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PRE-STANDARD

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

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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)

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

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

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

Ratio-1

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

Ratio-2

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

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[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]