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Report from the Inaugural Meeting on the Opportunities at the SEEMS Facility June 11–12, 2019

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January 2020

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Neutron Sciences Directorate

REPORT FROM THE INAUGURAL MEETING ON THE OPPORTUNITIES AT THE SEEMS FACILITY JUNE 11–12, 2019

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1. EXECUTIVE SUMMARY

The Inaugural Meeting on the Opportunities at the Single Event Effects—Muon Spectroscopy (SEEMS) facility was held June 11–12, 2019, at Oak Ridge National Laboratory (ORNL). Capabilities of the SEEMS facility concept were reviewed, with emphasis on particle beams for single event effects (SEE) testing of electronic devices (integrated circuits) and systems—a topic of growing interest and concern in aerospace avionics, satellites, supercomputing, autonomous cars, unmanned aerial vehicles and more. Participants from these industries and their regulators attended. A clear consensus on the growing and urgent need for SEE test capabilities like those offered by SEEMS was expressed. Subsequent to the meeting, letters of support for SEEMS were sent by The Boeing Company and Honeywell to the ORNL Laboratory Director, Thomas Zacharia.

Naturally occurring radiation in the atmosphere originating from cosmic rays and solar particles can cause errors in semiconductor devices as a result of ionization; these are known collectively as SEE. The primary source of SEE from atmospheric radiation is high-energy neutrons. The energy spectrum of neutrons has long been characterized and is known to vary with altitude, latitude, and space weather. Evaluation of the vulnerabilities of critical electronic systems to this radiation is now required in the commercial aircraft certification process. These evaluations are based upon device error rates determined by testing in representative radiation environments. A properly designed spallation neutron source—as offered by SEEMS—can provide neutrons matching the atmospheric spectrum but at greater fluxes to enable accelerated testing.

The one existing US facility offering high-energy neutron testing matching the atmosphere uses a nearly 50-year-old accelerator at the Los Alamos National Laboratory. Known as the “ICE House” [1], it is over-subscribed, and its operating model is unaccommodating for the rapid access demands of industry. It lacks the capability to irradiate complete, large (meter scale) systems like those now deemed necessary by meeting attendees. SEEMS at the Spallation Neutron Source complex at ORNL [2] could provide 50 years or more of future operation.

Several technology trends affecting aerospace electronics are driving increasing demand for SEE testing infrastructure with more capacity and capabilities. First, there is increasing use of highly sophisticated systems (using more devices) for aircraft operation. Second, the latest devices employ smaller gate features, with lower voltages, making them inherently more susceptible to bit upsets. Third, commercial devices are updated frequently, but error rates cannot be reliably extrapolated from earlier generations; so system SEE evaluations require updating with new error data. Fourth, the increasingly common use of boron in integrated circuit fabrication adds SEE vulnerability from thermal neutrons. Thermal neutrons are introduced in aircraft by the moderation of atmospheric neutrons from fuel and passengers.

The prospective users and commercial aircraft regulators attending the inaugural SEEMS meeting further asserted that these trends represent only one aspect of the growing need for SEEMS. Electronic systems can be engineered with mitigations for SEE (with some performance impacts); however, verification of mitigations at the system level requires testing of the complete systems in large-area neutron beams. This capability is explicitly offered by SEEMS, in addition to small beams for device testing.

The SEEMS facility concept is rooted in an earlier study [3] seeking options to address the growing needs of the commercial aerospace electronics industry. Other SEE test applications operating from ground level to high altitude can also be served, e.g., autonomous cars, unmanned aerial vehicles, high performance/integrity computing systems, and defense applications. Systems in those applications are affected by the same technology trends as are commercial aircraft avionics, and where system functions are critical, they need assurance that SEE vulnerabilities are sufficiently mitigated.

Space applications (e.g., satellites) are concerned regarding SEE largely caused by high-energy protons. While the original facility concept emphasized high-energy neutrons, with thermal neutrons on demand, proton and pion irradiation can be provided in SEEMS if user demand solidifies. Proton irradiation up to 1.3 GeV is possible at SEEMS in the large area between the neutron test caves.

Presentations from ORNL staff and attendees fed discussions of how to realize SEEMS construction and support its operations. The co-located and compatible mission for muon spectroscopy was explained. Both SEE testing and muon spectroscopy are presently outside the neutron scattering science missions conducted by ORNL for the Department of Energy's Office of Basic Energy Sciences. Muon spectroscopy techniques are highly complementary to neutron scattering for material characterization. There is interest from the National Science Foundation in the muon spectroscopy aspect of the project. SEE testing is thought to have high interest beyond that represented by the attendees, and it was recommended that measures be taken to engage other applications.

A clear path for SEEMS facility construction was not apparent, but the ORNL staff were strongly encouraged to pursue it. A multi-prong approach to more broadly engage prospective users, laboratory leadership, and funding agencies is needed. A request was made to the industrial participants to express their support for SEEMS by sending letters of support to ORNL Laboratory Director Thomas Zacharia. By August 2019, letters had been received from The Boeing Company and from Honeywell.

It was also recommended that the ORNL SEEMS team formulate a plan with clear steps toward establishing the path to project initiation. Funding to execute the plan will be needed; funding options discussed included ORNL Program Development or Laboratory Directed Research and Development funds, the Federal Aviation Administration, and the Aerospace Vehicles Systems Institute. A second meeting on the SEEMS facility should be held about 6 months after the inaugural meeting to review progress on the plan.

2. INTRODUCTION

A proposed Single Event Effects—Muon Spectroscopy (SEEMS) facility at Oak Ridge National Laboratory (ORNL) would serve two user communities:

- Condensed matter science researchers exploiting high-resolution muon spin relaxation (μSR) techniques

- Industrial and academic research on single event effects (SEE) in semiconductor electronic components and systems

An Inaugural Meeting on the Opportunities at the SEEMS Facility was held at the Spallation Neutron Source (SNS) on June 11–12, 2019. It focused on the second of the user communities—industrial and academic researchers. Indeed, the SEEMS design concept started with a Spallation Neutron Source (SNS) study conducted for the Federal Aviation Administration (FAA) (issued in 2015) [3] that examines test facility options for providing neutron radiation simulating that in the atmosphere originating from cosmic rays and solar particles. The study was stimulated by earlier work calling for neutron radiation facilities with increased capacity and capabilities to meet current and future needs [4]. Regulators, aircraft producers and avionics equipment suppliers recognize the growing urgent need for SEE testing in prototypical radiation fields. Industry standards formalizing procedures to assure that critical systems are robust against SEE phenomena have been issued. Regulatory bodies including the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) now requiring that updated standards are met for aircraft certification [5].

Although the aircraft and avionics industries have been leaders in calling for improving SEE test capabilities in the United States, other electronics applications also need SEE testing infrastructure improvements. For example, a National Academies of Science report citing the need for spacecraft to ensure robustness against SEE phenomena highlighted the poor state of US radiation testing infrastructure [6]. Space radiation conditions differ from the conditions under which typical avionics operate, as high-energy (HE) protons are most relevant for many satellite applications. Proton irradiation would be possible in the proposed SEEMS facility. Ground-based and low-altitude applications with critical electronic functions are challenged by increasing complexity and technology trends driving up fundamental SEE vulnerabilities. Examples include high-performance computing systems, transportation systems, autonomous ground vehicles, and unmanned aerial vehicles (UAVs). Ground-based and low-attitude systems are exposed to the same HE neutron spectrum as are aircraft avionics. Effective SEE mitigation techniques need to be tested in accelerated, prototypical radiation conditions.

The inaugural meeting on the SEEMS facility was held to gage the interest of a small group of potential SEE test stakeholders in the facility, to broaden the prospective user base, and to seek support for advancing a project. The participants were persons from industry and regulatory agencies with expertise in atmospheric and space SEE phenomena, SEE analysis and testing practices, and requirements for aircraft certification. A meeting website was developed to provide background information and collect presentation materials: https://conference.sns.gov/event/163/. The agenda is included in APPENDIX A.

This report summarizes the presentations and discussions conducted at the meeting aimed at realizing the SEEMS facility.

3. ATTENDANCE

Nine persons from outside SNS attended the meeting, and another nine joined via computer conferencing. Representatives participated from Boeing, Honeywell, GE Aviation, Collins Aerospace, Embraer, the FAA, National Aircraft Certification Transport Canada, the National Civil Aviation Agency of Brazil, the Aerospace Vehicles Systems Institute (AVSI), and Vanderbilt University's Institute for Space and Defense Electronics. Eight persons from ORNL or the SEEMS collaboration team also participated. A complete participant list is included in APPENDIX B.

4. PRESENTATION SUMMARIES

4.1 PAUL LANGAN OF ORNL—OVERVIEW OF ORNL, SNS, AND THE NEUTRON SCATTERING PROGRAM

Paul Langan, associate laboratory director for the ORNL Neutron Sciences Directorate (NScD), provided an overview of ORNL, its history, and its current missions, and described the neutron scattering science program that is operated using the High Flux Isotope Reactor (HFIR) and SNS. The roadmap for the US Department of Energy (DOE) neutron science research program was outlined and coming upgrades to the SNS were highlighted. The Proton Power Upgrade and Second Target Station projects are indicative of decades of expected future operation at the SNS accelerator complex. As outside participants were less familiar with ORNL and the SNS, this overview was intended to provide an orientation.

4.2 MICHELLE BUCHANAN OF ORNL—OFFICIAL WELCOME AND INTRODUCTION

Michelle Buchanan, ORNL deputy director for Science and Technology, welcomed attendees, thanked them for their interest in the SEEMS project, and offered encouragement for a productive meeting.

4.3 BERNIE RIEMER OF ORNL—WORKSHOP OVERVIEW AND GOALS

Bernie Riemer of the SNS Upgrades Office explained that the primary mission of NScD is neutron scattering sciences for its funding agency, the DOE Office of Science, under the Basic Energy Sciences (BES) User Facilities Division [7]. ORNL constructed and operates the SNS, which operates for approximately 4,500 hours each year. ORNL has the expertise to design, build, and operate spallation neutron sources. A high-energy neutron source that simulates atmospheric neutron radiation from cosmic and solar rays could be added to the SNS accelerator complex to provide world leading capabilities. It would have a high number of hours of operation annually and would be available for decades to come. Adding high-energy proton irradiation capabilities for space SEE testing would be feasible if there is sufficient interest from users.

Riemer explained that the SEEMS concept emerged from a prior study done for the FAA investigating SEE test facility options at the SNS. The additional function as a muon source would exploit two features of an SNS-based neutron test facility concept:

1. Laser stripping could be used to divert a small fraction of protons from the primary accelerator beam to the new SEEMS target station.

2. The preferred direction for extracting the HE neutron test beams for SEE testing is at ±30° off the incident proton beam direction onto the target, whereas the ideal direction for muon extraction is ±90°.

In a combined facility, both the SEE testing and muon spectroscopy missions can be served with world-class capabilities, using the same target system and proton extraction and transport line, thus providing savings compared with single-purpose facilities.

Riemer said that neither of these missions is currently within the DOE BES scope, however, DOE could be persuaded to accommodate a SEEMS facility provided that

- Funding for construction is provided
- An operational model can be supported
- SEEMS operation does not impact the primary neutron scattering science mission

Importantly, Riemer emphasized that DOE will consider the SEEMS project only if user communities make their interests clearly and emphatically known. Requests from ORNL/SNS staff are not sufficient to obtain DOE support.

Riemer outlined the following goals of the meeting:

- Describe SEEMS capabilities to potential user community stakeholders
- Broaden the base of potential users
- Invite community feedback guidance on facility technical requirements
- Assess future usage of SEE testing for the coming decades from this user community (e.g., annual tests, experiments, visiting users)
- Discuss funding models and a proposal to the National Science Foundation (NSF)
- Obtain letters of support from stakeholders (industries, institutes, and academia)
- Plan future steps to realize the SEEMS facility

4.4 CRYSTAL SCHROF OF ORNL—CURRENT INDUSTRY PARTNERSHIPS WITH ORNL

Crystal Schrof, head of the NScD Scientific and Programs Services Office highlighted annual metrics of roductivity for ORNL neutron facilities. Using 30 instruments at both HFIR and SNS, some 3,000 annual users take advantage of ORNL's neutron scattering science capabilities. Industry usage was described and three avenues for access to the neutron sources highlighted: the General User Program, the Mail-in Program, and the Industrial Applications Program.

Schrof described broader ORNL interactions with the private sector via five paths: Technology Licensing, Sponsored Research, Industrial Partnerships, Economic Development, and Subcontracting. The path the SEE test user community might use was not yet apparent, but the information presented explained the general methods of access to ORNL. Perhaps most applicable to the SEEMS facility and this user community were the Neutron Spin Echo and VULCAN instruments, which were funded under Strategic Partnership Project agreements.

Collaborative Access Teams—models used by other DOE User Facilities for beam line construction and operation—are worth exploring for ORNL/SNS and the SEEMS project. These allow for teams to construct and operate beam lines, on which a percentage of the beam time will be reserved for the General User Program but the majority will go to the Collaborative Access Team. This option could be an important one should industrial partners agree to co-fund parts of the SEEMS construction and operate the facility.

4.5 LAURA DOMINIK OF HONEYWELL—SINGLE EVENT EFFECTS OVERVIEW, TESTING, AND FACILITIES

Laura Dominik, an engineer fellow at Honeywell, presented a high-level summary of particle cascades that lead to mainly HE neutrons in the atmosphere, which can interact with integrated circuits to cause SEE (Figure 1). High-energy neutron flux varies with altitude and latitude; fluxes are higher altitudes and latitudes. SEE describes a collection of faults resulting from disturbances caused by ionization from incident radiation. The impacts of SEE include corrupted data and CPU halts and interrupts, with unplanned output from the affected systems. Neutron-induced SEE can occur at ground level even though neutron flux is lower than at aircraft altitudes.

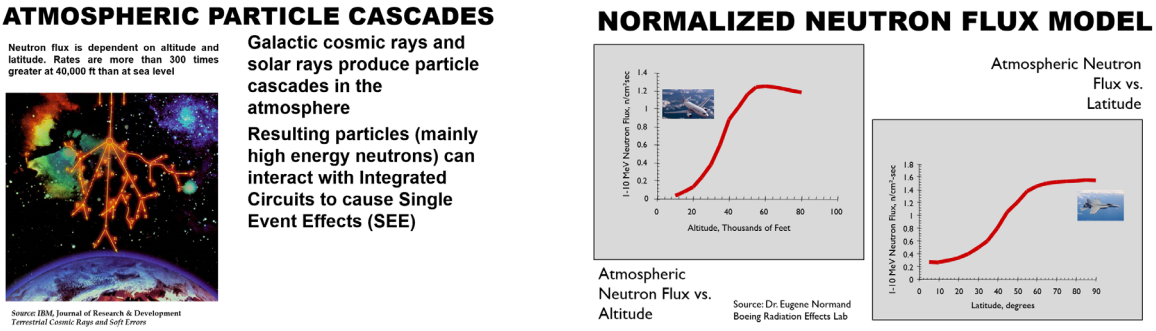

Figure 1. Atmospheric neutrons are caused by galactic cosmic and solar rays, which lead to SEE in integrated circuits (left). The atmospheric neutron flux varies with altitude and latitude (right). *Source*: presentation by L. Dominik.

Dominik explained how technology trends are driving increasing SEE vulnerabilities:

- Smaller circuit dimensions and lower voltages:
  - Typical charge found at storage nodes is decreasing.
  - Less energy is needed to disturb stored information.
  - Stored bit values are more easily corrupted.
- Cannot extrapolate behavior of future integrated circuit technologies from older devices.
- Significant increase in multiple cell upsets for devices with features smaller than 90 nm.
- Thermal neutron radiation (~ 25 MeV) has become a new SEE susceptibility because of the presence of boron-10 (^{10}B) in integrated circuit fabrication:
  - HE neutrons (> 1 MeV) are moderated to thermal energies by aircraft fuel, passengers, carbon airframes.

The state of current regulations specifically addressing SEE was reviewed. EASA issued a Certification Memorandum (EASA, CM No. CM-AS-004 Issue 01) in January of 2018 requiring that aircraft manufacturers applying for certification demonstrate that aircraft systems, whose failure could contribute to a failure condition classified as hazardous or catastrophic, are adequately mitigated against SEE. The FAA has been collaborating with EASA, having shared its draft Issue Paper on SEE within the Aircraft Safety Assessment process. The FAA now recognizes the recommended process of the newly issued SAE International AIR6219 document (see below) as an element of the overall Aircraft Safety Assessment.

Dominik listed several relevant industry standards related to SEE vulnerability and evaluation, which are included in Table 1.

She asserted that the aerospace/avionics industries urgently need an additional neutron simulation facility in the United States to deal with

- Increasing demand for SEE testing of components;
- Equipment and system level testing for robustness and mitigation verification;
- Thermal neutron testing.

Table 1. Industry standards related to recommended practices for evaluating SEE vulnerabilities for avionics.

Organization	Standard	Title
SAE International	AIR6219–2018 (Aerospace Information Report)	Development of Atmospheric Neutron Single Event Effects Analysis for Use in Safety Assessments
SAE International	ARP4761A* (Aerospace Recommended Practice)	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
JEDEC (Joint Electron Device Engineering Council Solid State Technology Association)	JESD89A–2006	Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices
JEDEC	JESD89-3*	Test Method for Beam Accelerated Soft Error Rate
IEC (International Electrotechnical Commission)	IEC TC107 62396*	Process Management for Avionics–Atmospheric Radiation Effects, Parts 1–7 Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

*Updates in progress

Benefits of the proposed SEEMS facility discussed Dominik included these:

- Additional capacity to meet current and future test needs for avionics and other reliability-critical industries
- More timely access
  - Current facility capacity limits rapid pace industrial program development schedules, as existing facilities are chronically oversubscribed months in advance
- Improved availability of more powerful and capable test beams
- Both device-level and equipment (systems) -level testing capabilities–small and large neutron beams
  - Equipment level testing allows for overall system robustness and mitigation verification
- Both high-energy and thermal (neutron) test capabilities at one location

4.6 GARY HORAN OF FAA—ATMOSPHERIC NEUTRONS–PART OF THE ATMOSPHERIC / ENVIRONMENT HAZARDS

Gary Horan's career at the FAA has been focused on engine controls. His most recent work involves development of rules and policies for electric and hybrid electric propulsion systems. He discussed why the FAA considers atmospheric neutrons as a genuine hazard to be considered in the aircraft certification process. FAA Issue Papers have been applied to all engine programs over the past 8 years which are aimed at inclusion of this external threat in system safety assessments.

The FAA has previously funded research in two SEE areas: (1) mitigation techniques and (2) test facility options for simulating atmospheric neutrons using the SNS accelerator. The latter study identified three options, the most viable of which was the basis for the SEEMS facility [3].

Horan reviewed some relevant industry actions. Notable is the work of AVSI at Texas A&M University. AVSI performs work through industry collaborations on topics of common interest. The FAA was part of the AVSI AFE72 working group "Mitigating Radiation Effects," which has published documents that are now part of the International Electrotechnical Commission Standards Series on SEE in avionics. AVSI's work also contributed to the SAE International AIR6219, the newly issued standard noted earlier by Dominik. This AIR defines how SEE is to be included in an aircraft system safety assessment.

Horan said that the FAA and EASA have been collaborating on the development of atmospheric neutron/SEE guidance for 7 years. The EASA Certification Memo [5] used the draft FAA Issue Paper in forming its certification requirements. Now that the SAE AIR6219 document has been published, the FAA is reviewing the document for possible formal recognition of the SEE process recommended in the AIR6219 as a required element of the aircraft safety assessment.

- The end goal of the AIR6219 analysis is to ensure that electronic systems incorporate sufficient mitigation in new designs.
- This will address the impact of the SEE threat on aircraft safety.
- These actions would be in harmony with the EASA CM on atmospheric neutrons.
- The FAA is ready to work with DOE on the expansion of capabilities at ORNL to further understanding of the risks to semiconductors in aviation.

Horan concluded with the statement that "Every avionics product shipped today needs to take into account radiation effects."

4.7 SCOTT MARSTON OF THE BOEING COMPANY—OUTLOOK ON FUTURE AEROSPACE ELECTRONIC TECHNOLOGIES AND SEE TESTING NEEDS

Scott Marston holds the position of associate technical fellow, Boeing Commercial Airplanes, Connected Digital Systems. His presentation was brief but highlighted the emerging need for a next-generation SEE testing facility. Increases in the demand and required capabilities are not being matched be the current testing facilities, and these increases are likely to continue. The key slides in his presentation are shown in Figure 2. He noted the urgent need for SEE testing facilities in the United States.

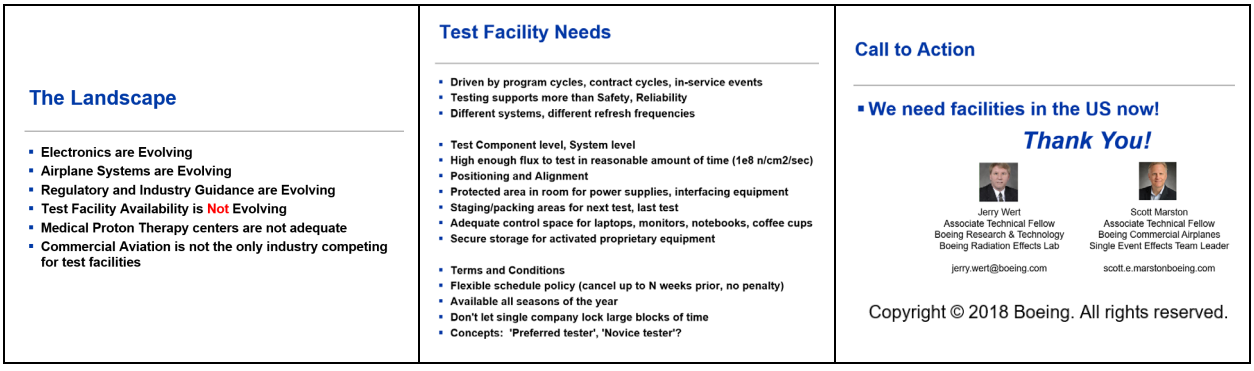

Figure 2. Key slides from Scott Marston of Boeing.

4.8 BERNIE RIEMER OF ORNL—SEEMS: FACILITY OVERVIEW AND SEE TESTING CAPABILITIES

Bernie Riemer described the SEEMS concept, emphasizing capabilities for SEE irradiation testing capabilities. The SEEMS spallation neutron source would be optimized to match the atmospheric spectrum. The beam size could be very small (millimeter scale) for device studies or very large for equipment/systems testing (meter scale). The flux would be adjusted by a combination of collimation, laser stripping duty cycle, sample distance from the source, and filtering. The test areas would have infrastructure to ease device and equipment alignment with the beam and for data acquisition. Clean power supplies and data cabling out of the test cave are envisioned. A general layout of the target station and test areas is shown on the slide in Figure 3.

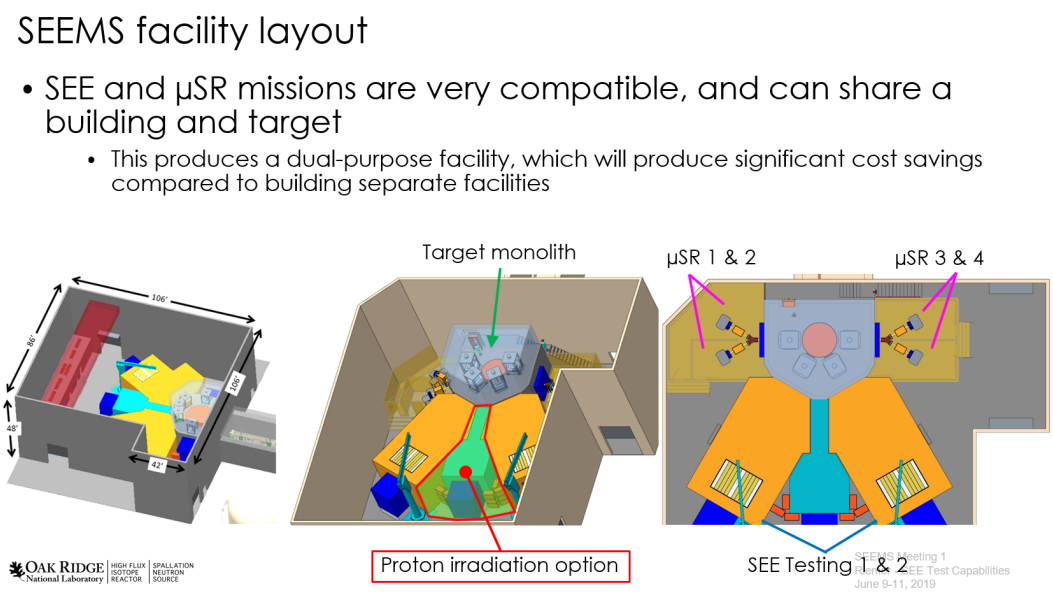

Figure 3. SEEMS facility layout including neutron and muon test areas and target monolith.

Facility availability would be a major improvement for the user community represented at the meeting. The SNS operates for about 4,500 hours annually. The available testing time at SEEMS would be as much as four times that of the existing, aging US facility at the Los Alamos National Laboratory. As the SNS is a relatively new accelerator, with a Second Target Station project moving forward for construction, the foreseen lifetime of the complex is roughly another 50 years. Establishing a user operating model with ample test time reserved for rapid access to serve urgent industry needs is foreseen as fundamental.

The neutron source concept includes the option to add thermal neutrons to the HE neutron beams to the test caves, on demand from users, using a small water moderator. Combined with a 30 cm beryllium reflector, the ratio of the thermal flux to the HE flux (above 10 MeV) is designed to be about one.

The proton beam power on the SEEMS target station would be about 5 kW. Helium gas cooling of the tungsten target would be sufficient, simplifying utility requirements and target design. Because of the high energy of the incident protons (1.3 GeV after the Proton Power Upgrade is completed), substantial shielding would be needed in the target station monolith. The neutron test caves likewise would require substantial shielding because of this energy.

Protons would scatter from the target toward the neutron test caves, but SEEMS would include magnetic deflection of charged particles that normally prevent neutrons from entering the neutron test caves. If desired by the user, the deflection could be disabled, allowing protons and other charged particles into the test caves. Pure proton irradiation is not part of the SEEMS baseline concept but can be added. A proton irradiation area could be located between the two neutron test caves. A proton beam could be directed there by either steering around the spallation target or moving the target out of the proton path. A pure proton beam would be mono-energetic at 1.3 GeV. Energy degraders might be possible, but no study has yet been made of such capabilities.

4.9 TRAVIS WILLIAMS OF ORNL—SEEMS: μSR CAPABILITIES AND INTEGRATION WITH DOE-BES PROGRAMS

Travis Williams is a neutron scattering scientist in the NScD with an interest in using muons for probing and characterizing materials in ways complementary to neutrons. Such muon capabilities are exploited elsewhere in the world but are not available in the United States. He explained to SEE meeting participants what those capabilities are and how SEEMS would be outstanding in muon spectroscopy techniques with world-leading resolution.

Important to the SEE community is the highly compatible nature of combining μSR with SEE capabilities in the SEEMS concept, thus affording savings and leverage for funding and operations. This is possible because muons are extracted from ±90° off the incident proton beam onto the target, whereas HE neutrons are extracted at ±30°. The proton power required to provide outstanding beams to either area is essentially the same.

Williams emphasized that SEEMS operation will not impact the operation of the existing neutron scattering target station nor the upcoming Second Target Station.

4.10 TRAVIS WILLIAMS OF ORNL—FUNDING PLANS, NSF and DOE INVOLVEMENT, AND OPERATIONAL MODEL

Travis Williams presented a rough cost estimate for the SEEMS facility. The construction cost was estimated at $142M, not including a dedicated proton irradiation area. The present-day context of the ongoing Proton Power Upgrade project and ramping up the Second Target Station project was explained; these projects are high priorities of ORNL and DOE/BES. Prospects for partial funding from the National Science Foundation were outlined. The support of industry is sought, as well as BES support. Funding of construction may be complicated but is workable if all parties can agree on a strategy.

Funding support for sustained operation of a SEEMS facility will also be needed. Fees collected for proprietary usage of beam time could be used to fund operation. However, if a Collaborative Access Team (see Section 3.4) arrangement were established for the construction of the SEE testing areas, team members might be exempted from such fees.

At this stage, funding and project sponsors are far from being defined. Goals for the one or two years include building user community support for the project, finalizing required performance parameters, establishing the project funding sponsors, and establishing the operating model.

4.11 CLARINA DELA CRUZ OF ORNL—USER FACILITIES AT ORNL

Clarina dela Cruz is a neutron scattering scientist with an interest in using muons for research. Her presentation illuminated the diverse user programs operated at ORNL for DOE, of which SNS is only one. She explained how users access these national resources, and specific options for industrial users.

5. DISCUSSION SUMMARIES

Four discussion sessions with topics were planned throughout the agenda. In practice, the topics traversed between the discussion periods. The planned topics were

1. SEE Testing Needs—Current and Future
2. SEE Industry Needs versus SEEMS Technical Capabilities
3. SEEMS Annual Operation and User Model
4. Future Outlook and Funding

The major points from all sessions are summarized as follows.

- The aerospace/avionics perspective is that the need for a US test facility like SEEMS is urgent.

- Gary Horan (FAA) stated growing demand for a suitable test facility was inevitable.

- Space SEE testers are also interested, but more outreach to this community is needed to clarify the degree of interest in SEEMS.

- Projected usage is difficult to quantify. The attending companies estimated two to three major test campaigns per year per company, but programs and testing needs vary year to year. Test campaigns typically take from 4 to 7 days.

- Jerry Wert of Boeing thought the SEEMS concept was a brilliant business model. He expressed confidence the facility will be fully subscribed.

- Jim Marko (Transport Canada) reiterated that SEE evaluation is now part of aircraft safety assessment so must it be addressed for aircraft certification. It is a usual hazard that does not fit into typical common mode hazard categories. Rapidly changing systems (e.g., engine controllers, flight computers) and components (integrated circuits) compound challenges to keep the hazard assessments current. System-level evaluation is needed; also needed are integrated systems evaluations in which new modes of failure can occur. A large test beam is essential for these aspects of SEE testing. Testing is needed to ensure compliance with new standards. SEEMS can only help with these growing and rapidly changing assessment needs. Having the option to add thermal neutrons is advantageous. The SEEMS concept is the right direction. Marko fully supports the SEEMS concept, with capabilities from device scale to large systems.

- Scott Marston of Boeing repeated that the changing technology landscape highlights the need to test. This need will grow and persist.
  - Unfortunately test facility capabilities and capacity have not kept up pace; rather, they are stagnant in the United States.
  - Medical accelerators (protons) are sometimes used when no options are available. But it is difficult to reserve time on them and they are very inconvenient for industry applications.
  - Marston thinks automotive and space industries will be interested in using SEEMS.
  - Boeing's needs are variable and come in surges.
  - Marston noted that a facility like SEEMS needs controlled accessed for user equipment (secured storage space for protection of industry secrets), good data acquisition spaces, and data acquisition features inside the test caves as well as in any external user room.
  - Clear agreement is required for user–ORNL terms and conditions, indemnity must be addressed in the user program.

    - Building up in-house (ORNL) user support capabilities is recommended to aid novice users. Perhaps either a staff subject matter expert or scientist or an expert from a university could be posted at SEEMS for this role.
- There were questions and discussion regarding the equivalence between HE neutron flux (above 10 MeV) and flight hours at altitude. The consensus was that the answer depends on scaling.

- Laura Dominik of Honeywell noted the typical life cycle for integrated circuit device error rate data is 18 months. SEE assessments quickly become obsolete when equipment/systems use new chips whose error rates cannot be extrapolated from prior devices. SEE assessments must have good data to properly conduct hazard evaluations. Demand for test time will grow in the coming decades.

- Space SEE testing was represented by Mike McCurdy (Vanderbilt University) and Michael B. Smith (ORNL). Other National Aeronautics and Space Administration (NASA) contacts were invited but did not attend. (Ken LaBel, noted space-based SEE expert at NASA Goddard was invited but did not respond; it was discovered that he had retired, and Jonathan Pellish at NASA Goddard is the new contact).

- The FAA has a growing responsibility for unmanned aerial vehicles. SEEs over urban landscapes add to hazard analysis considerations.

- Discussions regarding funding had little to build on. The situation is somewhat more complicated than a typical DOE/BES project. The key players are DOE, the National Science Foundation, and industry.

- It is too early for a consensus on an overall project construction funding strategy. Funding to support further design work, building user consensus on parameters and technical requirements, and maturing a cost estimate have genuine prospects. Perhaps AVSI David Redman) might be a vehicle for industry (and the FAA) to co-fund some work. AVSI project funding is typically in the tens of thousands of dollars; it perhaps could be larger (he will investigate).

- David Redmond argued that a major benefit of SEE testing is cost avoidance—avoiding later expensive problems or recalls for operators or suppliers.

- A question was raised regarding Aerospace Industries Association funding of the development of the SEEMS concept. No one knew of any contacts.
    - Potential defense applications (Department of Defense, defense industry) were discussed. The SEEMS team members said they have no such contacts but have reached out to ORNL managers who work with the Department of Defense. There is interest, but so far nothing of substance has come back.
    - Note: the SEE MAPLD workshop might be a good venue to make contacts (https://www.seemapld.org/)

- How much would be needed to move forward over next 2 years? The answer is uncertain. It was suggested that $2M/year for 2 years might be needed, but less than $1M/year may be sufficient.

- The SEEMS project needs a strong message of support from the user communities. Only a subset of the user community was represented at the meeting, but it was an important one. SEE testing is not part of the primary DOE/BES mission, and DOE will need to be persuaded to take it on.

- The National Science Foundation is likely to fund only the muon beam lines and instrumentation. Funding for the balance of the facility must be found. It was suggested that BES might be willing to

build the target station and proton transport line, the National Science Foundation to build the muon beam lines, and industry to industry build the SEE test areas.

- Greg MacDougal (University of Illinois) noted that Thiyaga P. Thiyagarajan (DOE/BES) has expressed an interest in SEEMS for electronics testing (this comment needs to be followed up).

- A user operating model must be developed in concert with users and operators. High levels of reserved rapid access time for SEE industries is essential. Technical operation of SEE test beams with muon beams also needs to be determined.
  - Q: Are there any compatibility issues with target operation?
  - A: None are apparent at this point.

- Could a joint letter of support come via AVSI?

- A timeline for the project had been drafted by Riemer of ORNL for an extended white paper that has not been published. This timeline was sent to participants; it is included in APPENDIX C.

- Another meeting of this community should be organized in about 6 months from the original meeting. Deliverables before that include this report, support letters, and plans for moving forward.

- The Nuclear and Space Radiation Effects Conference (NSREC) is scheduled for July 8–12, 2019. This conference series is closely connected to SEE issues. Representatives from Boeing, AVSI, and Vanderbilt will be attending and will have exhibits. They volunteered to hand out an SEEMS flyers or brochure, to be prepared by ORNL, to NSREC attendees. (The brochure is attached as APPENDIX D)

- This report will be sent in draft form to key meeting participants before being published.

- SEEMS proponents should use other relevant meetings/conferences besides NSREC to promote the project.
  - SEE MAPLD: May 18–22, 2020, San Diego, CA
  - NSREC 2020: July 20–24, 2020, Santa Fe, NM
  - Nuclear and Emerging Technologies for Space: April 6–9, Knoxville, TN

- Partial funding for near term work might be possible from FAA.

Note: Following the workshop, Riemer drafted a letter of support for industry consideration. The draft letter was sent to the Boeing and Honeywell participants. Understandably, signing and sending such a letter requires review by the companies' management and legal teams. It was requested that as many participants as possible send signed letters to ORNL laboratory director Thomas Zacharia to clearly indicate support for the SEEMS facility. Boeing and Honeywell have sent letters of support for SEEMS (see APPENDIX E). Additional letters will be helpful in building the case for SEEMS.

6. REFERENCES

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[2] "Spallation Neutron Source," https://neutrons.ornl.gov/sns, accessed November 2019.

[3] *Definition of Capabilities need for a Single Event Effects Test Facility*, DOT/FAA/TC-15/16, US Department of Transportation, Federal Aviation Administration, https://www.faa.gov/aircraft/air_cert/design_approvals/air_software/media/TC-15-16.pdf, accessed December 2019.

[4] L. Dominik, E. Normand, M. Dion, P. Ferguson, "Proposal for a New Integrated Circuit and Electronics Neutron Experiment Source at Oak Ridge National Laboratory," IEEE CFP09RPS-CDR 47th Annual International Reliability Physics Symposium, Montreal, 2009.

[5] *Single Event Effects (SEE) Caused by Atmospheric Radiation*, EASA Certification Memorandum CM–AS-004 Issue 01, European Aviation Safety Agency, January 8, 2018.

[6] National Academies of Sciences, Engineering, and Medicine, *Testing at the Speed of Light: The State of U.S. Electronic Parts Radiation Testing Infrastructure*, Washington, DC, The National Academies Press, 2018. Available at https://doi.org/10.17226/24993, accessed December 2019.

[7] DOE Office of Science, Basic Energy Sciences, https://science.energy.gov/bes/, accessed December 2019.

APPENDIX A. MEETING AGENDA

OAK RIDGE National Laboratory

AGENDA

ORNL IS MANAGED BY UT-BATTELLE, LLC FOR THE US DEPARTMENT OF ENERGY

Inaugural Meeting on the Opportunities at the SEEMS Facility

June 10–12, 2019

Tuesday, June 11, 2019 **Building 8600, C156**

Time	Event	Speaker
9:00–10:00 a.m.	Arrival/Badging Check-in/Folder distribution	ORNL Visitor Center / Building 5200 Building 8600, C156
10:00–11:30 a.m.	Welcome and SNS Tours	Travis Williams Neutron Scattering Scientist Neutron Scattering Division Bernie Riemer PPU STS Systems Manager SNS Upgrades Office
11:30 a.m.–1:00 p.m.	Overview of ORNL, SNS, and the Neutron Scattering Program ***(working lunch)***	Paul Langan Associate Laboratory Director Neutron Sciences Directorate
1:00–1:15 p.m.	Official Welcome and Introduction	Michelle Buchanan Deputy for Science and Technology Oak Ridge National Laboratory
1:15–1:30 p.m.	Workshop Overview and Goals	Bernie Riemer
1:30–2:00 p.m.	Current Industry Partnerships with ORNL	Crystal Schrof Manager Scientific & Program Services Office
2:00–2:30 p.m.	Single Event Effects Overview, Testing and Facilities	Laura Dominik Systems Staff Engineer Honeywell
2:30–3:00 p.m.	**BREAK**	
3:00–3:30 p.m.	Current State of SEE Regulations Worldwide	Gary Horan (FAA)
3:30–4:00 p.m.	Outlook on Future Aerospace Electronic Technologies and SEE Testing Needs	Scott Marston Associate Technical Fellow The Boeing Company
4:00–5:30 p.m.	*Discussion #1: SEE Testing Needs – Current and Future*	
5:30–6:00 p.m.	Travel to offsite dinner	
6:00–8:00 p.m.	Working Dinner—*The History of ORNL and the Neutron Scattering Program* **(Calhoun's, Melton Lake, Oak Ridge)**	Jaime Fernandez-Baca Lead, Triple-Axis Neutron Scattering Division

Contact: Toni Sawyer, 865.574.7399, 865.438.8139/cell, sawyertk@ornl.gov *updated: 06/7/2019*

OAK RIDGE National Laboratory

AGENDA

ORNL IS MANAGED BY UT-BATTELLE, LLC FOR THE US DEPARTMENT OF ENERGY

Inaugural Meeting on the Opportunities at the SEEMS Facility

June 10–12, 2019

Wednesday, June 12, 2019 **Building 8600, C156**

Time	Event	Speaker
8:30–9:00 a.m.	SEEMS: Facility Overview and SEE Testing Capabilities	Bernie Riemer PPU STS Systems Manager SNS Upgrades Office
9:00–9:30 a.m.	SEEMS: μSR Capabilities & Integration with DOE-BES Programs	Travis Williams Neutron Scattering Scientist Neutron Scattering Division
9:30–10:00 a.m.	*Discussion #2: SEE Industry Needs versus SEEMS Technical Capabilities*	
10:00–10:30 a.m.	**BREAK**	
10:30–11:30 a.m.	Funding Plans, NSF & DOE Involvement, and Operational Model	Bernie Riemer PPU STS Systems Manager SNS Upgrades Office Travis Williams Neutron Scattering Scientist Neutron Scattering Division
11:30 a.m.–12:30 p.m.	*Discussion #3: SEEMS Annual Operation & User Model*	
12:30–1:30 p.m.	User Facilities at ORNL ***(working lunch)***	Clarina Dela Cruz Science Initiative Leader Quantum Materials
1:30–3:00 p.m.	*Discussion #4: Future Outlook and Funding*	
3:00–3:30 p.m.	Meeting Closeout: Conclusions and Report	Bernie Riemer PPU STS Systems Manager SNS Upgrades Office
3:30 p.m.	**Adjourn**	

Contact: *Toni Sawyer, 865.574.7399, 865.438.8139/cell, sawyertk@ornl.gov*

updated: 06/7/2019

APPENDIX B. MEETING REGISTRANTS / ATTENDEES

Outside registrants				**Attendance**
1	Laura Dominik	Laura.Dominik@honeywell.com	Honeywell	Attended
2	Scott Marston	scott.e.marston@boeing.com	Boeing	Attended
3	David Bruno	david.bruno@collins.com	Collins Aerospace	Attended
4	Chuck Bailey	charles.r.bailey@nasa.gov	NASA Johnson	Did not join
5	Mike McCurdy	mike.mccurdy@vanderbilt.edu	Vanderbilt Institute for Space and Defense Electronics	Attended
6	Paul Bakker	paul.bakker3@ge.com	GE Aviation, US	Attended
7	Kirk Baker	kirk.baker@faa.gov	FAA	Attended
8	Robert REED	robert.a.reed@vanderbilt.edu	Vanderbilt Institute for Space and Defense Electronics	Canceled
9	Jim Marko	jim.marko@tc.gc.ca	National Aircraft Certification Transport Canada / Government of Canada	Telecom
10	Gary Horan	gary.horan@faa.gov	FAA	Telecom
11	Jerry Wert	jerry.wert@boeing.com	Boeing	Attended
12	Michael B. Smith	smithmb@ornl.gov	ORNL Advanced Reactor Engineering	Attended
13	Judy Heredia	judy.heredia@faa.gov	FAA	Telecom
14	Marcelo Prado de Oliveira	oliveira.marcelo@embraer.com.br	Embraer	Telecom
15	Alexandre Barbosa dos Santos	albsanto@embraer.com.br	Embraer	Telecom
16	Benjamin Blalock	bblalock@utk.edu	UTK	Canceled
17	David Redman	dredman@tamu.edu	Texas A&M	Attended
18	Sergio Roberto Ferreira Machado	sergio.roberto@anac.gov.br	ANAC (National Civil Aviation Agency of Brazil)	Telecom
19	David Walen	dave.walen@faa.gov	FAA	Telecom
20	Steven Bennet	steven.bennett@nrl.navy.mil	Naval Research Lab	Did not join
21	Claudio Federico	claudio.federico40@gmail.com	Institute for Advanced Studies, Brazil	Telecom
22	Dean Thompson	dean.r.thompson@faa.gov	FAA	Telecom
ORNL and Co-PIs				**At SNS?**
1	Bernie Riemer	riemerbw@ornl.gov	ORNL / SNS Upgrades Office	Attended
2	Travis Williams	williamstj@ornl.gov	ORNL / Neutron Scientist	Attended
3	Clarina dela Cruz	delacruzcr@ornl.gov	ORNL / Neutron Scientist	Attended
4	Franz Gallmeier	gallmeierfz@ornl.gov	ORNL / Neutronics Analysis	Attended
5	Paul Langan	langanpa@ornl.gov	ORNL / Neutron Sciences Directorate Associate Lab Director	Attended
6	Michelle Buchanan	buchananmv@ornl.gov	ORNL / Deputy Director for Science and Technology	Attended

ORNL & Co-PIs				At SNS?
7	Crystal Schrof	schrofca@ornl.gov	ORNL / Neutron Sciences Directorate Science and Programs	Attended
8	Greg MacDougall	gmacdoug@illinois.edu	University of Illinois Urbana-Champaign / Department of Physics	Attended

APPENDIX C. DRAFT TIMELINE FOR SEEMS PROJECT

It is necessary to quickly consolidate consensus from stakeholders to finalize the facility function and parameters. The known stakeholders are the neutron SEE testing and μSR research communities. Proton SEE testers are potential users and their interest will be further gauged. With appropriate funding support, facility scope consensus will be defined through workshops and meetings. Evaluation of facility mission scope vs. its complexity, cost and foreseen operations will be concluded. It is recognized that trying to serve too many functions can dilute excellence in key areas.

Two operating models must be developed: one for technical operation of how the proton beam will be shared or simultaneously serve beam line functions and one for how operating costs will be covered. Critically, sponsors for construction of the facility and its sustained operation must be identified.

Presuming success with identifying sponsors, the envisioned project phases and estimated times are summarized in Table C.1 (from an unpublished white paper), and graphically in Figure C.1. It is expected that it will take 10 years to be ready for operation, after support is provided to obtain consensus on mission scope from all stakeholders. Key project milestone nomenclature is based upon Department of Energy project management conventions.

Table C.1. Envisioned SEEMS project stages and estimated times to complete.

Stage	Phase / description	End milestone CD: Critical decision	Estimated time to complete (years)
1	Consensus on function and scope, definition of facility missions. Sponsors identified for construction and operation		1.5
2	Initiation: Prepare Technical Design Report	CD-0	1.0
3	Definition: Prepare Conceptual Design Report, cost range, evaluate alternatives	CD-1	1.5
4	Execution: Establish definitive cost, scope, schedule; prepare Preliminary Design Report	CD-2	1.5
5	Execution Project: Be ready for implementation; finalize design; start construction	CD-3	1.5
6	Transition / Closeout: complete construction; ready for transition to operations	CD-4	2.5
7	Transition to operations		0.5
	Total time (years)		**10.0**

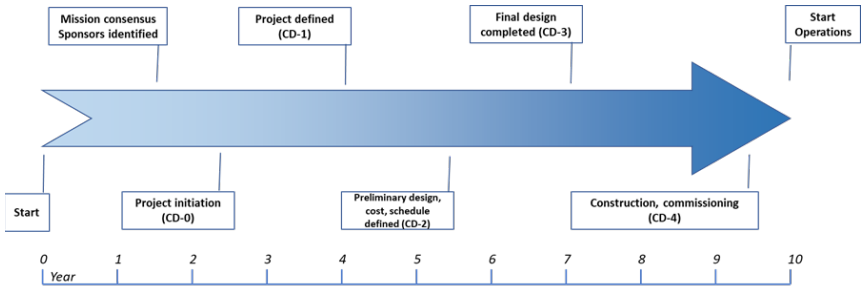

Figure C.1. Timeline for SEEMS project.

APPENDIX D. SEEMS BROCHURE

Muon Spectroscopy

SEEMS:

a Single Event Effects & Muon Spectroscopy facility at the Spallation Neutron Source

The proposed facility will have the following capabilities:

- Pulsed muon beams with a pulse width of 50ns and a facility-wide muon flux greater than 10^9 μ^+/sec
- Four surface, decay and/or low-energy μSR beamlines
- More than 200 operational days per year, with peer-reviewed beamtime proposal calls
- Dedicated support staff including instrument scientists, software engineers, sample environment technicians and administrative staff
- World-class sample environments, including ultra-low temperature, magnetic field and in-situ measurements
- Co-located with a world-leading neutron scattering program, using an accelerator that is projected to operate for decades to come

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

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SEEMS is a proposed world-class Muon Spectroscopy (μSR) facility to be located at the Oak Ridge National Laboratory in Tennessee. The goal is to deliver impactful μSR studies with high flux and high resolution enabled by the accelerator at the Spallation Neutron Source. Coupled with state-of-the-art sample environment, measurement techniques and computational resources, SEEMS will be a next-generation μSR facility in the United States.

For more information, please contact:
Travis Williams
williamstj@ornl.gov
865-576-0610

APPENDIX E. INDUSTRY LETTERS OF SUPPORT FOR SEEMS

The Boeing Company
P.O. Box 3707
Seattle, WA 98124-2207

July 30, 2019

Dr. Thomas Zacharia, Laboratory Director
Oak Ridge National Laboratory
P.O. Box 2008, MS6255
Oak Ridge, TN 37831-6255

Subject: Support for SEEMS facility at ORNL for Single Event Effects Testing of Electronics

Dr. Zacharia;

This letter is to express Boeing's support for the Single Event Effects / Muon Spectroscopy ("SEEMS") test facility being proposed as an addition to the Spallation Neutron Source facility at Oak Ridge National Laboratory.

Natural atmospheric radiation is known to cause Single Event Effects (SEE) in electronic devices. These effects can cause momentary or permanent state changes in circuits, leading to unintended behavior. Airplane electronics designers must consider these effects and appropriate mitigations, through a combination of analysis and testing, when designing and certifying systems.

As electronics continue to evolve, with ever smaller transistor structures, lower operating voltages, and higher levels of integration, the need for testing and analysis is increasing. However, access to test facilities in the US that can provide a representative radiation environment is not increasing. It is already difficult for our equipment designers and suppliers to get timely access to neutron test facilities. We are aware of no new facilities becoming available in the foreseeable future.

Our Boeing team was briefed on the proposed new SEEMS facility at ORNL in June, 2019. We understand that this proposal was developed at the request of the Federal Aviation Administration, and that the proposed facility would accurately reproduce the radiation environment at airplane altitudes, would support testing in both high- and thermal-energy environments, and would be designed to support testing at the circuit card, electronics box, or system level. We expect that, once operational, the facility as proposed would fill the Single Event Effects test needs of the US aerospace industry for the foreseeable future.

ORNL is recognized as having the expertise in designing, building and operating world-class spallation neutron sources. We are very interested in the successful execution of the SEEMS project, and thank you for considering our inputs in this planning process.

Sincerely,

Todd W. Zarfos

Vice President
Engineering Functions
Washington State Design Center

BOEING

cc: Dr. Michelle Buchanan, Deputy for Science and Technology, MS6240
Dr. Paul Langan, Associate Laboratory Director for Neutron Sciences, MS6477
Mr. Bernard Riemer, SNS Upgrades Office, MS6476

Honeywell

August 2, 2019

Dr. Thomas Zacharia, Laboratory Director
Oak Ridge National Laboratory
P.O. Box 2008, MS6255
Oak Ridge, TN 37831-6255

Re: Support for Neutron Beam facility at Oak Ridge National Laboratory (ORNL) for Single Event Effects Testing of Electronics

Dr. Zacharia,

This letter is to express Honeywell's support for a neutron test facility at ORNL, based at the Spallation Neutron Source, providing radiation beams for Single Event Effects (SEE) testing of electronics.

Natural atmospheric radiation is known to cause SEEs in electronic devices. These effects can cause a momentary or permanent change in the state of a device, leading to unintended behavior. Newly revised industry standards have formalized the SEE assessment approach for critical systems, and regulatory bodies in the US and Europe have moved to enforce conformance to these standards.

As electronics continue to evolve, with ever smaller transistor structures, lower operating voltages, and higher levels of integration, the need for testing and analysis is increasing. However, access to test facilities in the US that can provide a representative radiation environment is not increasing. We are aware of no new facilities becoming available in the foreseeable future.

Honeywell participated in a briefing on the proposed new facility at ORNL in June, 2019. We understand that this proposal was developed at the request of the Federal Aviation Administration, and that the proposed facility would accurately reproduce the radiation environment at airplane altitudes, would support testing in both high- and thermal-energy environments, and would be designed to support testing at the circuit card, electronics box, or system level. We expect that, once operational, the facility as proposed would fill the Single Event Effects test needs of the US aerospace industry for the foreseeable future.

ORNL has the expertise in designing, building and operating world-class spallation neutron sources. We are very interested in the successful execution of this neutron beam project and thank you for considering our inputs in the planning process.

Best Regards,

Stevan Slijepcevic
President Electronic Solutions

Cc: Dr. Michelle Buchanan, Deputy for Science and Technology, MS6240
Dr. Paul Langan. Associate Laboratory Director for Neutron Sciences, MS6477
Mr. Bernard Riemer, SNS Upgrades Office, MS6476