

Incorporation of Atmospheric Neutron Single Event Effects Analysis into a System Safety Assessment

2011-01-2497

Published
10/18/2011

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doi:[10.4271/2011-01-2497](https://doi.org/10.4271/2011-01-2497)

ABSTRACT

Atmospheric Neutron Single Event Effects (SEE) are widely known to cause failures in all electronic hardware, and cause proportionately more failures in avionics equipment due to the use altitude. In digital systems it is easy to show how SEE can contribute several orders of magnitude more faults than random (hard) failures. Unfortunately, current avionics Safety assessment methods do not require consideration of faults from SEE. AVSI SEE Task Group (Aerospace Vehicle Systems Institute Committee #72, on Mitigating Radiation Effects in Avionics) is currently coordinating development of an atmospheric Neutron Single Event Effects (SEE) Analysis method. This analysis method is a work in progress, in close collaboration with SAE S-18 and WG-63 Committees (Airplane Safety Assessment Committee). The intent is to include this method as part of current revisions to ARP4761 (Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment).

INTRODUCTION

Atmospheric radiation is an issue for avionics designers today, with every indication of becoming a greater issue in the future. Atmospheric radiation causes Single Event Effects (SEE) in electronics, resulting in various system failure conditions, including hazardous misleading information. SEE within avionics systems, induced by the atmospheric neutron environment, have been known and documented since 1992 [1].

To ensure a system meets all its safety and reliability requirements, SEE induced upsets and potential system failures need to be considered. A proposal has been submitted to SAE for the incorporation of an atmospheric neutron single event effects analysis method as part of the ARP4761 airborne system safety assessment guidelines. The proposed SEE analysis would be used in conjunction with other analyses to provide a consistent and quantitative method for incorporating SEE into the systems safety assessment process; to be utilized as part of a Preliminary System Safety Assessment (PSSA) and System Safety Assessment (SSA). Specifically, atmospheric radiation induced faults should be considered in addition to the random failure rates to provide a complete safety analysis. The outcome of this analysis may indicate that mitigation is necessary, which may result in employing a single approach or a combination of strategies.

There are several key reasons why the risk of SEEs in avionics electronics systems is increasing. First, technology is trending towards smaller feature sizes, higher densities, and lower voltages, resulting in greater sensitivity to atmospheric radiation. Second, the number of memory bits and registers in a typical system are greatly increasing. Third, the number of flights at higher altitudes is increasing due to better aircraft efficiency. And finally, the number of polar flights is increasing.

There are a number of industry specifications and standards in use today to provide systems designers with background information on the radiation environment, general information on SEE, and testing methods. Most notably for the avionics industry is the International Electro Technical Committee (IEC) TS/62396 [4]. This technical specification

informs avionics systems designers, electronic equipment, component manufacturers and their customers of the kind of ionising radiation environment that their devices will be subjected to in aircraft, the potential effects this radiation environment can have on those devices, and some general approaches for dealing with these effects. There are also several JEDEC Standards addressed SEE Testing; including JESD89-A Test Method for Beam Accelerated Soft Error Rate, and JESD89-1A Test Method for Real-Time Soft Error Rate [3].

This proposal for a SEE analysis method has been put forward by a task group with the Aerospace Vehicle Systems Institute (AVSI). AVSI is a cooperative of aerospace companies, with Department of Defense and Federal Aviation Administration representatives, working to improve the integration of complex subsystems in aircraft. The purpose of AVSI is to connect industry members, government agencies, and academia in an effort to accomplish cooperative research and development within the avionics industry. AVSI is a research center of the Texas Engineering Experiment Station; a member of the Texas A&M University System.

AVSI consists of various task groups; all focusing on issues facing avionics systems today. The AVSI SEE Task Group (AVSI #72-on Mitigating Radiation Effects in Avionics) focuses on the atmospheric radiation effects on current and future aircraft avionics systems and electronic devices. The AVSI SEE Task Group has recommended that SEE analysis be considered as a formal part of the airborne system development process. Specifically, AVSI SEE Task Group has recommended technical content for review by the SAE S-18 and WG-63 committees in the development of an Atmospheric Neutron Effects Analysis Method for the System Safety Assessment Processes.

ATMOSPHERIC RADIATION

Cosmic radiation, including high energy neutrons, is constantly showering the earth. Galactic cosmic rays and solar rays hit the earth's atmosphere, interact with oxygen and nitrogen atoms, and produce particle cascades of secondary radiation. This secondary radiation leads to a high flux of energetic particles, including protons, neutrons and pions. Of the possible secondary particles, neutrons have been shown to be mainly responsible for causing single event upsets (SEUs) in memories and other devices in aircraft since the early 1990s. Neutrons interact with the silicon structures of a component and release energy that can change the state of a bit.

While the flux density varies with global position, altitude and solar activity, all surface locations are exposed to this radiation, including ground level. Typical commercial airliners operate up to 40,000 feet, where the flux density is in the range of 300 to 450 times greater than at sea level. This results in greater incidences of SEEs for avionics equipment compared to ground based equipment. [Figures 1](#) and [2](#) are data from Dr. Eugene Normand, Boeing Radiation Effects Lab, and relate the atmospheric neutron flux as a function of both altitude and latitude. The information in these two diagrams is often referenced when discussing SEEs and the atmosphere.

Altitude variation of atmospheric neutrons derives from competition between various production and removal processes that affect how the neutrons and the initiating cosmic rays interact with the atmosphere. The result is a maximum in the flux at about 60,000 feet, called the Pfozter maximum. [Figure 1](#) provides a comparison of the neutron flux at different altitudes.

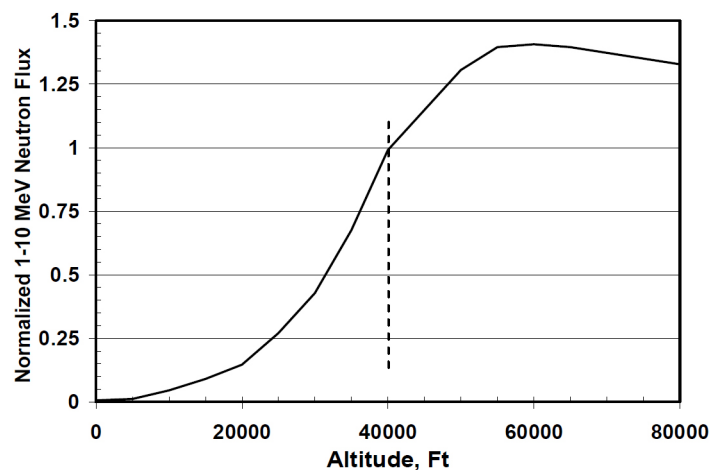


Figure 1. Simplified model of atmospheric neutron flux variation with altitude - Re-plotted from associated graph in [1].

Although altitude is the largest single factor driving atmospheric neutron flux, latitude is also very important. The variation with latitude, as shown in [Figure 2](#), is due to the bending of primary particles' trajectory by the earth geomagnetic field; increasing by a factor of six between equatorial latitude and the high latitude polar-regions.

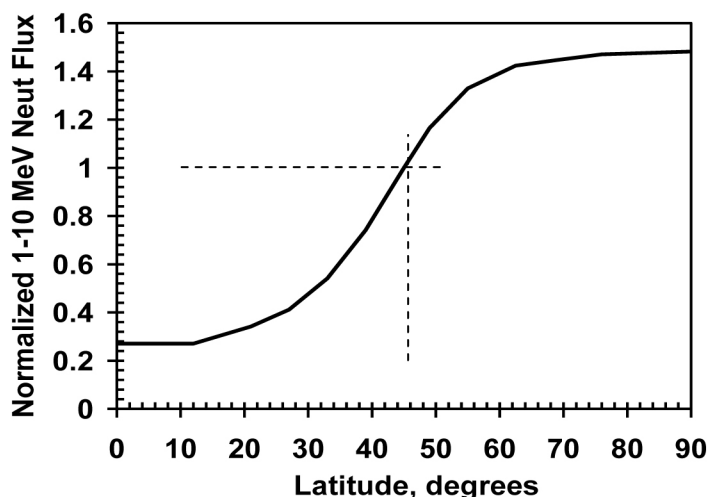


Figure 2. Simplified model of atmospheric neutron flux variation with latitude - Re-plotted from associated graph in [1].

The energy variation of atmospheric neutrons is usually presented by plotting the differential flux (flux per unit energy interval) as a function of energy, which is often called the spectrum. Neutron spectrum measurements at altitude are more complex than the neutron flux measurements at altitude and latitude, but they have been made and are in good agreement with detailed and elaborate neutron transport calculations. The energy spectrum of atmospheric neutrons is shown graphically in IEC/TS 62396-1 [4].

The level of atmospheric radiation is also dependent on the sun. During a typical 11-year sunspot cycle, the sun produces about 100 severe coronal mass ejections (CMEs) or solar flares, and about four extreme CMEs into the solar system--only a fraction of which usually hit the Earth. Particles from these solar flares 'typically' have energies much lower than particles produced by galactic cosmic rays from outside the solar system. During periods of low solar activity the surface of the sun is comparatively stable and the particles produced 'normally' contribute very little (< 2%) to the resulting secondary neutron particle creation in the atmosphere. But during times of high activity, large solar flares occur. These can produce large numbers of high energy solar energetic particles over a period of a few hours; creating SEE rates from 30 to 300 times normal. Documented occurrences have been rare over the last 60 years, and therefore this should be considered a specific risk.

During the solar maximum period, the sun's magnetic field pushes out away from the sun shielding the earth from galactic particles; the atmospheric neutron flux decreases. Conversely, during the solar minimum, the magnetic field collapses and is not effective at deflecting galactic particles, and the atmospheric neutron flux increases.

SINGLE EVENT EFFECTS

Single event effects are caused by a single particle, most likely a neutron, and can take on various forms. The definition of a single event is the disturbance of an active electronic device, such as a transistor, caused by the energy deposited in a device by a single energetic particle. The effect is caused when a radiation generated ionization charge exceeds the device's critical charge. There are various types of these events, but they all are the result of a single particle depositing sufficient energy to cause a disturbance in an electronic device. A typical event occurs when a neutron collides with a Si nucleus with the resulting recoil causing an ion to be ejected from the Si nucleus.

When charged particles lose energy by ionizing the medium through which they pass, they create a path of electron-hole pairs. These electron-hole pairs collect at the source and drain of a transistor, and produce a current pulse. While the majority of the neutrons passing through a microelectronic device will have no impact, if the particle deposits enough charge, a malfunction of the device results; the state of a node can change from logic 1 to logic 0 and vice versa.

Various failure modes in electronic systems can occur, such as data corruption or unplanned events. Additional types of undesirable effects may include:

- damage to hardware
- corrupted software residing in volatile memory
- corrupted data in memory
- microprocessor halts and interrupts
- writing over critical data tables

The industry trend is for continued decreases in component feature size and operating voltages, while the number of gates on a given device continues to increase. As this trend continues to deep sub-micron gate lengths the expected critical charge decreases and the expected sensitivity to radiation increases. Note that extrapolating the level of susceptibility and resulting behavior of future IC technologies from older devices cannot be guaranteed without measurement.

There are various types of SEEs which result in different types of failure modes. These include single and multiple event upsets, latch-up, transients, single event functional interrupts, and burn out. Hardware can be damaged, as in the case of a burn out or gate rupture, but most often the failures are non-destructive. Single event upsets are the most common type of event. Under current IC technology conditions, many devices are being fabricated with feature sizes of 90nm, 65nm and below. At this technology point, many SRAMs are experiencing multiple cell upsets (MCU) in which a single

neutron interaction leads to two or more physically adjacent cell upsets.

Single event latch-up (SEL) is another area of a concern. Latchup is caused by a charged particle creating a localized short circuit across the device. When the condition occurs, there is a loss of device functionality due to a single event induced high current state. Often the device is not permanently damaged, but power cycling is required to resume normal device operation.

Table 1 provides definitions for the most common types of SEEs. A fault due to atmospheric radiation is considered an independent event. Due to the randomness of the neutron energy, event time, and event location, and the highly localized nature of an SEE, faults are independent and rates are probabilistic.

Table 1. SEE Types

Single Event Effect Type	Circuit Response
Single Event Upset (SEU)	<i>A change of state in a memory bit or latch</i>
Multiple Bit Upset (MBU)	<i>An upset to more than one bit in the same binary word.</i>
Multiple Cell Upset (MCU)	<i>Occurs when multiple bits are upset in several physically adjacent bits in an IC, but in different binary words.</i>
Single Event Transient (SET)	<i>A spurious signal or voltage propagating through a circuit path during a single clock cycle.</i>
Single Event Functional Interrupt (SEFI)	<i>A single event effect in a complex device such that a control path is corrupted, leading the IC to cease to function properly.</i>
Single Event Latchup (SEL)	<i>A condition that causes the loss of gate or device function or control due to an induced high current state. May or may not cause permanent fault/failure, but requires power cycling to return the IC to normal operations if undamaged.</i>
Single Event Burnout (SEB)	<i>A condition which can cause device destruction due to a high current state in a power semiconductor device.</i>

SEE ANALYSIS PROCESS

The development of highly reliable and available systems requires consideration of both the occurrence of single event effects and the impact they have on system performance. The proposed *Atmospheric Neutron Single Event Effects Analysis* provides guidance for performing an SEE evaluation for avionics systems to be used in conjunction with other systems analyses in the context of a complete systems safety analysis; providing a consistent and quantitative method for incorporating SEE into an existing safety assessment. By

obtaining this information, mitigation can then considered, if deemed necessary. SEE mitigation solutions can be implemented at the chip, subsystem and system design levels.

The proposed analysis method consists of an SEE investigation to be performed for each semiconductor integrated circuit (IC) within a system. Figure 3 provides an overview of the process for performing this SEE evaluation for a system. The process includes assessing each component in the design for radiation sensitivity, obtaining the neutron cross section for sensitivity in each device, incorporating the IC effect rates, determining mitigation requirements, and finally summarizing the total SEE faults for the system.

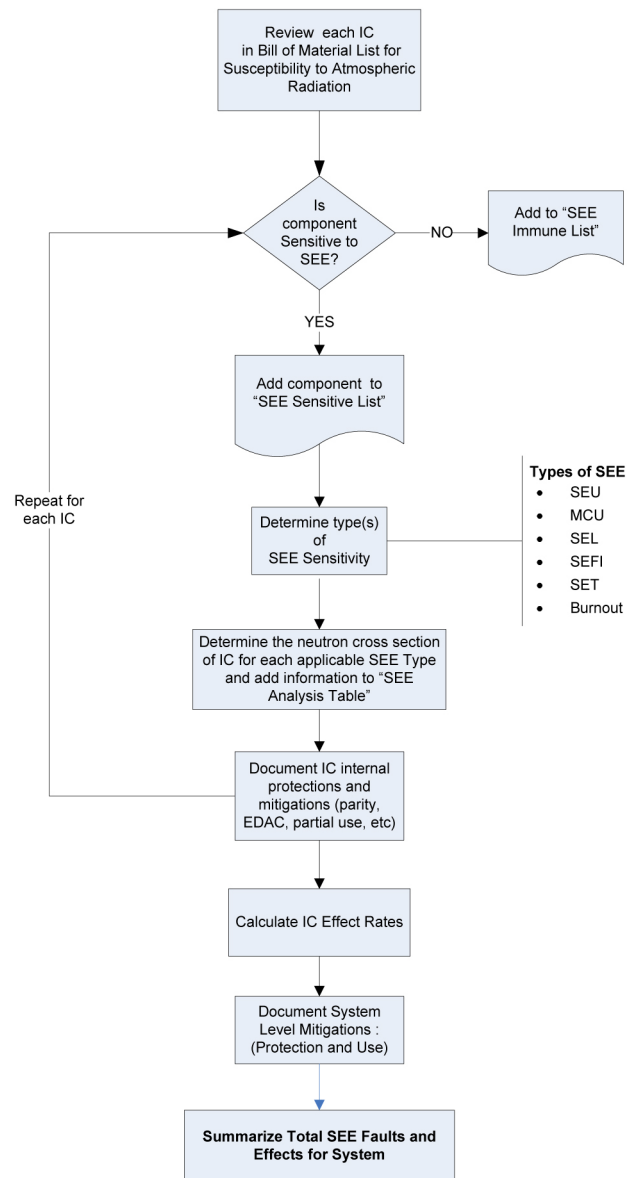


Figure 3. SEE Analysis Process Flow

The process begins with a review of the complete list of microelectronics devices for the system under consideration; this can be found in the Bill of Materials (BOM) or parts list. An evaluation of each IC component determines if it is sensitive to atmospheric radiation in one or multiple ways. Once all devices have been categorized, an evaluation of the sensitive devices is performed.

Data is gathered for each sensitive device to determine the type(s) of sensitivities to neutrons, and the cross section for each SEE type.

The SEE response of a component is characterized as the SEE cross section of that component. The SEE rate, as provided in the Technical Specification IEC TS 62396-1 [4], is calculated as follows:

$$SEE \text{ rate per device} = 6,000 [n/cm^2/hr] * SEE \text{ cross section } [cm^2/\text{device}]$$

The cross section is a figure of merit that establishes how sensitive the component is to the effects of atmospheric radiation. The different types of effects, such as SEU or SEL, will have different cross sections.

Next, system level information is obtained from the designers and/or design tools for the operation of the system. For simple microelectronics, used functions and capabilities are straightforward, but for complex devices, such as microprocessors, FPGAs, SRAMs or DRAMs, the used functions, capabilities, and amounts of RAM may not be straight forward. Mitigations would then be associated with the specific utilized function. Any mitigation that has been employed needs to be documented and accounted for when determining the failure rates due to SEE.

The process ends with the summarization of the faults and system level effects due to SEEs. This information can then be incorporated into a safety assessment process.

To incorporate the SEE data, the atmospheric radiation induced faults should be combined with random failure rates to provide a complete safety analysis. The sum of both SEE and random failure rates provides the overall failure rate for the system.

The next section describes the proposed content for the Atmospheric Neutron Single Event Effects Analysis method.

SEE ANALYSIS GUIDANCE APPENDIX FOR ARP4761

As previously mentioned, SEE are a class of faults that should be included as part of the Safety Assessment processes. A new appendix to ARP4761 is being proposed and developed to provide guidance for the Safety Analyst. This appendix is currently intended to provide general and

specific guidance on: parts needing SEE investigations; how to calculate SEE fault rates; identifying SEE mitigations, and types of data and information to be reported.

EVALUATE THE BOM

Diverse technical information is needed to carry out a SEE evaluation of an avionics system. The complete list of microelectronics devices must be obtained (BOM), and supplemented with additional IC device data.

Semiconductors are the only devices known to be sensitive to SEE. Although some very high voltage ($\sim > 200V$) Field Effect Transistors (FET's) might be prone to SEB, the most risk is associated with integrated circuits (IC's) that may be sensitive to the effects summarized earlier in Table 1.

SEE Immune IC's

The neutron SEE analysis should be carried out on only those microelectronics that have a potential for interacting with atmospheric neutrons and inducing a failure via a single event effect. If a number of IC devices can be identified as being immune from neutron-induced SEE for various reasons, it will be beneficial to eliminate them at the outset.

There are classes of devices which are immune to most forms of SEEs; several examples include high current bipolar transistor devices that have not shown sensitivity to SEE and ICs without memory elements that are not sensitive to SEU and MBU. While SEE sensitive IC's are usually built using Complimentary Metal Oxide Semiconductors (CMOS), there are some CMOS process variations that do not have specific sensitivities. For Example, Silicon-On-Insulator (SOI) CMOS is immune to latchup and SEL will not be an issue. Some IC's do not have the circuit structures that make them sensitive to some SEE. For IC's with heavy ion test results (sometimes done for space programs), those devices shown to have a linear energy transfer (LET) "threshold" (lowest LET causing SEE) $> 15 \text{ MeV-cm}^2/\text{mg}$ will be immune from neutron-induced SEE; some examples may be found in [2].

Multiple Sensitivities in an IC

For devices that are not immune to SEE, multiple effects must be considered. Any given IC may have sensitivities to SEU, SEL, SET, and SEFI. Additionally, complex IC's may have multiple sensitivities to SEU and MBU from various different RAM blocks, flip-flops, buffers and latches.

Flash memory blocks are frequently included in complex devices, and **Flash SEU immunity cannot be assumed for state-of-the-art technologies**. Although still much less sensitive than SRAM, Multi-Level Cell (MLC) NAND flash is a flash memory technology using multiple electrical levels per physical flash cell, allowing more bits to be stored in that cell. MLC NAND Flash can be particularly more sensitive to