IEC/PAS 62396-5

Edition 1.0 2007-09

PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

Process management for avionics – Atmospheric radiation effects –
Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems

IEC/PAS 62396-5:2007(E)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE P

ICS 03.100.50; 31.020; 49.060

ISBN 2-8318-9206-6

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC-PAS 62396-5 has been processed by IEC technical committee 107: Process management for avionics.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:
Draft PAS	**Report on voting**
107/58/NP	107/70/RVN

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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 5: Guidelines for assessing thermal neutron fluxes and effects in avionics systems

1 General

The purpose of this PAS is to provide a more precise definition of the threat that thermal neutrons pose to avionics as a second mechanism for inducing single event upset (SEU) in microelectronics. There are two main points that will be addressed in this PAS: 1) a detailed evaluation of the existing literature on measurements of the thermal flux inside of airliners and 2) an enhanced compilation of the thermal neutron SEU cross section in currently available SRAM devices (more than 20 different devices). The net result of the reviews of these two different sets of data will be two ratios that we consider to be very important for leading to the ultimate objective of how large a threat is the SEU rate from thermal neutrons compared to the SEU threat from the high energy neutrons (E >10 MeV). The threat from the high energy neutrons has been dealt with extensively in the literature and has been addressed by two standards ([2][1] in avionics and [1] in microelectronics on the ground).

The two ratios that this PAS considers to be so important are: 1) the ratio of the thermal neutron flux inside an airliner relative to the flux of high energy (> 10 MeV) neutrons inside the airliner and 2) the ratio of the SEU cross section due to thermal neutrons relative to that due to high energy neutrons. These ratios are considered to be important because with them, once we know what the SEU rates are from the high energy neutrons for an avionics box, a topic which has been dealt with extensively, such as [1], then the additional SEU rate due to thermal neutrons can be obtained with these ratios. Thus, given the SEU rate from high energy neutrons, multiplying this by the two ratios gives the SEU rate from the thermal neutrons. The total SEU rate will be the combination of the SEU rates from both the high energy and thermal neutrons.

The process for calculating the SEU rate from the thermal neutrons is shown in the following set of equations, (1) to (5).

SEU Rate (Hi E, Upset/dev·h)

$$\Phi_{Hi}\text{ (neutron flux} = 6000\text{ n/cm}^2\text{hr)} \times \sigma\text{(Hi E, SEU X-Sctn. cm}^2\text{/dev)} \quad (1)$$

SEU Rate (thermal neutron, Upset/dev·h)

$$= \text{SEU Rate (Hi E)} \times \frac{\Phi_{therm}\text{(neutron flux)}}{\Phi_{Hi}\text{(neutron flux)}} \times \frac{\sigma\text{(therm SEU X-Sctn.)}}{\sigma\text{(Hi E SEU X-Sctn.)}} \quad (2)$$

Ratio-1

$$= \frac{\Phi_{thermal}\text{(neutron flux)}}{\Phi_{Hi}\text{(neutron flux)}} \quad (3)$$

Ratio-2

$$\frac{\sigma\text{(therm SEU Cross Section)}}{\sigma\text{(Hi E SEU Cross Section)}} \quad (4)$$

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

$$\text{SEU Rate (thermal neutron, Upset/dev·h)} \quad \text{SEU Rate (Hi E neutron Upset/dev·h)} \times \text{Ratio-1} \times \text{Ratio-2} \tag{5}$$

The objective of this PAS is to provide values of Ratio-1, the ratio of the thermal to high energy neutron flux within an airplane, and of Ratio-2, the ratio of the SEU cross section due to thermal neutrons relative to that due to high energy neutrons. We believe that Ratio-1 should be relatively similar in various types of commercial airliners, but it could vary significantly in other types of aircraft, such as military fighters. However, in the larger type of military aircraft, such as AWACS (Advanced Warning and Command System, E-3, which is based on either a Boeing 707-320-B or 767) and JSTARS (Joint Surveillance Target Attack Radar System, E-8C, which is based on Boeing 707-300 airframe), the ratio should be very similar to that in airliners.

With regard to the ratio of the thermal neutron SEU cross sections, until recently, not very many such SEU cross sections were reported in the literature. There were a few, and these were cited in [1], but they were relatively few. Due to the data that has recently become available, the number of devices in which the thermal neutron SEU cross section has been measured has increased significantly. This additional data allows us to have good confidence on the values that have been measured and the resulting average value of the ratio.

2 Thermal neutron flux inside an airliner

2.1 Definition of thermal neutron

Thermal neutrons have been given this name because while most neutrons start out with much higher energies, after a sufficient number of collisions with the surrounding medium, the neutron velocity is reduced such that is has approximately the same average kinetic energy as the molecules of the surrounding medium. This energy depends on the temperature of the medium, so it is called thermal energy. The thermal neutrons are therefore in thermal equilibrium with the molecules (or atoms) of the medium in which they are present.

In a medium that has only a small probability of absorbing, rather than scattering, neutrons, the kinetic energies of the thermal neutrons is distributed statistically according to the Maxwell-Boltzmann law. Therefore, based on this Maxwell-Boltzmann distribution, the neutron kinetic energy that corresponds to the most probable velocity is kT, where T is the absolute temperature of the medium and k a constant. For a temperature of 20 °C, room temperature, this is 0,025 eV. This is based on a highly idealized model of elastic collisions between two kinds of particles, nuclei and neutrons, within a gaseous medium, and so there are departures from it in the real world.

Therefore, even though a neutron energy of 0,025 eV is officially taken to be the true definition of thermal neutrons, for purposes of this PAS, we will consider neutrons with energies < 1 eV to be thermal neutrons. Additional details on this are found in 3.2.

2.2 Overview

In a modern airliner, we know that the thermal neutron flux inside the aircraft should be higher than the thermal neutrons outside of the airplane because of the presence of all of the hydrogenous materials within it (fuel, plastic structures, baggage, people, etc.). The hydrogenous materials "slow down" the high energy neutrons through nuclear collisions, primarily with the hydrogen atoms. After a large number of such interactions, the high energy neutrons (energy > 10 MeV) have had their energy reduced by about seven orders of magnitude. For practical purposes, we consider neutrons with E < 1 eV as thermal neutrons. However, the more accurate definition of thermal neutrons are neutrons with energies close to 0,025 eV (equivalent to those at room temperature, hence the term "thermal"). Thus, we expect, and have seen it verified by measurements, that the high energy neutrons inside an airliner and outside it within the atmosphere would be very similar. However, for thermal neutrons, this is not true. The presence of the airplane structure and its contents produces far more thermal neutrons inside the aircraft than are present in the atmosphere just outside the airplane.

2.3 Background on aircraft measurements

The thermal neutron flux inside an airliner is a rather elusive quantity that has not been measured very often despite the fact that hundreds and in fact thousands of ionizing radiation measurements have been and are currently been made inside of aircraft. Firstly, most of the thousands of measurements are of the dose equivalent that passengers and crew accumulate during flight. Although it varies depending on the location of the flight path, in general, the dose equivalent is approximately (50 to 60) % from the neutrons, about (25 to 35) % from electrons and the remainder from other charged particles, mainly protons (10-20) %, gamma rays (<10 %) and muons (<10 %) [3]. Most of these kinds of instruments measure the combined dose rate from all of the charged particles present in the atmosphere.

Thus, to measure only the neutrons in the atmosphere required a detector system that was sensitive only to neutrons. The early systems that were flown in the 1960s consisted of detectors that were optimized to measure mainly neutrons in the energy range of (1 to 10) MeV. This data was used to develop the simplified Boeing model [4] based on the variation of the (1 to 10) MeV neutron flux with altitude and latitude. The original variation was not with latitude but rather as a function of the vertical rigidity cutoff, a parameter indicating how effective the earth's magnetic field is at any location in allowing the primary cosmic rays to reach the atmosphere. The vertical rigidity cutoff varies mainly with latitude, but there is also a variation due to longitude. Similarly, NASA-LaRC developed a more elaborate model [5] that was also based on the (1 to 10) MeV measurements.

Since that time there have been more recent flight measurements made with neutron-specific instruments that respond to the entire neutron spectrum. These have been primarily a series of Bonner spheres, a set of instruments with a detector that measures thermal neutrons surrounded by varying thicknesses of moderating material. The moderating material, generally polyethylene, is used to "slow down" the high energy neutrons which constitute most of the neutrons, through nuclear interactions with the hydrogen within it. The larger the sphere of surrounding polyethylene the more thermal neutrons are produced and the larger the signal by the detector. Careful calibrations are needed of the set of Bonner sphere detectors before a collection of in-flight measurements can be transformed into neutron fluxes within specific energy ranges. This is a painstaking process and therefore is undertaken by a limited number of research groups.

Two such sets of measurements have been made, one by a NASA-Ames group [6], and the other by a Japanese group [7], and these are used in this evaluation. In addition, the most highly regarded set of such measurements [8] were made by P. Goldhagen of the Environmental Measurements Laboratory (formerly part of DOE, now a part of the Homeland Security Administration). Unfortunately, Goldhagen's measurements were made in an ER-2 aircraft.

The ER-2 is drastically different from a modern airliner. Exacerbating the situation even more, the detector that Goldhagen relied upon for the thermal neutron measurement was located in the very tip of the nose of the ER-2 [9]. For all practical purposes, this detector was located in a part of the airplane that is almost indistinguishable from the atmosphere outside of the airplane. Thus, the thermal neutron flux measured by Goldhagen in the ER-2 is too low compared to what we expect within a large airliner. In this case, we are mainly interested in Ratio-1, i.e., the ratio between the thermal neutron flux and the high energy (E > 10 MeV) neutron flux.

A more recent paper by a group at EADS [10] that used a simpler detector system, again Bonner spheres, but specifically designed to be used in an airliner was examined. Unfortunately, the high energy neutron fluxes from this paper are considered to be far too low to be realistic. Thus, we do not believe that the data collected by this detector system and contained in [10] can be considered to be accurate enough and consistent enough to be used for our purposes of obtaining a reliable and representative value for Ratio-1.

2.4 Calculational approach

There is one paper in the literature [11] that represents a very significant step forward. It is based on applying an elaborate calculational method to a geometry consisting of a large airliner (a 747) and the atmosphere around it. The gross take-off weight of a large 747 is close to 1 million pounds (450 000 kg) and the overall internal volume is approximately 30 000 cubic feet (850 cubic metre) (based on the cargo capacity of cargo versions of the 747). The actual size is therefore enormous (length of aircraft is ~250 ft (~76 m) and wingspan of ~225 ft (~69 m) compared to most structures or vehicles that are modelled for purposes of radiation transport calculations. Out of necessity, the calculation had to simplify the true geometry by orders of magnitude in order to be able to develop the model and carry out the calculations in a relatively short time. As a result, the full aircraft is described as being comprised of approximately 30 smaller volumes, into which the different proportions of the full 1 million pounds are distributed, using gross approximations for the various materials (fuel, baggage, aluminium structure, interior, etc.).

Thus, it is unclear how accurate the results of these calculations are, especially for the thermal neutrons. For the high energy neutrons, it is clear that for most locations the neutron flux should be very similar inside the airplane as it is outside the airplane, and that is true in the results of [11], so this serves as a consistency check. However, for the thermal neutrons, there are no consistency checks. The thermal neutrons are much higher everywhere inside the aircraft compared to outside within the atmosphere, so we have no idea of how accurate a result [11] represents. It may be correct, but it also may be that especially for locations where the electronics are located, a much smaller model, greatly reduced in overall size but much more detailed in terms of the internal structures and the mass distribution that is used, would be needed to calculate the thermal neutron flux accurately.

Therefore, we will use the results from [11, but we will also compare them to the measurements from [6] and [7], to obtain Ratio-1. The results from [11] will represent the upper bound and the results from the in-flight measurements will represent a lower bound.

2.5 Processing of in-flight neutron flux data

For the comparison of in-flight measurements data is taken from four groups, [6, 7, 8 and 10], and in addition the calculations from two other groups, [11] and Armstrong [12] are used. First the measured spectra from the four aircraft measurements are shown in Figure 1, along with the calculated spectrum from [12]. A tabulation of the main features concerning where the measurements were taken and which aircraft were used is given in Table 1.

Table 1 – Tabulation of the various atmospheric neutron measurements used

Researcher	Organization	Detector	Aircraft	Year	Altitude, Ft	Ref.
Goldhagen	EML	Bonner sphere	ER-2	1997	40 000 (12,2 km)	[8]
Hubert	EADS	7-detect spectrometer	A300	2004	34 800 (10,6 km)	[10]
Hewitt	NASA-Ames	Bonner sphere	C-141	1974	40 600 (12,4 km)	[6]
Nakamura	Tohoku U.	Bonner sphere	DC-8	1985	37 000 (11,3 km)	[7]
Armstrong	ORNL	Calculation	Atmosphere	1973	39 000 (11,9 km)	[12]

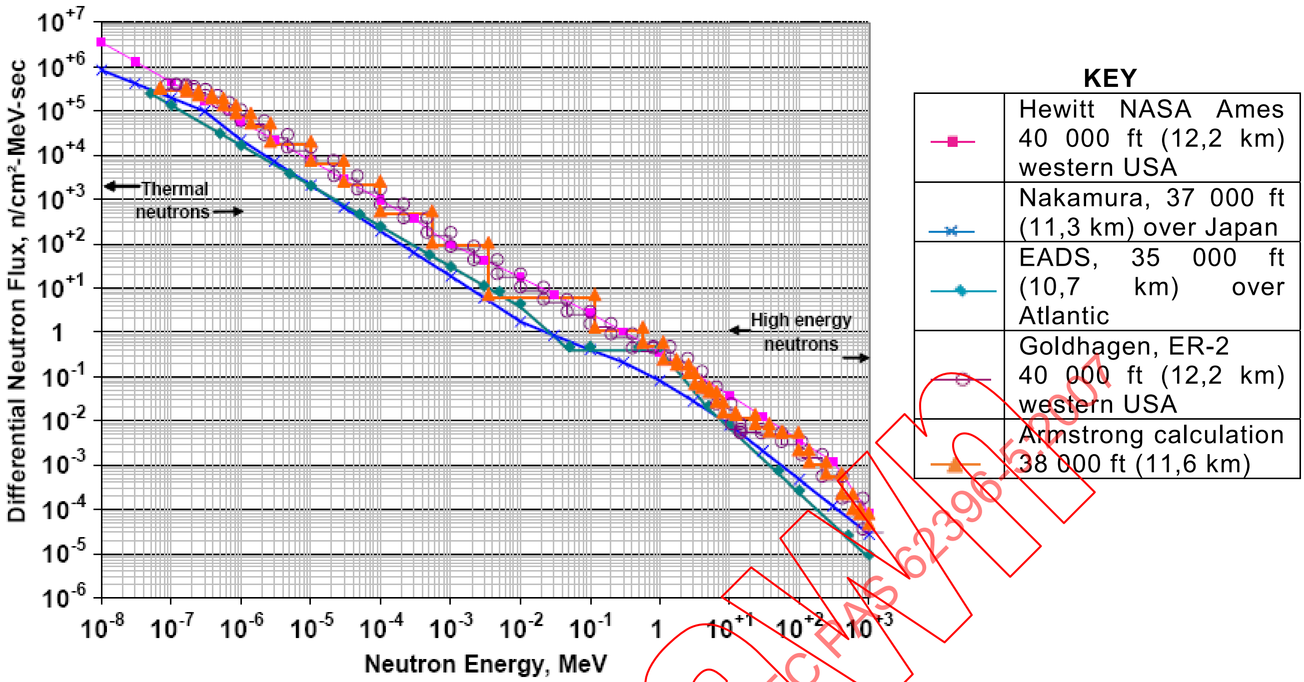

Figure 1 – Atmospheric neutron spectra measured in four aircraft

All of the spectra have relatively similar shapes over 11 orders of magnitude, however two of the spectra seem to be lower than the other three, and these are the in-flight measurements by Nakamura over Japan and by the EADS group over the Atlantic. The differential neutron flux spectrum by Nakamura is lower than the others across the entire spectrum. The reason for this is that the measurements were made in an airplane over Japan. The simplified Boeing model of the neutron flux as a function of latitude and longitude is not adequate to deal with this situation. Taking San Jose, CA as the approximate location for the ER-2 flights, the latitude for San Jose is approximately 37° which is similar to that for Nagoya, Japan, the approximate location for Nakamura's measurements. The earth's magnetic field varies with longitude as well as latitude. Although the variation is small in most locations, for other sites it can be large with the result that two locations very similar latitudes can have significantly different vertical rigidity cutoffs. In the case of these two cities, the rigidity cutoff over Nagoya, Japan is much larger than it is in California, meaning that the cosmic rays are deflected much more over Japan than California and so the atmospheric neutron flux is much lower. Using a recent model by Gordon and Goldhagen for the variation of the atmospheric neutron flux with location [13] that is based on the vertical rigidity cutoff parameter, the net result is that the neutron flux over Japan is a factor of 3 to 4 lower compared to the flux over the western US (factor of 3 compared to San Jose, CA and factor of 4 for Denver, CO). This is based on altitudes of 37 000 ft (11,3 km) for Nagoya, Japan and 40 000 ft (12,2 km) for the western US locations.

Thus if we were to increase the spectrum in Figure 1 by a factor of 3 to 4 to make the measurement over Japan be equivalent to that over the western US, the Nakamura curve would lie right within the NASA-Ames and Goldhagen curves. For this reason, we believe the Nakamura curve is accurate and reliable. The EADS spectrum in Figure 1 is another matter. This measurement was made at 35 000 ft (10,7 km), which represents the lowest altitude of all the in-flight data. Using the model in [13], the spectrum at 35 000 ft (10,7 km), is expected to be lower than that at 40 000 ft (12,2 km) by a factor of 1,5, but this applies over the entire spectrum. As seen in Figure 1, over the (1 to 10) MeV portion of the spectrum, the EADS curve is similar to all of the other curves. However, especially at the highest energies, > 10 MeV, the EADS spectrum is far too low, by about an order of magnitude, so a factor of 1,5 to account for the difference between 35 000 ft (10,7 km) and 40 000 ft (12,2 km) will not improve the situation very much. Thus, the EADS spectrum is judged to be not reliable.

In addition, in looking at Figure 1 carefully and the other three spectra, the two in-flight measurements by Goldhagen and NASA-Ames and the calculated spectrum from Armstrong, there appears to be relatively good agreement except at the higher energies, E > 10 MeV. Above 10 MeV, the NASA-Ames spectrum appears to be noticeably too high.

Using the actual spectra shown Figure 1 in terms of the differential neutron flux, we integrated each to obtain the high energy portion of the neutron flux (E > 10 MeV) and the thermal neutron portion of the flux (E < 1 eV), both in units of n/cm^{2}s. In addition, we include the high energy and thermal neutron fluxes as calculated by Armstrong and also as calculated by Dyer-Lei in [11]. The results are shown in Table 2, and the last column of the table contains the ratio of the thermal neutron flux to the high energy (E > 10 MeV) neutron flux. This is Ratio-1 that we are interested in, as defined in Equation (3). In two cases, we multiplied the original results by a specified factor to make them applicable to 40 000 ft (12,2 km) altitude over the western US, like the measurements of Goldhagen and NASA-Ames.

Table 2 – Comparison of thermal and high energy neutron fluxes and their ratios

Researcher	Altitude ft (km)	Condition	Neutron flux, Hi E (>10 MeV) n/cm²s	Neutron flux, Therm (<1 eV) n/cm²s	Ratio-1, Therm/Hi Energy E
Hubert	34 800 (10,6 km)	A300 over Atlantic	0,13	0,063	0,5
Hubert (×1,5)*	34 800 (10,6 km)	A300 over Atlantic	0,19	0,09	0,5
Goldhagen	40 000 (12,2 km)	ER-2, California	0,74	0,18	0,24
NASA Ames	40 600 (12,6 km)	C-141, western US	1,52	0,21	0,14
Nakamura	37 000 (11,3 km)	Over Nagoya, Japan	0,23	0,11	0,49
Nakamura‡	37 000 (11,3 km)	Over Nagoya, Japan	0,80	0,41	0,49
Armstrong	39 000 (11,9 km)	Calc. -atmosphere	0,94	0,19	0,20
Dyer-Lei	33 000 (10,1 km)	Calc. -atmosphere	0,70	0,1	0,15
Dyer-Lei	33 000 (10,1 km)	Calc, 747, cockpit	1,0	1,75	1,75
Dyer-Lei	33 000 (10,1 km)	Calc, 747, window	1,0	1,70	1,70
Goldhagen	Ground	Bonner Sphere	$3,2\times10^{-3}$	$2,4\times10^{-3}$	0,75

* Multiplied by factor of 1,5 to make equivalent to altitude of 40 000 ft (12,2 km).

‡ Multiplied by factor of 3,5 (equivalent to location over western US at altitude of 40 000 ft (12,2 km).

In looking at Table 2, it is clear that the ratio derived from all of the in-flight measurements are much lower than what was calculated by Dyer-Lei in [11]. The high values of Ratio-1 based on the Dyer-Lei calculations was mentioned in 2.4. In terms of the flight measurements, the data from Hubert and the EADS group, although it gives the highest ratio of all of the in-flight measurements, cannot really be used. We already remarked that the high energy portion of this spectrum seems abnormally low, as seen in Figure 1, so that if the high energy portion were increased by a factor of 2 or 3, Ratio-1 would be reduced by that same factor. Thus, we cannot rely on the Ratio-1 value from the EADS measurements.

With regard to Goldhagen's measurements in the ER-2, the high energy neutron flux appears to be correct, but the thermal neutron flux seems to be too low. This was already discussed in 2.2 and so this results in a value for Ratio-1 that is too low.

The NASA-Ames measurement for the high energy neutron flux appears to be too high. This can be seen in Table 2, but we already commented on this above based on looking at the curve for this spectrum in Figure 1. It is not clear why the high energy portion of the spectrum is too high, but the most likely reason is a problem with the data reduction of the entire set of

Bonner sphere measurements. It could be that the Bonner sphere detectors were not calibrated carefully enough or that the process for reducing the data, which involves convolution of the Bonner sphere response functions, was not carried out carefully enough. Goldhagen, whose ER-2 data is considered by far to be the best set of in-flight airplane measurements, spent several years in reducing his data before publishing them.

The last set of in-flight measurements is that due to Nakamura. The Ratio-1 that his data gives is 0,5. In Table 2, we see that when we multiply his values by a factor of 3,5 (a value between 3 and 4) to adjust the measurements to a location over the western US and at 40 000 ft (12,2 km), we obtain high energy fluxes that are consistent with what Goldhagen measured and what Armstrong calculated. The thermal neutron flux is higher than what Goldhagen measured, but we have already explained why Goldhagen's thermal neutron flux is too low to be applicable to an airliner. Thus, based on the most applicable set of in-flight measurements we have a value of the ratio of the thermal to high energy neutron flux within an airplane as 0,5.

Table 2 also contains the results of the calculations by Dyer-Lei. We use the two most appropriate locations for which we have their data, the cockpit and the window, and also include their point outside the airplane. However, neither the cockpit nor the window is a location where most of the avionics are located. We note that for the external point, there is relatively good agreement between their results and the calculation of Armstrong. For both internal locations, the cockpit and a window, Ratio-1 is high, a value of 1,75 and 1,7 respectively, much higher than the value of 0,5 that was obtained from the in-flight measurements by Nakamura.

As explained in 2.4, it is not clear how accurate the calculated values are. Our main concern is that out of necessity, the geometric modelling was done on such a gross basis, mixing materials (fuel, baggage, structural members, etc.) within very large volumes within the airplane, that there is a lot of uncertainty as to the accuracy of the final results at much more localized positions. Therefore, we propose that an approximate average between the two values of 0,5 and 1,75 be used, which is taken as 1,1, for the value of Ratio-1. However, it could just as easily be taken as 1,0 to simplify matters. Furthermore, based on the calculations, it is certainly possible that there can be some locations in an airliner where Ratio-1 can be as large as 2 or higher.

Table 2 also contains the results of earlier measurements made by Goldhagen at ground level. From this neutron spectrum, the ratio of thermal neutrons to high energy neutrons is 0,75, which is not too different from the value of ratio of 1,1 that we indicated applies to an airliner. However, it is known that at ground level the thermal neutron flux can vary by a factor of 2 due to local conditions (weather, i.e., rain, bodies of water, nature of the surrounding buildings, etc.).

3 Thermal neutron SEU cross sections

3.1 Overview of the issue

It has been known for about 20 years that thermal neutrons can cause single event upsets in microelectronics (see [14] for the earliest reference). About ten years later, this topic was again investigated as part of a way to use a nuclear reactor to simulate the SEU environment posed by atmospheric neutrons to avionics [15]. After that, as the feature size of IC technologies continued to decrease, resulting in a continuing decline in the critical charge of devices, the threat of thermal neutrons to induce SEUs in the devices became more of a problem. This thermal neutron threat was recognized as a potential problem for ICs being used in both avionics and ground level applications. However, only within the last five years have researchers tested devices in both a thermal neutron environment and a high energy neutron/proton environment to allow the two types of SEU cross sections, due to high energy and thermal neutrons to be compared. More of this kind of neutron SEU data is currently available and will be utilized in this chapter.

3.2 Mechanism involved

The thermal neutrons cause single event upsets because of their interaction with the Boron-10 isotope within the IC (glassivation layer over the silicon), rather than with the silicon atoms. B-10 is about 20 % of naturally occurring boron, with the remaining 80 % being B-11 which does not interact with the thermal neutrons. The boron is usually present as borophosphosilicate glass, BPSG, which is also used as the dielectric between the metallization layers in the overlayer that covers the silicon transistors.

The reaction that is responsible for the increased SEU rate due to thermal neutrons is:

$$^{10}B + \text{neutron} \rightarrow {}^{7}Li \text{ (0,84 MeV)} + {}^{4}He \text{ (alpha, 1,47 MeV)} + \text{gamma (0,48 MeV)}$$

This reaction creates two energetic ions, Li-7 and an alpha particle, both of which can deposit enough energy to cause an upset in devices having low critical charges (deposition of the complete 0,84 MeV from the Li-7 ion in silicon leads to 37 fC of charge).

As used by microelectronics manufacturers, the BPSG layers are comprised of 4 to 9 % of boron. The range of the Li-7 and the 1,47 MeV alpha is relatively short, ~ 3 µm so only a portion of the track of these particles would be effective in depositing enough charge locally to cause an upset. However, the IC devices also contain boron in much lower concentrations through other constituents on the die (e.g. the p dopant). For that reason, the thermal neutron SEU cross section from these other boron sources would be reduced by 2 to 3 orders compared to that in BPSG and hence may be ignored.

In 2.1, for the purposes of this PAS, we defined thermal neutrons to be those with energies of < 1 eV even though the formal definition of a thermal neutron is one having an energy of approximately 0,025 eV. There are practical reasons for this revised definition, for example, the way that calculated and measured neutron fluxes inside an aircraft are displayed, using a finite number of energy groups (see Figure 1).

However, there are also physics considerations. The tendency of a material to interact with a neutron is called the neutron cross section, which is measured in the unit of barns (1 barn = 10^{-24} cm^2). The silicon atom has a total neutron cross section of approximately 2 to 3 barns for most of the 10 orders of magnitude of the energy range, 0,01 eV to 100 MeV, with only slight deviations. For boron, it is drastically different; the neutron cross section increases with decreasing energy because of the behaviour of the cross section of the B-10 atom with energy. For natural boron, the total neutron cross section at 1 eV is ~100 barns (~600 barns for Boron-10), but at 100 eV it is only 12 barns and at 0,1 eV it is 400 barns. At an energy as low as 1 eV, the neutron cross section is 50 times higher in a boron atom compared to that in a silicon atom (and more than 200 times higher for Boron-10). Thus, we can say that the low energy neutrons, all those with E < 1 eV, will behave in a similar manner when interacting with a microelectronics device. There is a > 99,5 % probability that for such low energy neutrons the interaction will be with the Boron-10 rather than with a silicon atom.

In addition, there is another reason why 1 eV serves very well as the thermal energy cutoff. There are two kinds of thermal neutron facilities that have been used for testing: 1) one which produces only low energy thermal neutrons, such as a specialized reactor at the National Institute of Standards and Technology, NIST, and 2) a facility that has neutrons over a broad spectrum of energies, including thermal neutrons. For the broad spectrum facility, testing for the thermal neutron SEU response is carried out by performing two tests with a microelectronics device. In one test, the device and/or test card is bare, exposed to the beam and the resulting number of upsets are recorded. In the second test, the device is covered with an efficient thermal neutron absorber material, usually a thin foil or sheet of cadmium metal or a boron compound, and the test is repeated. Cadmium is used because it is such a good absorber of thermal neutrons below an energy of ~0,4 eV which is often called the cadmium cutoff (its neutron cross section changes from 20 barns at 1 eV, 200 barns at 0,5 eV and 7 000 barns at 0,2 eV). Thus, the difference in the response of the device with and without the cadmium is due to the thermal neutrons. The fact that the cadmium cutoff of ~0,4 eV is so close to 1 eV makes the energy of 1 eV a good value for the thermal energy cutoff.

3.3 Thermal neutron SEU cross sections and Ratio-2

The earliest testing of RAMs with thermal neutrons to induce SEUs [14] was carried out over 20 years ago and the results are not very relevant because the devices are so old and are no longer in use. Nevertheless, the results provide an interesting basis for comparison. Seven SRAMs were tested in the NIST reactor (then called NBS) with a high purity thermal neutron beam and only one of them exhibited upset, the SEU cross section being 2×10^{-14} cm^2/bit. In addition, eight DRAMs were tested and three of them had upsets induced by the thermal neutrons, but the SEU cross section was about two orders of magnitude lower compared to the SRAM.

The testing carried out by Sandia in their SPR-III (Sandia Pulsed Reactor) is reported on in [15]. Six SRAMs were tested and in all cases the SEUs were induced by the thermal neutrons. The normal neutron spectrum in the central cavity at the SPR-III reactor was modified by using polyethylene around the cavity to produce additional thermal neutrons. Based on the data provided in [15] the thermal neutron SEU cross sections for the six SRAMs are in the range of 6×10^{-15} to 6×10^{-14} cm^2/bit. It is unclear whether additional devices were tested that did not exhibit SEUs due to the thermal neutrons.

There has been more recent testing performed on SRAMs in which SEUs have been induced by both thermal neutrons and high energy (> 10 MeV) neutrons. This is the data of greatest interest because it enables us to tabulate Ratio-2, the ratio of the SEU cross section due to thermal neutrons relative to that due to high energy neutrons. In Table 3, we compile this data and note that the testing was performed at diverse facilities, with the only requirement being that the data contain the results of measurements of neutron-induced SEU cross sections caused by both high energy and thermal neutrons. In some cases, the high energy SEU measurements were made by using a high energy proton beam rather than a high energy neutron source. In most cases, the thermal neutron contribution was obtained as the result of two measurements, with and without a thermal neutron absorber surrounding the device or test card being exposed to the neutrons.

The last row contains the average for all of the measurements, however, it includes only the data in which a non-zero thermal neutron SEU cross section was measured. Thus, the two Hitachi parts that had no response to thermal neutrons (rows 3 and 4 in the table) were not included in the averaging process. When all the ratios were combined and averaged, the value of Ratio-2 is 2,7. All of the data in Table 3 is for SRAMs. It is likely to also apply to other kinds of devices, but almost all of the devices that have been tested for SEU susceptibility with thermal neutrons are SRAMs.

Another important factor that comes out of the data in Table 3 is how likely it is for a SRAM to be susceptible to SEUs from thermal neutrons. Ref 18 tested six SRAMs and four of them were susceptible to thermal neutrons inducing SEUs, thus 67 % were susceptible to thermal neutron SEU. In [19], a total of 14 SRAMs were tested and of these 8, or 57 % were susceptible to SEUs from thermal neutrons and in [20] three of the five, or 60 % of the SRAMs tested were susceptible to SEUs from thermal neutrons. [18 and 19] are the two studies in the open literature with the largest number of devices tested for susceptibility to thermal neutron induced upsets. In combination, they lead to the conclusion that an average of 60 % of currently available SRAMs are susceptible to SEUs from thermal neutrons.

We have heard that major microelectronics vendors are aware of the problem of thermal neutrons inducing upsets in their devices, and have committed to eliminate this problem by removing the use of BPSG in the IC fabrication process where it can lead to SEUs from the thermal neutrons. Another option for the IC vendors is to use 100 % B-11 rather than naturally occurring boron in the BPSG. Furthermore, smaller IC vendors may not follow the larger companies in eliminating the B10 from their fabrication processes. However, the major IC vendors proceed, the changes they make will affect future devices, making it likely that most such devices will not be susceptible to SEUs from thermal neutrons. However, as shown in Table 3, right now, for devices that are likely in avionics systems at the present time (2007), the assumption has to be that at least half, actually 60 % of all SRAM devices are sensitive to thermal neutrons causing upsets.

Table 3 – SRAM SEU cross sections induced by thermal and high energy neutrons

Device	**Mfr.**	**DC/Feat Size**	**Ref.**	**Hi E SEU X-Sect†,** cm^2/bit	**Therm. neut SEU X-Sec,** cm^2/bit	**Ratio-2, Therm/Hi E SEU X-Sec**
TC554161AFT	Toshiba	N A / N A	16	$7,3\times10^{-15}$	$1,15\times10^{-14}$	1,57
N/A	N/A	N/A/0.18	17	$2,90\times10^{-14}$	$1,12\times10^{-13}$	3,6
HM628512ALP-7	Hitachi	9809/0,5	18	$6,0\times10^{-14}$	0	0,00
HM628512BLP-7	Hitachi	9925/0,35	18	$4,5\times10^{-14}$	0	0,00
TC54001FL	Toshiba	9827/0,5	18	$8,20\times10^{-15}$	$8,70\times10^{-15}$	1,06
TC54001AF	Toshiba	9929/0,4	18	$7,50\times10^{-15}$	$2,70\times10^{-15}$	0,36
M5M5408AFP	Mitsubishi	9839/0,4	18	$1,88\times10^{-13}$	$1,80\times10^{-13}$	0,96
KM684000BLP	Samsung	9844/0,	18	$6,90\times10^{-14}$	$2,10\times10^{-13}$	3,04
CY62147V18LL	Cypress	0036/0,5	19	$3,00\times10^{-13}$	$1,80\times10^{-13}$	6,0
K6F1616U6A	Samsung	0208/0,25	19	$1,00\times10^{-14}$	$2,00\times10^{-14}$	2,0
M5MY416CW	Mitsubishi	N/A/0,18	19	$4,00\times10^{-14}$	$2,40\times10^{-13}$	6,0
0Y62147CV33LL	Cypress	0225/0,16	19	$4,00\times10^{-14}$	$1,80\times10^{-13}$	4,5
CY62157DV18LL	Cypress	0311/0,13	19	$4,00\times10^{-14}$	$3,00\times10^{-14}$	0,8
HM62V16512LB	Hitachi	0251/0.13	19	$2,50\times10^{-14}$	$2,50\times10^{-14}$	1,0
HM62V162100LB	Hitachi	0328/0,13	19	$3,00\times10^{-14}$	$1,10\times10^{-13}$	3,7
K6X4016C3F	Samsung	0307/0,13	19	$5,00\times10^{-15}$	$1,0\times10^{-14}$	3,0
8 other devices	Various	2002-03/ 0,13 to 0,25	19	10^{-14} to 10^{-13}	0	0
CY7C1360A	Cypress	0231/0,25	20	$3,07\times10^{-14}$	$5,1\times10^{-14}$	1,8
IBM0436A81	IBM	0139/0,25	20	$4,85\times10^{-14}$	$2,41\times10^{-13}$	5,1
MCM69P737	Motorola	9823/0,4	20	$6,66\times10^{-15}$	$1,62\times10^{-14}$	2,4
K7B803625M	Samsung	0019/?	20	$1,20\times10^{-15}$	0	0
K7A803600M	Samsung	0016/?	20	$1,24\times10^{-15}$	0	0
Average all non zero data						2,77

† The high energy neutron SEU cross section is based on the best data available in the reference, with priority being given to neutron measurements (WNR or TRIUMF) and then high energy proton measurements.