SINGLE EVENT EFFECTS TEST FACILITY AT OAK RIDGE NATIONAL LABORATORY

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Abstract

Increasing use of microelectronics of ever diminishing feature size in avionics systems has led to a growing Single Event Effects (SEE) susceptibility arising from the highly ionizing interactions of cosmic rays and solar particles. Single event effects caused by atmospheric radiation have been recognized in recent years as a design issue for avionics equipment and systems. To ensure a system meets all its safety and reliability requirements, SEE induced upsets and potential system failures need to be considered, including testing of the components and systems in a neutron beam. Testing of integrated circuits (ICs) and systems for use in radiation environments requires the utilization of highly advanced laboratory facilities that can run evaluations on microcircuits for the effects of radiation. This paper provides a background of the atmospheric radiation phenomenon and the resulting single event effects, including single event upset (SEU) and latch up conditions. A study investigating requirements for future single event effect irradiation test facilities and developing options at the Spallation Neutron Source (SNS) is summarized. The relatively new SNS—with its 1.0 GeV proton beam, typical operation of 5000 h per year, expertise in spallation neutron sources, user program infrastructure, and decades of useful life ahead—is well suited for hosting a world-class SEE test facility in North America. Emphasis was put on testing of large avionics systems while still providing tunable high flux irradiation conditions for component tests. Makers of ground-based systems would also be served well by these facilities. Three options are described; the most capable, flexible, and highest-test-capacity option is a new stand-alone target station using about one kW of proton beam power on a gas-cooled tungsten target, with dual test enclosures. Less expensive options are also described.

Introduction

This paper describes the atmospheric radiation environment, resulting effects of radiation on electronics, and proposes building an additional US neutron beam facility to provide resources needed for atmospheric radiation testing of semiconductor devices and electronic systems.

Galactic cosmic rays and solar rays constantly penetrate the earth's atmosphere and produce particle cascades, consisting mainly of neutrons, which can interact with the silicon structure in a semiconductor device and cause adverse behavior. The energy level associated with these atmospheric neutrons are considered high energy (HE), i.e., above 1 million electron-volt (MeV) and up towards 1 billion electron-volt (GeV). Such neutrons have been associated with causing Single Event Effects (SEE) in electronics – a known safety and reliability issue for avionics equipment [1]. Testing at an accelerated flux neutron beam facility is performed to quantify the susceptibility of a device to atmospheric radiation and in the parts selection process. This test data is necessary to evaluate the effects of atmospheric radiation at both the component and system levels, and is used as an input into the system safety analysis.

Typical commercial airliners operate at up to 40,000 feet, where the atmospheric neutron flux is approximately 300 times greater than at sea level. The effects from radiation can result in various failure conditions, including hazardous misleading information and system failures. There 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. These result in lower critical charge and greater susceptibility to atmospheric radiation. Furthermore, the number of memory bits and registers are greatly increasing, the number of flights at higher altitudes is

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increasing due to better efficiency, and the number of polar flights is increasing. The flight path trends are to locations of higher neutron flux.

Testing enables designers to characterize the device, as well as measure the effectiveness of design mitigations and protections. Characterizing the radiation susceptibility of components and systems necessitates accelerated testing at a high energy neutron facility. Avionic industries require timely access to such test facilities to ensure the reliable operation of the continually evolving systems and components.

Cognizant of the potential effects of SEE on aircraft systems and equipment, the Federal Aviation Administration (FAA) is contemplating new guidance material addressing atmospheric radiation. The FAA recognizes that existing facilities have insufficient test capacity to meet the resulting demand; desires more flexible irradiation capabilities to test complete, large systems; and would like capabilities to also address thermal neutrons. To date, the testing has been focused on the effects of high energy neutrons. With the addition of Boron-10 into the manufacturing process of ICs, there is a need to test the device susceptibility for thermal energy neutrons as well. For these reasons, the FAA funded a study by Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) with the purpose to develop options for a SEE test facility using high-energy neutrons at the SNS complex.

This paper incorporates the results of that study in proposing a cosmic ray neutron simulation facility be built at the SNS facility of ORNL. This facility would provide improved availability of a powerful and capable test beam in a facility that is the one of the world's most intense pulsed accelerator-based neutron sources.

This paper proposes that a new Cosmic Ray Neutron Simulation Facility be built to meet the growing demands for SEE testing. This test facility is needed to provide sufficient test capacity for the various safety/reliability critical industries, provide thermal energy testing, and would accommodate the component and system level testing needs of the avionics industry.

This paper provides an overview of the atmospheric radiation environment and resulting SEE; a review of the current status of test facilities; and the reasons why an additional neutron beam is recommended. Finally, the options for the design of the neutron beam at ORNL are summarized. The complete report “Definition of Capabilities Needed for a System Test Facility”, prepared by ORNL, is now available to the public [2]. An FAA version is also accessible at:

http://www.tc.faa.gov/its/worldpac/techrpt/tc15-16.pdf .

ORNL has the two of the world's highest performing neutron sources – the High Flux Isotope Reactor, and a pulsed accelerator-based neutron source – the SNS. The SNS is a new and state of the art facility for condensed matter research which provides world-class neutron scattering capabilities [3]. This facility is currently operational and reliably delivering neutrons for about 5000 hours per year to its user community. The addition of testing capability for SEE would only require an expansion to the existing facility as the existing accelerator is well-suited to produce neutron test beams with a HE spectrum closely matching that in the atmosphere.

SEE effects can cause various failure conditions in electronic systems, such as data corruption or unplanned events, up to and including system failure. 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;
- unplanned events, including loss of mission.

Today, technology is trending towards smaller feature sizes, higher densities, and lower voltages. As semiconductor technology further progresses below the 100-nanometer scale, the likelihood of occurrence of SEE is increasing to the point that the reliability of future aerospace electronic systems will be impacted.

Component level testing is needed for determination of semiconductor device cross section. The cross section rate of a component is a measure of its susceptibility to radiation. This measure enables analysis of the device susceptibility, an important factor in the analysis of the SEE rate. Currently, system level atmospheric radiation testing is unavailable. The addition of system level test capability is needed to enable evaluation of system failure modes as well as mitigation effectiveness.

There is also a growing need for thermal neutron testing; recent tests of static random-access memory (SRAM) devices in the 65 to 45 nanometer range were shown to be highly susceptible to thermal neutrons [4][3]. In addition to causing SEE directly, the high-energy neutrons can lose energy by collisions and produce low-energy neutrons by a process called thermalization. Thermal neutrons are low energy neutrons that have scattered sufficiently to be in thermal equilibrium with their surroundings. In this context, thermal energies are those roughly from 25 to 200 milli electron-volts (meV).

The majority of the thermal neutrons inside the aircraft are created by the interaction of the atmospheric HE neutrons with the aircraft structure, its fuel and passengers, and other contents. Thermal neutrons can be significant because they have a very high probability of interacting with certain material isotopes – such as Boron-10 (^{10}B), that are found in some microelectronics. In the ^{10}B case, energetic alpha particles are produced with the interaction which can then deposit charge in the device and cause an upset bit.

Atmospheric Radiation

When cosmic 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 energetic particles. For each primary cosmic ray entering the atmosphere, many more secondary particles are created. The secondary particles include neutrons, protons, muons and pions.

Neutrons are the secondary cosmic particles that have been shown to be most responsible for causing single event upsets in aircraft electronics. Specifically, these neutrons are a result of the cosmic rays interacting with oxygen and nitrogen atoms in the earth's upper atmosphere. The charged and neutral particles combine creating an ionizing radiation environment in the atmosphere. The flux varies with global position, altitude and solar activity, but all the earth's surface locations are exposed to this radiation.

Neutron flux levels vary, with the flux at the poles greater than at the equator. Atmospheric neutron energies range from 1 to 1000 MeV and are able to interact with silicon-based technologies. The flux reaches a maximum around 60,000 feet and decreases by approximately two orders of magnitude down to sea level.

Typical commercial airliners operate up to 40,000 feet, where the flux is approximately 300 times greater than at sea level. The flux is dependent on several factors, including latitude, but the largest single variant is altitude. The variation with latitude is due to the shielding provided by the earth geomagnetic field; increasing by a factor of six between equatorial latitude and the high latitude polar-regions. Shown in Figures 1 and 2 are data from Dr. Eugene Normand, Boeing Radiation Effects Laboratory, and relates the atmospheric neutron flux as a function of both altitude and latitude [5].

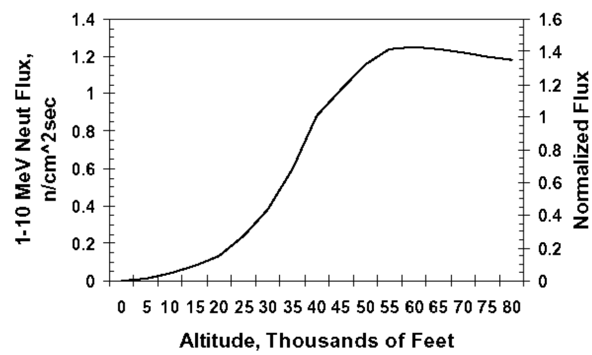

Figure 1. Atmospheric Neutron Flux vs. Altitude (Source: Dr. Eugene Normand, Boeing).

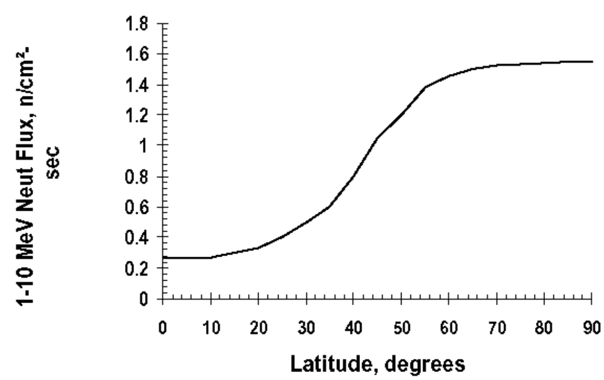

Figure 2. Atmospheric Neutron Flux vs. Latitude (Source: Dr. Eugene Normand, Boeing).

The level of atmospheric radiation is also dependent on the sun. The sun's activity varies with a period of 11 years. During periods of low activity its surface is comparatively stable, but during times of high activity, large solar flares occur, producing large numbers of high energy energetic particles over a period of a few hours. These particles produce secondary neutrons when they interact with the atmosphere. During very large solar events it has been calculated that the flux can rise by several hundred times over nominal values. Indeed, observations during an extreme February 1956 solar flare were 300 times above nominal [6].

Single Event Effects

SEE disturbances can take on various forms. The effects are the result of energy deposited within the device by a single particle interacting with the device. While the majority of the primary and secondary neutrons passing through an electrical component will have no impact, those that strike silicon atoms can flip bits. These high-energy particles are not blocked by the aircraft structure.

High-energy particles interacting in electronics lose energy by ionizing the medium through which they pass, creating a path of electron-hole pairs behind. These electron-hole pairs collect at the source and drain of a transistor, and produce a current pulse. If the particle deposits enough charge, through the recoils it creates within a sensitive portion of a device, a malfunction of the device results; the state of a node can change from logic 1 to logic 0 and vice versa.

Among the resulting single event effects are: damage to data in memory, microprocessor halts, over-written critical data tables and unplanned events, including loss of mission. For an avionics system, an error can propagate through a run-time operational flight program causing erroneous outputs from flight-critical systems. To ensure a system meets all its safety and reliability requirements, SEE induced upsets and potential system failures need to be considered.

An SEE can manifest itself in several ways. 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. The events can cause a momentary or permanent change in the state of a 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. Consideration of each SEE type is useful as an input to the design phase, when determining mitigation techniques, and the part selection process.

Single Event Upset (SEU) is the most common type of a single event effect. An SEU is caused by the deposition of charge in a device that is sufficient to change the logic state of a single bit. Multiple Bit Upsets (MBUs) occur when a single high energy neutron upsets several bits in a localized area. Devices susceptible to SEUs commonly contain memory bits, register bits or latches.

A single event functional interrupt (SEFI) occurs in a complex device such that a control path is corrupted, leading the IC to cease to function properly. Often induced from SEU in control registers of a complex device and recovered by reset or power cycle.

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

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. Many component parameters are scaled as technologies are downsized: gate length, junction size, junction depth, doping concentrations, oxide thickness, and power supply voltage. The gate length is frequently the defining characteristic of a technology [7].

As this trend continues to deep sub-micron gate lengths, component designs are achieving higher densities and lower voltages, resulting in smaller active charge regions. In general, for decreasing feature size of silicon based cells, the expected critical charge decreases and the expected sensitivity to radiation increases. Subsequently, process geometries in the new ICs are shrinking and memory elements are holding less charge leading to increased SEE susceptibility to neutrons. Figure 3 shows is an example of the relationship of the semiconductor feature size to error rates.

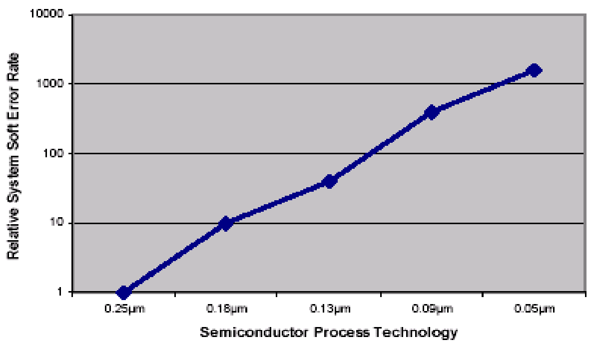

Figure 3. From Semico Research Corporation, "Gate Arrays Wane While Standard Cells Soar: ASCI Market Evolution Continues".

Current Status of SEE Testing

The aerospace industry has been aware of SEE effects for the last several decades. There are currently several accelerator based neutron testing facilities to enable 'accelerated' reliability testing of components for the atmospheric radiation environment. The Weapons Neutron Research (WNR) facility at Los Alamos National Laboratory currently provides an accelerated neutron test beam which closely matches that of the cosmic ray neutrons in the atmosphere. The Los Alamos accelerator facility – operating since 1972 –added a second beam line for SEE testing in recent years. However, as the demand for this facility has consistently increased, accessibility to this facility has become an escalating problem for the variety of industries and companies that want to use it for testing their devices in a simulated neutron environment. The other available facilities do not provide a similar energy spectrum. The ISIS Facility, located in the United Kingdom at the Rutherford Appleton Laboratory, produces neutrons used almost exclusively for neutron scattering experiments for materials science [8]. A new project at ISIS will establish a test facility purposefully designed for SEE testing that was initiated in response to the recognized need for additional facilities.

The continued growth in atmospheric radiation testing demand, from the avionic and other safety/reliability industries, will further tax the current facilities. A new test facility in North America would provide a solution to this bottleneck, offering neutron beams to meet the atmospheric radiation testing demands of industry. The design would include needed beam capabilities beyond what exist today, and greater test time availability. Other SEE test user applications are likely, such as providers of high-reliability ground based systems, or space based system application.

Reasons for the ORNL facility

Both industry requirements and regulations are being updated to address the changing SEE issue. Additional emphasis is being placed on analysis and safety impacts. This on-going work in the aerospace industry continues to define SEE, the impact to electronic systems, and provide the guidance to deal with the results. Listed below are several of the aerospace industry organizations which continue to address the topic of atmospheric radiation effects.

- International Electrotechnical Commission, IEC [9]
- GEIA Avionics Process Management Committee (APMC) [10]
- Aerospace Vehicle Systems Institute (AVSI), Project #72: Mitigating Radiation Effects on Current & Future Avionics Systems
- JEDEC Solid State Technology Association [11]

The JEDEC Solid State Technology Association and the Electronic Industries Alliance (EIA) have published two versions of the standard entitled "Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices". These are JESD89 (July 2001) and JESD89A (October 2006). This document provides the standard requirements and procedures for terrestrial soft error rate testing of integrated circuits, both from the atmospheric neutrons and the alpha particles emitted by the IC package. Basic test methodologies, processes and beam parameters are also provided. An update to the JESD89A is currently in development.

Another standards body that has been working on this issue is the IEC. This organization prepares and publishes international standards for electronic and related technologies. The IEC TC107 single event effects working group, Avionics Process Management, was set up to investigate integrated circuit susceptibility to atmospheric radiation effects, and as a result a series of IEC Technical Standards has been produced. At this time IEC TS 62396 Parts 1 through 5 are available. The document provides guidelines for single event effects testing for avionics systems. The initial technical information for the specifications was authored by AVSI Task Group #72 members. Two additions to the IEC 62396 standard are currently in development; Part 6 - Extreme Space Weather, and Part 7 - Process for Incorporating Radiation Analysis into the System Design Process.

The SAE International Group is currently updating the ARP4761 System Safety Assessment Guidelines and will be including the SEE topic in the APR4761A with the addition of an AIR - *Development of Atmospheric Neutron Single Event Effects Analysis for use in Safety Assessments*.

Regulatory agencies are also addressing the SEE issue. EASA has issued a notification of a proposal to issue a Certification Memorandum CM-AS-004 Issue 01, Subject: "Single Event Effects (SEE) Caused by Atmospheric Radiation." The document addresses – "Certification Considerations and an Analysis Method to Demonstrate the Acceptability of Effects on Aircraft, Engine, APU and Propeller Systems and Equipment, caused by Atmospheric Radiation". The FAA has a project specific SEE issue paper.

Availability and timely access to Los Alamos has been an on-going issue, with oversubscription and reduced experiment windows a common occurrence. The facility schedule currently allows for component testing for less than six months per year and the facility has no system level testing capability. The issues with accessibility and timeliness to the facility impacts product development schedules. Also, as other industries have increased their testing requirements, access issues will continue to grow. Continued operations of the accelerator depend on multiple funding agencies, most critically the National Nuclear Security Administration. Recently the Office of Science funded neutron scattering part of the facility closed.

Increasing the overall capacity and test scope is critical to the aviation industry. These improvements are vital as the semiconductor industry continues to develop components that have short production cycles causing the need for additional testing of obsolescence replacement parts in addition to new product development. The addition of a US based neutron beam test facility at ORNL has been proposed previously [12] to provide the needed capability. The SNS is ideally suited for such expansion.

Characteristics of the SNS facility include:

- A 1-GeV, 1.4-mA (1.4 MW) short pulse (< 1 μs) spallation neutron source;
- 1-GeV protons (over 86% of c) are incident on a liquid mercury target producing ~26 neutrons/proton ($2x10^{14}$ protons/pulse on target @ 60 Hz);
- Neutrons are moderated, or slowed down, in 3 supercritical hydrogen (20 K) moderators and 1 light water moderator;
- The SNS is a relatively new accelerator facility with decades of expected future life;
- About 5000 hours of neutron production is scheduled each year;
- SNS operational availability has been > 90%;
- The primary neutron scattering mission serves a large number of users from around the world, hence user access and support are established parts of operations.

SEE Test Facility Options at the SNS

After investigation of current SEE test practices and assessing future testing requirements, three concepts were identified covering a range of test functionality, neutron flux levels and fidelity to the atmospheric neutron spectrum. The costs and times to complete each facility were also estimated. SEE testing is generally performed by accelerating the event rate to a point where the effects are still dominated by single events and double event causes of failures are negligible. In practice, acceleration factors of as high as 10^6 are applicable for component testing, whereas for systems testing acceleration factors of 10^4 seem to be the upper limit. It is strongly desirable that the irradiation facility be tunable over a large range of high-energy neutron fluxes of 10^2-10^4 for systems testing and from 10^4-10^7 n/cm^2/s for components testing.

Option 1: High Energy-neutron Test Station (HETS)

A complete and flexible SEE irradiation station is proposed around a green-field dedicated target station that would require only a kilowatt-level proton beam incident on a gas-cooled tungsten spallation target. Named the High Energy neutron Test Station (HETS) – this target station would house two independent HE irradiation test areas and would allow for placing additional beam ports for other applications if required. The facility would sit between the SNS accumulator ring and water tower as illustrated in Figure 4. This location has minimal interference with underground site infrastructure, and necessary utility connections are close by.

Figure 4. CAD model of the High Energy neutron Test Station superimposed on an aerial photo of the Oak Ridge Spallation Neutron Source site.

The required proton beam can be extracted from the SNS beam transport line by laser stripping of the accelerated negative hydrogen ion beam. Extraction would take place prior to primary beam injection into the accumulator ring as shown in Figure 5. Laser stripping is a proven technology that was developed at SNS and regularly used in production systems [13]. HETS operation would be unnoticeable by neutron scattering users at the 1.4 MW SNS target station. The H^- beam laser stripping technique would allow for fine control of beam power on the HETS target independent from power delivered to the SNS.

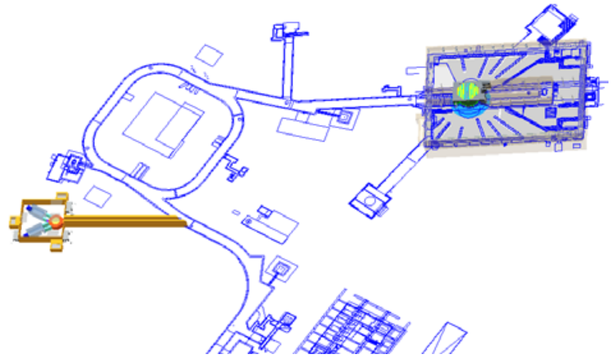

Figure 5. Location of beam extraction from main SNS H^- beam for HETS.

A compact, helium-cooled tungsten rod is envisioned as the spallation source target. Energy deposition and thermal calculations indicate a modest helium flow can easily keep maximum tungsten temperature below 150°C. Despite the relatively low power, the HE beams require substantial shielding to allow for unrestricted access around the target monolith and test enclosure boundaries. Allowing space for neutron moderators, collimators, filters, beam shutters and other components along the neutron beam lines, the outer radius of the target monolith is approximately 4 m. Computer model illustrations of the facility concept are shown in Figure 6.

Large systems with frontal areas of up to 1×2 m^2 placed at 14 m from the target could be accommodated in the test enclosures which are situated at +/- 30° off of the incident proton beam direction. Integral HE (above 10 MeV) flux values over this area above 10^4 n/cm^2/s are achievable. An operating mode for components (at 5 m) with flux levels up to 10^7 n/cm2/s on beam sizes of up to 0.2×0.2 m^2 is provided. Selectable moderating material and neutron filters would allow tailoring of the neutron spectrum to user demands; charged particle deflectors could be switched to allow or deflect protons, pions, and muons.

The absolute normalized neutron flux spectra are shown in Figure 7. Assuming that the component irradiation area is positioned at 5 m distance from the target, a mean proton beam power of 1.35 kW is necessary to obtain the peak above-10 MeV flux levels.

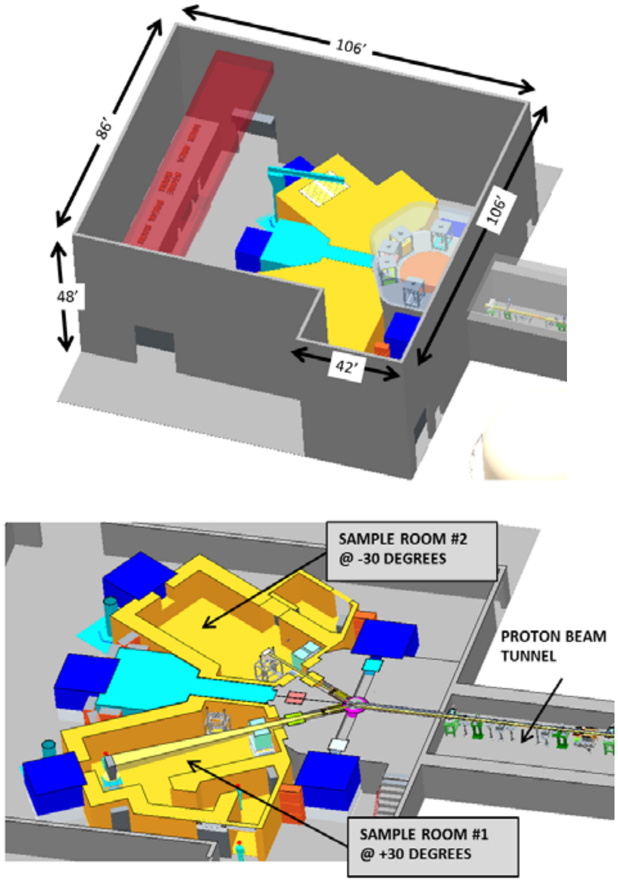

Figure 6. HETS target station layout.

A thermal component in the neutron spectrum can be generated by placing hydrogenous materials at the target. Figure 7 also shows the addition of a thermal beam component for a target surrounded with a 2.5 cm thick water layer compared to a bare target, and also for a configuration that had the target and water layer additionally surrounded by 30 cm of beryllium. Here, the simulated beams were extracted at 30° off the incident proton direction. The water layer not only builds up the thermal spectrum, but also reduces the 0.1–10 MeV hump caused by the evaporation stage of the spallation reaction. The water layer plus beryllium reflector configuration exhibits a thermal-to-above-10-MeV ratio of 0.9. IEC Technical Standard 62396-5 summarizes the current research on thermal neutron flux (below 1 eV) in commercial airliners to be at levels about 0.2–2 times the HE neutron flux (above 10 MeV).

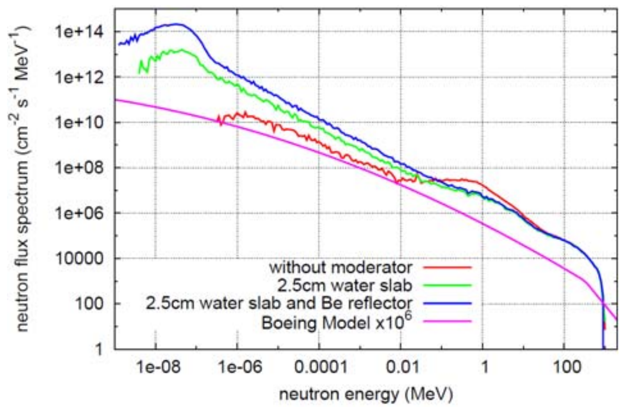

Figure 7. Neutron spectrum at 30° from a 1 kW 1 GeV proton beam incident on a bare tungsten target, from a 2.5 cm water slab at the tungsten target, and from a 2.5 cm water slab at a reflector surrounded by beryllium, to a 30 cm radius, at a tungsten target.

It is estimated that HETS would take 5 years to complete after award of contract, including engineering design and construction. Commissioning would take at least another 6 months. Interference with SNS principal operations was not considered in the construction time estimate; connection of the proton transport line and tunnel from the accelerator high energy beam transport (HEBT) and construction around existing site utilities would require careful planning and coordination with neutron scattering operations at the SNS. HETS is the most expensive option proposed in the study, with a cost to complete of approximately $100 million.

Option 2: SNS Beam Line Instrument / Test Facility

A HE neutron test facility using an available beam line on the SNS target station is a technically and financially attractive option. Inspired by the new ChipIR instrument [14] on the ISIS TS-2 spallation source in the UK, a similar facility could be placed on an unused beam line in the SNS instrument hall. The performance would approach that of an HETS, but it would be operationally more limited, with only a single user at a time. Space is more limited, so the maximum system size (placed at 24 m) would be about half of that in an HETS. While this concept was not as fully explored and characterized, preliminary work indicates very high HE flux levels should be possible, with ample thermal neutrons as well. Estimated neutron spectra are shown in Figure 8.

Flux control would be more difficult than at HETS because proton power on target will be whatever the SNS is operating at for neutron scattering. Neutron attenuation devices would have to be employed with as-yet undetermined control resolution. However, no new buildings would be needed, and the necessary utilities are already present in the SNS Experiment Hall. A CAD layout figure of a test facility on beam line 8 is shown in Figure 9.

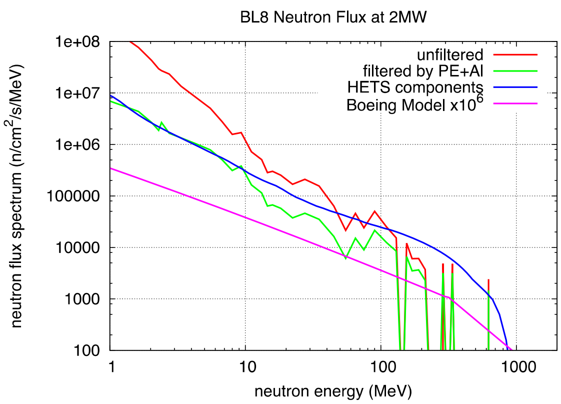

Figure 8. High-energy neutron flux spectra at SNS beam line 8 at 9 m distance from the moderator compared to the Boeing model and the HETS option.

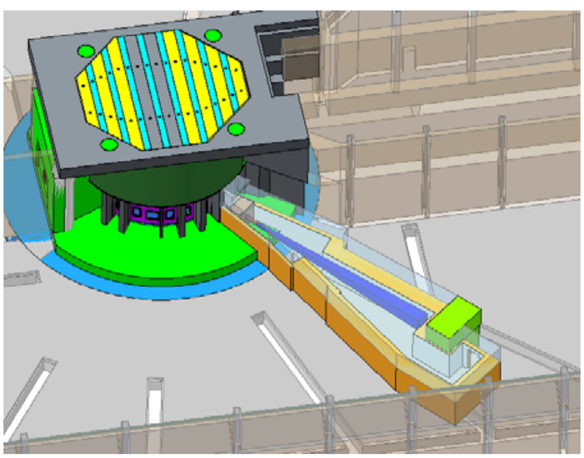

Figure 9. Views of a proposed BL-8 SEE test instrument; existing neutron scattering instruments have been removed for clarity.

The estimated cost for a beam line option is around $15 million; the time to complete would be 3 years after award of contract, plus at least 6 months for commissioning. Interference of construction activities with SNS operations should be negligible. However the presently open beam lines are highly desirable locations for proposed neutron scattering instruments and obtaining one of them for an SEE test facility will come only with persuasive and timely arguments to SNS leadership and its funding sponsor.

Option 3: High Energy Neutron Cave (HENC)

A third option proposed is a tunnel extension/target cave facility providing the most basic system-level irradiation capability with minimal flexibility. Again not as well developed a concept as HETS, it would also use a laser-stripping technique and redirect protons to a tunnel similar to the initial HETS proton transport tunnel. Indeed, this concept is intended to be upgradable to a full HETS facility.

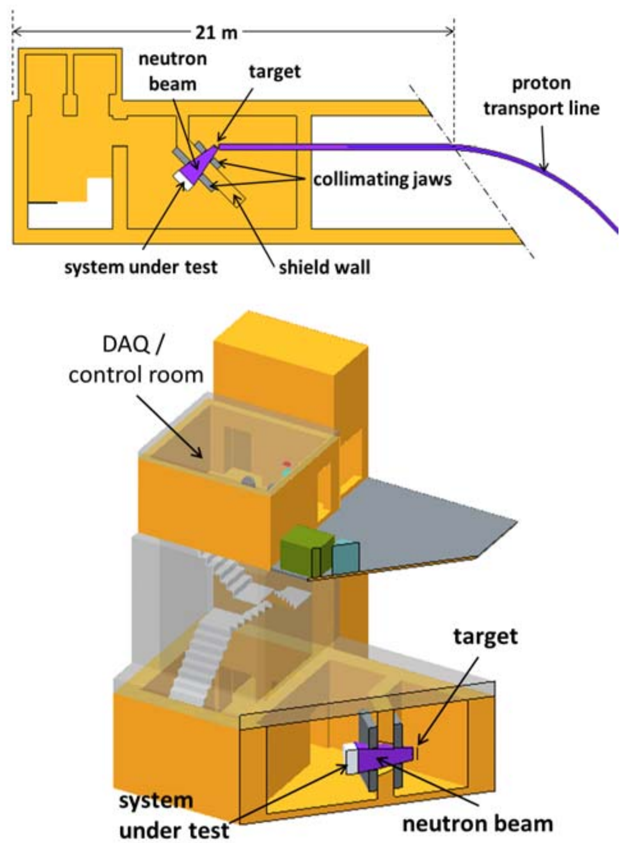

Figure 10. HE neutron tunnel / cave facility plan (T) and isometric (B) sections.

The target and testing area would be staged in the tunnel (the cave) as illustrated in Figure 10. Background radiation and area activation would be reduced by separating the target and testing area by a 60-cm-thick high-density concrete shield wall. In addition, 30 cm thick vertical and horizontal jaw collimators at the upstream and downstream side of the wall are proposed. This shielding configuration will allow some tailoring of the beam size to the needs of the experimenter and reduce background radiation. Neutron beam monitoring and diagnostics would be located at the downstream side of the shielding/collimator wall. The area upstream of the target to the HEBT tunnel will be filled in with shielding after transport magnets and supporting equipment are installed.Only a small fraction of a watt of proton power would be used in this basic configuration, though. An uncooled target and primitive shielding arrangement would provide beam on modestly sized systems that must be placed in close proximity to the target. The neutron fluence would be less uniform over the system than with the HETS or the beam line option. A data acquisition room and support area would be located on the ground level; access to the target cave would be via elevator and/or stairway.

As a result of the required excavation, new tunnel construction, shielding, data acquisition building, utilities, and other items, the estimated cost is $30 million. The time to complete is expected be more than 3 years; here again construction interference with SNS operations has not been accounted for, but it could have a significant impact.

High Level Comparison of Options

HETS

- Target station w/ kW level proton beam
- Dual test areas
- Components & systems
- Most flexible irradiation conditions
- Most expensive
- Longest to complete
- Construction coordination with SNS more difficult

Beam-line

- Neutron beam-line on MW SNS target station
- Single test area
- Components & systems
- Intermediate irradiation condition flexibility
- Least expensive
- Shortest to complete
- Construction coordinate with SNS operations least difficult
- Uses (2) beam-lines
  - strong competition

HENC

- Target cave with mW level proton beam
- Single test area
- Mainly systems
- Least irradiation condition flexibility
- Mid expense
- Mid completion time
- Construction coordination with SNS operations more difficult
- Upgradable to HETS

Summary

The development of a new test facility is necessary to meet the increasing industry and government demands for atmospheric radiation testing. Building a Cosmic Ray Neutron Simulation Facility at ORNL would provide the additional resources needed to meet current and future testing of microelectronic devices and systems for atmospheric radiation effects susceptibility.

Present testing capacity and capability is limited and restrictive. An additional test facility would provide the required increases in capacity and accessibility, and enhanced capabilities including the ability to accommodate system level testing. Potential users would have timely access, increased testing capabilities, and extended research opportunities.

The ORNL SNS – with its 1.0 GeV protons (1.3 GeV with the STS upgrade), typical operation of 5000 hours per year, expertise in spallation neutron sources, user program infrastructure, and decades of useful life ahead – is ideally suited for hosting a world-class SEE test facility. A number of options at the SNS were contemplated but ultimately reduced to three. Each offers different levels of functionality, performance, cost and programmatic viability; all can address system testing needs.

Three SNS facility options are described that cover ranges of capability, flexibility, cost and testing throughput – and different sets of challenges. The preferred choice depends in part on the SEE user community's assessment of what is needed now and in the future, and what funding can be provided. The HETS is clearly the best performing but also the most expensive option with the longest time to complete. It will have the most throughput capacity and have the greatest irradiation condition flexibility. A beam line facility will perform very well for much less cost, with minimal construction coordination concerns, but it lacks the same abilities for spectrum adjustment and flux intensity that HETS provides, and has half test throughput potential. Competition for a suitable available beam line on the SNS is intense. If a beam line cannot be assigned and funding is a limitation, the cave option can serve as a system test facility, with minimal irradiation flexibility, and lesser component test functionality. In any case, a new SEE test facility at the SNS could provide irradiation capabilities to the avionics system industry and SEE researchers for decades to come.

Acronyms and Abbreviations

APMC	Avionics Process Management Commission
AVSI	Aerospace Vehicle Systems Institute
B10	Boron 10
EASA	European Aviation Safety Agency
EIA	Electronic Industries Alliance
FAA	Federal Aviation Administration
HETS	High Energy neutron Test Station
HENC	High Energy Neutron Cave
IC	Integrated Circuits
IEC	International Electrotechnical Commission
JEDEC	Joint Electron Device Engineering Council
MBU	Multiple Bit Upset
ORNL	Oak Ridge National Laboratory
SEB	Single Event Burnout
SEE	Single Event Effects
SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEU	Single Event Upset
SEL	Single Event Latch-up
SET	Single Event Transient
SNS	Spallation Neutron Source
SRAM	Static Random-Access memory
WNR	Weapons Neutron Research

References

[1] Taber, A., E. Normand, 1993, Single Event Upset in Avionics, IEEE Transactions on Nuclear Science, Vol. 40, No. 2, 120-126.

[2] Riemer, B. W., F. X. Gallmeier, 2014, Definition of Capabilities Needed for a System Test Facility, ORNL/TM-2014/553, Oak Ridge National Laboratory, http://info.ornl.gov/sites/publications/files/Pub52543.pdf .

[3] Oak Ridge National Laboratory Neutron Sciences, Spallation Neutron Source, http://neutrons.ornl.gov/facilities/SNS/.

[4] Wen, Shi-Jie, et al. 2010, Thermal Neutron Soft Error Rate for SRAMs in the 90nm-45nm Technology Ranges, IRPS 2010.

[5] Normand, E., T. J. Baker, 1993, Altitude and Latitude Variations in Avionics SEU and Atmospheric Neutron Flux, IEEE Trans. Nucl. Sci., 40, 1484.

[6] Edwards, R., 2004, Abstract - Technical Standard For Atmospheric Radiation Single Effects (SEE) on Avionics Electronics, NSREC Poster Presentation (IEC).

[7] Actel Corporation, 2002, Effects of Neutrons on Programmable Logic, White Paper.

[8] ISIS Spallation Neutron Source, http://www.isis.stfc.ac.uk/ .

[9] IEC Technical specification IEC TS 62396 part 1– Process management for avionics-Atmospheric radiation effects - Standard for the accommodation of Atmospheric Radiation Effects via Single Event Effects within Avionics Electronic Equipment, International Electrotechnical Commission, 2006.

[10] GEIA-STD-0002-1, Aerospace Qualified Electronic Component (AQEC) Requirements, Volume 1 – Integrated Circuits and Semiconductors, 2005.

[11] JEDEC Standard, JESD89-3, Test Method for Beam Accelerated Soft Error Rate, September 2005.

[12] Dominik, L., et al, 2009, Proposal for a New Integrated Circuit and Electronics Neutron Experiment Source at Oak Ridge National Laboratory, IEEE CFP09RPS-CDR, 47th Annual International Reliability.

[13] Danilov, V., et al., May 2007, Proof-of-principle Demonstration of High Efficiency Laser-assisted H-Beam Conversion to Protons, Phys. Rev. ST Accel. Beams 10, 053501.

[14] Frost, C., April 2009, A New Dedicated Neutron Facility for Accelerated SEE Testing at the ISIS Facility, ISBN 978-1-4244-2889-2/09, Proc. of the IEEE 47th Annual Reliability Physics Symposium, Montreal, IEEE International.

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