

Incorporating Atmospheric Radiation Effects Analysis into the System Design Process

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ABSTRACT

Natural atmospheric radiation effects have been recognized in recent years as key safety and reliability concerns for avionics systems. Atmospheric radiation may cause Single Event Effects (SEE) in electronics. The resulting Single Event Effects can cause various fault conditions, including hazardous misleading information and system effects in avionics equipment. As technology trends continue to achieve higher densities and lower voltages, semiconductor devices are becoming more susceptible to atmospheric radiation effects. To ensure a system meets all its safety and reliability requirements, SEE induced upsets and potential system failures need to be considered.

The purpose of this paper is to describe a process to incorporate the SEE analysis into the development like-cycle. Background on the atmospheric radiation phenomenon and the resulting single event effects, including single event upset (SEU) and latch up conditions is provided. The approach to assess radiation effects susceptibility of components and the evaluation of SEE impacts on system functionality is described. The process includes a radiation analysis plan, parts assessment, radiation effects susceptibility evaluation, and a radiation effects report.

CITATION: Dominik, L., "Incorporating Atmospheric Radiation Effects Analysis into the System Design Process," *SAE Int. J. Aerosp.* 5(1):2012, doi:10.4271/2012-01-2131.

INTRODUCTION

Single event effects (SEE) can cause various failure conditions, including data corruption and system faults. Since aircraft electronics were first demonstrated to be susceptible to errors induced by cosmic rays in 1992, the topic of the resulting SEE in avionics equipment has become progressively important. [1] Government and customer specifications increasingly require assessments of the single event effects probability in electronics from atmospheric neutrons.

The purpose of this paper is to describe a process to incorporate the SEE analysis as part of a system development process. The atmospheric radiation environment and resulting SEE are reviewed. An approach to assess radiation effects susceptibility of components and the evaluation of SEE impacts on system functionality is described. The process includes a radiation analysis plan, parts assessment, radiation effects susceptibility evaluation, and a radiation effects report.

The following are several reasons why the risk of SEEs in avionics electronics systems is increasing:

- Technology is trending towards smaller feature sizes, higher densities, and lower voltages; resulting in greater susceptibility to atmospheric neutrons

- The number of memory bits and registers are greatly increasing
- The number of flights at higher altitudes is increasing due to better efficiency
- The number of polar flights is increasing

Atmospheric Radiation Environment

Cosmic radiation is constantly bombarding the earth. When cosmic ray particles penetrate the magnetic fields of the earth and reach the earth's atmosphere, they collide with atomic nuclei in the air and create secondary radiation which leads to a high flux of various energetic particles. For each primary cosmic ray entering the atmosphere, many more secondary particles are created. The secondary particles include neutrons, protons and pions, all of which can cause SEE in electronics. At the altitudes flown by modern aircraft, neutrons are the main area of concern and have been shown to be most responsible for causing Single Event Upsets (SEU) in aircraft electronics.

The neutron flux varies with global position, altitude and solar activity, but all surface locations are exposed to this radiation. Where typical commercial airliners operate the flux density is approximately 300 times greater than at sea level. This results in greater incidences of SEE for avionics

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.

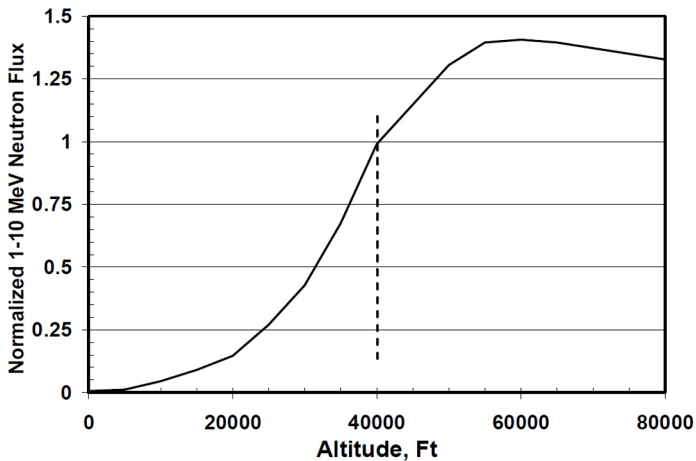


Figure 1. Simplified model of atmospheric neutron flux variation with altitude - Re-plotted from associated graph in [1].

Although altitude is the largest single factor driving atmospheric neutron flux, latitude is also 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.

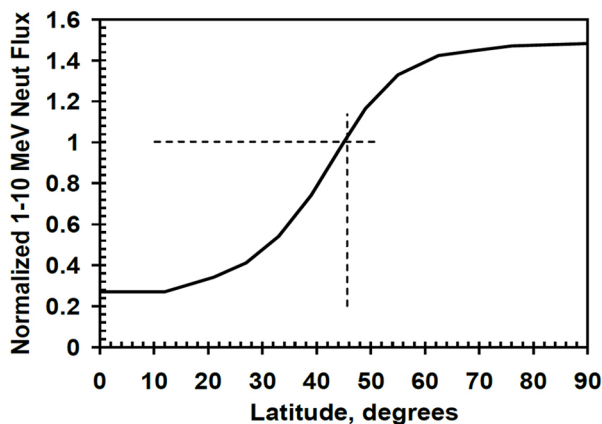


Figure 2. Simplified model of atmospheric neutron flux variation with latitude - Re-plotted from associated graph in [1].

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 [2].

Single Event Effects

Single event effects caused by atmospheric radiation are a design issue for avionics systems, as well as for high reliability ground-based systems. These effects are the result of a single particle, most often a neutron and can take on various forms, such as bit flips, functional interrupts and latch up.

Types of undesirable effects include:

- corrupted logic residing in volatile memory
- corrupted data in memory
- microprocessor halts and interrupts
- unplanned events, including loss of mission
- damage to hardware

Specifically, SEE is a disturbance of an active electronic device caused by energy deposited from the interaction with a single energetic particle. The effect is caused when a radiation generated ionization charge exceeds a device critical charge. Because secondary neutrons are uncharged they do not generate ionization directly. Rather, the neutrons collide with atoms in the electronic device, normally silicon atoms, momentum is transferred and the recoiling charged ion generates ionization. The probability for an SEE to occur at a particular energy is determined by the device cross section for that effect. Deposited charges, through the recoils they create within a sensitive portion of a device, result in malfunction of the device.

There are various types of these individual events, but all are the result of a single particle depositing sufficient energy to cause a disturbance in an electronic device. These events include Single and Multiple Event Upsets, Single Event Latch-up, Single Event Transient, Single Event Functional Interrupts, burn out and gate rupture. Hardware can be damaged, as is the case of a burn out or gate rupture, but most often the failures are non-destructive.

The definition of SEE encompasses all of the potential effects on a semiconductor device caused by the interaction of a single element of radiation, in this case secondary neutrons. The different types of SEE are defined in Table 1. When measuring a system's susceptibility to radiation, the components, the probability of exposure, and the functional unit criticality all need to be taken into account.

Table 1. SEE Types

Single Event Effect Type	Circuit Response
Single Event Upset (SEU)	A change of state in a memory or latch in a device induced by the energy deposited by an energetic particle.
Multiple Cell Upset (MCU)	Occurs when the energy deposited in the silicon of an electronic component by a single ionising particle induces one or more bit upsets in several physically adjacent bits in an IC.
Multiple Bit Upset (MBU)	Occurs when the energy deposited in the silicon of an electronic component by a single ionising particle causes upset to more than one bit in the same word.
Single Event Transient (SET)	In digital and analog circuits, a spurious signal or voltage propagating through a circuit path during a single clock cycle.
Single Event Functional Interrupt (SEFI)	A single event upset in a complex device such that a control path is corrupted, leading the IC to cease to function properly.
Single Event Latchup (SEL)	A condition that causes the loss of gate or device function or control due to a single event induced high current state. May or may not cause permanent failure, but requires power cycling to return IC to normal operations if undamaged.
Single Event Burnout (SEB)	A condition which can cause device destruction due to a high current state in a power semiconductor device.

Not every upset or event that propagates through a system will result in a fault. For example, if a fault occurs in an unused part of the system, there is no effect. Those faults that do propagate through the system result in either a detected or undetected error. The types of faults which can occur include:

- Soft error - nondestructive and recoverable; generally affects storage elements, such as memory, latches and registers. Worst case effect results in hazardous misleading information (HMI).
- Hard error - not recoverable by software reset and requires removal of power to recover normal operation.
- Hard failure - results in loss of function in the device and the need for device repair. An example of a hard failure in a memory cell is a gate or dielectric rupture which permanently damages the device.

RADIATION 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 radiation effects analysis process assesses the radiation

effects susceptibility of the components and their impact on system performance. This includes radiation effects analysis, test of electronic devices, integrated circuits and systems, and identification of mitigation options. This information can then be utilized when performing a system safety and reliability assessment.

The process begins during the program planning and ends with a Radiation Effects Report delivered to the safety analysis team to be utilized for both the Preliminary System Safety Assessment (PSSA) and the System Safety Assessment (SSA). First, an Atmospheric Radiation Analysis Plan needs to be included in the planning for a new program, which could be a new product development, system upgrade, or parts obsolescence program. The radiation analysis begins with the assessment and classification of all components included in an initial parts list or Bill of Materials (BoM). A review of the information results in either the need for an evaluation or a determination that the assessment is acceptable and can be directly incorporated into a safety assessment.

If an evaluation is required, each susceptible part is assessed as described later in this paper and existing component and system mitigations are taken into account. When this phase of the evaluation is complete, a determination is made on whether testing is needed for any of the critical and susceptible parts where no data is currently available. All test results are incorporated in an updated evaluation and the data from a Radiation Analysis Report is utilized in the safety assessment.

The diagram shown in [Figure 3](#) outlines the steps involved in a radiation effects analysis process. The data is analyzed, cross-sections of the susceptible components are determined, and an impact analysis on system operation is performed. With this information, the need for and the degree of mitigation can be determined. If necessary, testing is performed. When the evaluation is complete, SEE faults and system effects are summarized.

There are a number of industry specifications and standards in use today to provide systems designers with background information on the atmospheric radiation environment, general information on SEE, and testing methods. Most notably for the avionics industry is the International Electro Technical Committee (IEC) TS/62396 - Part 1 [2]. This technical specification informs avionics systems designers, electronic equipment and component manufacturers, and their customers of the type of ionising radiation environment that their devices are subjected to in aircraft, the potential effects this radiation environment can have on those devices, and some general approaches for dealing with these radiation effects.