shown in the figure, there can be large enough variations over energy with the result that the average SEU cross section using the two different fitting approaches, a smoothed fit versus a linear fit, could differ by more than 25 %.

$$\text{Spectrum Averaged SEU } \sigma = \int_{1}^{1000} \sigma(E)(dN/dE)dE \,/\, \int_{1}^{1000} (dN/dE)dE \quad (4)$$

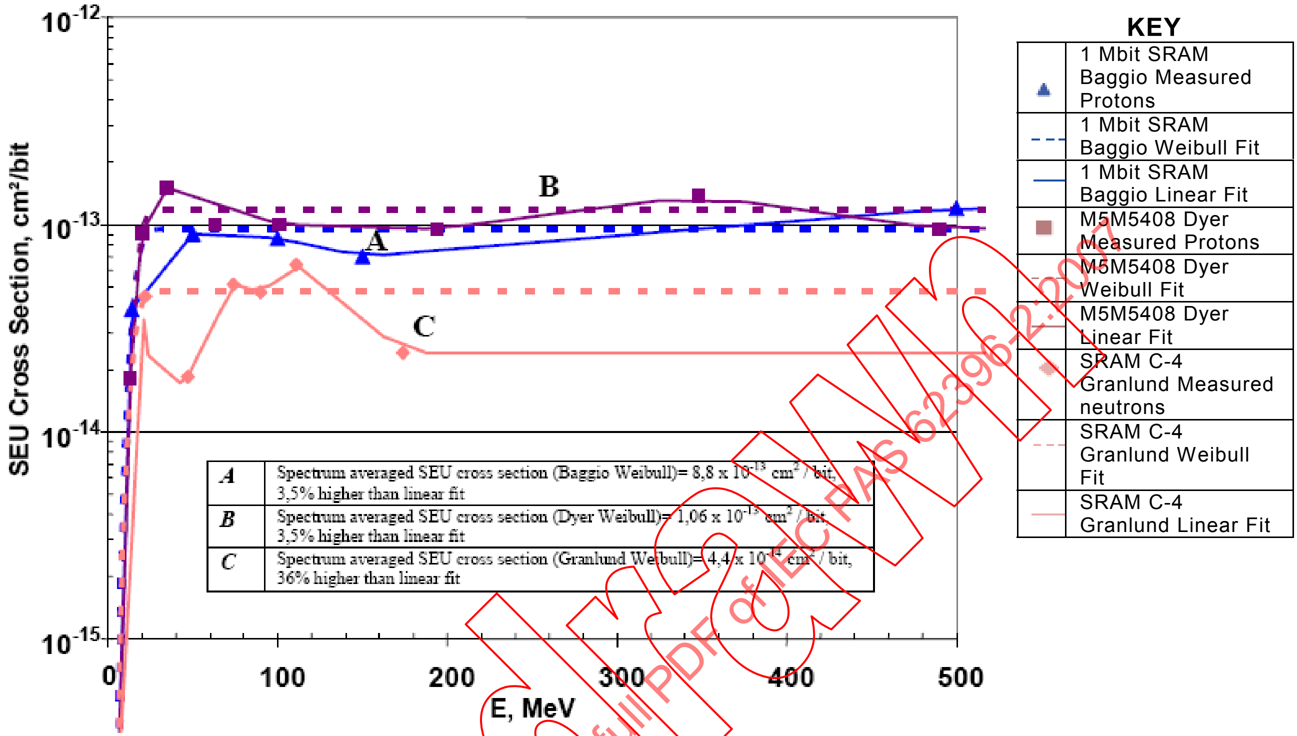


Figure 3 — Comparison of mono-energetic SEU cross sections with Weibull and Piece-Wise Linear Fits

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 Equation (4) 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 Equation (4) 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, e.g., 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.