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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Definition of Capabilities Needed for a Single Event Effects Test Facility

May 2015

Final Report

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16. Abstract

The Federal Aviation Administration (FAA) is contemplating new regulations mandating testing of the vulnerability of flight-critical avionics to single event effects (SEE). A limited number of high-energy (HE) neutron test facilities currently serve the SEE industrial and institutional research community. The FAA recognizes that existing facilities have insufficient test capacity to meet new demand from such mandates; the FAA desires more flexible irradiation capabilities to test complete, large systems and would like improved capabilities to address greater concerns for thermal neutrons. For these reasons, the FAA funded this study by Spallation Neutron Source (SNS) staff with the ultimate aim of developing options for SEE test facilities using HE neutrons at the SNS complex. 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 placed on test capabilities for large avionics systems while still providing tunable high-flux irradiation conditions for component evaluations. Makers of ground-based systems would also be served well by these facilities. Three facility options are described; the most capable, flexible, and highest-test-capacity option is a new standalone target station using approximately 1 kilowatt of proton beam power on a gas-cooled tungsten target, with dual test enclosures. The standalone target station can deliver peak neutron fluxes above 10 megaelectron-volts neutron energy of more than 10^7 n/cm^2/s for component irradiation and 10^4 n/cm^2/s for system irradiation. Systems of 1 x 2 m^2 in frontal area can be accommodated. Less expensive—and less capable—options are also described.

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LIST OF ACRONYMS

AVSI	Aerospace Vehicle Systems Institute
BES	Basic Energy Sciences
BL	Beam line
CAD	Computer aided design
DAQ	Data acquisition
DOE	Department of Energy
eV	Electron-volt(s)
FAA	Federal Aviation Administration
FSAD	Final Safety Assessment Document
FY	Fiscal year
GeV	Gigaelectron-volt(s)
HE	High-energy
HEBT	High-energy beam transport
HENC	High-energy neutron cave
HETS	High-Energy Neutron Test Station
IC	Integrated circuit
ICE	Irradiation of Chips and Electronics
IEC	International Electrotechnical Commission
kW	Kilowatt
LANSCE	Los Alamos Neutron Science Center
MeV	Megaelectron-volt(s)
MW	Megawatt
mW	Milliwatt
NScD	Neutron Sciences Directorate
ORNL	Oak Ridge National Laboratory
PE	Polyethylene
PI	Principal investigator
PPS	Personnel Protection System
R&D	Research and development
RID	Ring injection dump
SEE	Single event effects
SNS	Spallation Neutron Source
SOW	Statement of work
TRIUMF	TRI-University Meson Facility
WBS	Work breakdown structure
WNR	Weapons Neutron Research

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) is contemplating new regulations mandating testing of the vulnerability of flight-critical avionics to single event effects (SEE). A limited number of high-energy (HE) neutron test facilities currently serve the SEE industrial and institutional research community. The FAA recognizes that existing facilities have insufficient test capacity to meet new demand from such mandates; it desires more flexible irradiation capabilities to test complete, large systems and would like capabilities to address greater concerns for thermal neutrons. For this reason, the FAA funded this study by Spallation Neutron Source (SNS) staff with the ultimate aim of developing options for SEE test facilities using HE neutrons at the SNS complex.

After an investigation of current SEE test practices and assessment of 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 required to complete each facility were also estimated. The SEE testing is generally performed by accelerating the event rate to a point in which the effects are still dominated by single events and double event causes of failures are negligible. In practice, acceleration factors as high as 10^6 are applicable for component testing, whereas systems testing acceleration factors of 10^4 appear to be at the upper limit. It is desirable that the irradiation facility be tunable over a large range of HE neutron fluxes of 10^2–10^4 n/cm^2/s for systems testing and from 10^4–10^7 n/cm^2/s for components testing.

The most capable, most flexible, and highest test capacity option is a new standalone target station named the High-Energy Neutron Test Station (HETS). The HETS is also the most expensive option, with a cost to complete of approximately $100 million. Dual test enclosures would allow for simultaneous testing activity, effectively doubling overall test capacity per HETS operating hour. Using about 1 kilowatt of proton power extracted from the accelerator before injection in the accumulator ring, its operation would be unnoticeable by neutron scattering users at the SNS target station. The H^- beam laser stripping technique would allow for control of beam power on the HETS target independent from power delivered to the SNS. Large systems with frontal areas of up to 1 x 2 m^2 could be accommodated with integral HE flux values (above 10 megaelectron-volts) to, at most, 10^4 n/cm^2/s; components could also be tested with flux levels to, at most, 10^7 n/cm^2/s on beam sizes of up to 0.2 x 0.2 m^2. 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. It is estimated that HETS would take 5 years to complete after award of contract, including engineering design and construction. Commissioning would take a minimum of an additional 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 and construction around existing site utilities would require careful planning and coordination with beam operations at the SNS.

An HE neutron test facility using an available beam line (BL) on the SNS target station is a technically and financially attractive option. Inspired by the new ChipIR instrument on the ISIS (physical and life science research center located at the Rutherford Appleton Laboratory near Oxford, United Kingdom) TS-2 spallation source in the UK, a similar facility could be placed on an unused BL in the SNS instrument hall (e.g., on BL-8 [both A and B channels would be needed] or on BL-10). The performance would approach that of a HETS (~80%), but it would be operationally more limited, with only a single user at a time. Space is more limited, so the maximum system size would be about half of that in a HETS. Flexibility to tailor the spectrum would be more limited. Although this concept was not as fully developed and characterized, preliminary work indicates very high HE flux levels should be possible, with ample thermal neutrons as well. Flux control would be more difficult than at HETS because proton power on target will be wherever the SNS was operating for neutron scattering. Neutron attenuation devices would have to be used 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. The estimated cost for a BL option is approximately $15 million; the time to complete would be 3 years after the award of contract, plus at least 6 months for commissioning. Interference of construction activities with SNS operations should be negligible. This option would require negotiation with the Department of Energy (DOE) Basic Energy Sciences (BES) office—the primary stakeholder of SNS—for an application outside the usual scope of neutron scattering sciences. Furthermore, these presently open BLs are highly desirable locations for proposed neutron scattering instruments; obtaining one of them for a SEE test facility will come only with persuasive and timely arguments to SNS leadership and the DOE BES.

The third option is a tunnel extension/target cave facility providing the most basic system-level irradiation capability with minimal flexibility. Though the concept is not as well developed as HETS, it would use a laser-stripping technique like a HETS, redirecting protons to a tunnel similar to the initial HETS proton transport tunnel. This concept is intended to be upgradable to a full HETS facility. Only a small fraction of a watt of proton power would be used in this basic configuration. An uncooled target and primitive shielding arrangement would provide a 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 BL option. A data acquisition (DAQ) room and support area would be located on the ground level; access to the target cave would be by elevator/ stairway. As a result of the required excavation, new tunnel construction, shielding, DAQ building, utilities, and other items, the estimated cost is $30 million. The time to complete is expected to be more than 3 years; construction interference with SNS operations has not been accounted for, but it could have a significant impact.

Promotion of a SEE test facility based at the SNS site requires strategy, planning, and effort beyond the scope of this study. However, a few points are offered for consideration. Acceptance from the BES office for an SNS facility is essential. Achieving that will require communication and persuasion regarding the importance of the national need for such a facility and the unique capability that an HE spallation source offers. The BES has primary ownership of the SNS, and any SEE footprint would require negotiation with BES for an agreeable construction and operation model. Dedicated funding to construct and provide full and sustained operation of any facility option must be found and must augment the budget that BES provides for operating the SNS through its Scientific User Facilities program. Finally, further optimization of any preferred option is needed to develop a true conceptual level, a necessary requirement before proceeding to full engineering design.

1. INTRODUCTION

The Federal Aviation Administration (FAA) funded this study to investigate capabilities for single event effects (SEE) avionics system testing at the Spallation Neutron Source (SNS) [1] because there is a recognized need to increase the available testing capacity and improve on existing test facility capabilities, particularly in North America [2]. Industry trends, such as greater use of complex flight-critical avionic systems, smaller integrated circuit (IC) feature sizes, and lower IC voltage, in aggregate, point to increasing susceptibility to adverse effects of atmospheric radiation. The dominant radiation form leading to SEE phenomena in aircraft avionics is high-energy (HE) neutrons (above 1 megaelectron-volt [MeV]), which have their origins from cosmic radiation and its interactions with the upper atmosphere[3].

Cosmic radiation in outer space is primarily (92%) HE protons with smaller contributions from alpha particles and other heavier ions, with energies up to 10^{19} electron-volts (eV) [4]. Through interaction with the atmosphere, radiation from space is transformed to predominantly neutrons (96%) with a spectrum of energies up to approximately 10^{11} eV. The SEE occur when atmospheric radiation, comprised of HE neutrons and other particles, collide with specific locations on semiconductor devices contained in aircraft systems. Interaction with IC materials can lead to elastic or inelastic collisions resulting in ionization/displacement of circuit material. Memory devices, microprocessors, and field-programmable gate arrays are most sensitive to SEE. Low-energy or thermal neutrons (25–200 millielectron-volts) can also lead to SEE; these are produced within aircraft through moderation of HE neutrons with fuel, personnel, or carbon-based materials, which are now more widely used in airframe construction. Thermal neutron interaction with Boron-10—a dopant sometimes used in IC manufacturing and intimately located within the devices—leads to a reaction producing energetic lithium ions or alpha particles with similar adverse effects on IC function.

New regulations for industry are being contemplated to mandate assessment of avionic system SEE vulnerability with HE and thermal neutrons and for qualification testing of mitigation techniques against SEE phenomena. Example avionic systems include:

- Aircraft control systems that use fly-by-wire technology
- Autopilot
- Flight warning
- Communication (high frequency, very high frequency, satellite voice)
- Navigation
- Displays
- Full Authority Digital Engine Control
- Engines (including auxiliary power units) or propeller control systems
- Any other systems containing digital/electrical devices

A suitably designed SNS—using an incident proton beam of approximately 1 gigaelectron-volt (GeV)—can provide a close match to the atmospheric HE neutron spectrum at substantially accelerated rates. As envisioned by the FAA, the anticipated scale of required testing exceeds the current capacity of U.S. facilities. Furthermore, improvements over existing capabilities are sought, for example, in the size of avionic systems that can be tested, and in the flexibility to additionally test with lower-energy neutrons (thermal, epi-thermal) and protons. Assessment regulations are also being proposed by the European Aviation Safety Agency.

The initial concept for an SNS-based SEE test facility proposed using an existing waste proton beam directed to the SNS Ring Injection Dump (RID), to which some 100 kilowatts (kW) of beam power can be sent. Early in the study, this option was determined to be impractical and to pose potential risks to neutron scattering operations. Reconfiguration of the RID itself would be an endeavor entailing radiation and contamination hazards; the RID was not designed for reconfiguration. The region of the accelerator facility leading into the RID is congested with components for charge stripping, beam steering, and control, as well as for diagnostics. Radiation levels are high relative to most of the accelerator complex. There is very little space to add new steering magnets or other components that might be used to direct a beam to a nearby new spallation target and SEE test area. Neutronics studies confirmed that 100 kW was much more power than is needed to provide necessary neutron flux levels at a purpose-built test station, so significant collimation/attenuating devices would be needed.

A technique using a laser to strip electrons off the H^- beam after the end of the high-energy beam transport (HEBT) bend could be used to send a modest and useful amount of proton power (a few kW) to a new target and test facility. The laser stripping technology exists and has been demonstrated at this power level [5]. It allows for fine adjustment of power to target, a feature that could be exploited depending on user demands for neutron intensity. Although other areas of the SNS complex besides the RID were examined for test facility potential, the laser stripping approach has the best prospects for providing either a full-featured test facility or a low-cost option with upgrade potential.

Emphasis has been placed on accommodating testing avionic systems as opposed to individual components (e.g., IC chips on boards). Systems were clearly identified in the study's statement of work (SOW) negotiated with the FAA. The required dimensions are a driver for test enclosure size and, therefore, for the volume of neutron shielding, which is a significant facility cost driver. However, the definition of large was not clear. Informally, at a meeting among SNS staff, FAA staff, and an Aerospace Vehicle Systems Institute (AVSI) representative, it was agreed that the minimum size was approximately that of a household microwave oven, and the maximum size that of a jet engine. In the course of reviewing worldwide facility capabilities, it was noted that the ChipIR SEE test instrument (now under commissioning) at the ISIS (physical and life science research center located at the Rutherford Appleton Laboratory near Oxford, United Kingdom) TS-2 spallation source was designed for neutron irradiation of systems of up to 1×1 m^2 in frontal area [6–8]. Consideration has been given to including ground-based computer systems that are also adversely impacted by SEE phenomena, albeit at a slower rate. Although this study focused on needs for the aviation industry, the ground-based electronics community would also be a large base of potential users of a future SNS facility. For design purposes in this study, a maximum beam size for system irradiations of 1×2 m^2 in frontal area was considered, which is big enough for a 42U computer rack cabinet.

Component testing was not explicitly defined in the study's SOW. However, the SNS study team expects sustained demand for component testing by the avionics industry and institutional researchers and considers component test capability a priority. This was confirmed at a meeting with the FAA and an AVSI member in November 2013. Key differences between component and system testing are the required neutron flux and beam spot size. Goals for both types of testing have been defined. The beam spot size for components could be as small as a few square millimeters but as large as approximately $0.2 \times 0.2\ m^2$. The high flux levels anticipated for component testing—even with the relatively small spot size compared with the system requirement—are a driver for enclosure shielding thickness and facility cost. Flux levels will be discussed in detail.

Study of the ChipIR instrument at ISIS indicates that it will provide world-leading capabilities superior to those of the Irradiation of Chips and Electronics (ICE) House at the Los Alamos Neutron Science Center (LANSCE) [9] in terms of system irradiation capabilities, component flux levels, spectrum modification, data acquisition (DAQ) infrastructure, available operating hours, and ease of access for European Union users. A full-featured and world-class option for North America at the SNS would have features partially based on ChipIR. Technically, this could be achieved with either of two options at SNS: an HE neutron SEE test instrument using one of the SNS target station's unused instrument beam lines (BLs), or a new High-Energy Neutron Test Station (HETS) optimized for SEE testing. Although the former would be substantially less expensive to construct, the reality is that the Department of Energy (DOE) Office of Basic Energy Sciences (BES) has made a large investment in the SNS for the purpose of neutron scattering science. The BLs on the SNS target station are highly valued.

This study has focused on the HETS option. Regardless of competition for an available SNS BL, capabilities and cost estimates for an SNS BL instrument are also included in less detail because it is possible this option could ultimately be approved. A third low-cost, low-capability option is included that could provide some system testing functionality in a shorter time frame with less flexibility and performance than a HETS, but that is consistent with upgrading to the full-featured facility should resources later become available.

2. THE SOW AND DELIVERABLES REVIEW

Four tasks and related deliverables were identified in the SOW for the study.

2.1 TASK 1—INVESTIGATE CURRENT SEE TEST PRACTICES IN AVIATION

Testing for SEE is currently taking place at a number of facilities, both inside and outside the United States. The purpose of Task 1 is to gain an understanding of current test practices through literature searches and interviews with active researchers in the field. Understanding the tests that researchers desire, and how they go about trying to complete the tests, is the first step in understanding if a gap in current testing exists.

Deliverable for Task 1—Briefing via teleconference or Web presentation. In addition, a summary report in the form of PowerPoint® slides or short text shall be delivered. This deliverable will be incorporated in the final report.

2.2 TASK 2—DETERMINE THE CAPABILITIES OF WORLD-LEADING SEE TEST FACILITIES AND DETERMINE THE SHORTCOMINGS OF THESE FACILITIES BY WORKING WITH THE AVSI AFE 72 WORKING GROUP

In Task 2, it will be determined, in conjunction with the AVSI working group, where the current testing ability is inadequate or could be improved for system-level testing (development of design criteria). Recommendations for improvements shall be documented and ranked according to how important these changes are for a new facility.

Deliverable for Task 2—Briefing via teleconference, Web presentation, or on-site at the FAA Technical Center. In addition, a summary report in the form of PowerPoint slides or short text shall be delivered. This deliverable will be incorporated in the final report.

2.3 TASK 3—STUDY AND DETERMINE WHAT CAPABILITIES ARE REQUIRED TO GENERATE THE ATMOSPHERIC CONDITIONS THAT ARE DESCRIBED IN TASK 2 FOR SYSTEM LEVEL TESTING

In Task 3, Monte Carlo models of a possible facility at SNS will be developed. Calculations will be completed to determine if, or to what extent, the design criteria developed in Task 2 can be met. Anticipated studies will be completed to answer questions, such as:

1. What is the maximum energy achievable?
2. What are the tradeoffs between flux and maximum energy?
3. Can solar flare testing be accommodated?
4. What is the impact of apertures and filters? How much phase space can be accommodated?
5. What beam size can or should be accommodated, knowing beam size is related to cost?
6. How does target view impact spectrum and performance?
7. What is the impact of extracted beam size on incident flux?
8. To what extent can the thermal beam component be enhanced through the introduction of a neutron moderator?

Deliverable for Task 3—Briefing via teleconference, Web presentation, or on-site at the FAA Technical Center. In addition, a summary report in the form of a short document shall be delivered. This deliverable will be incorporated in the final report.

2.4 TASK 4—BASED ON THE CURRENT SHORTCOMINGS OF CURRENT SEE TEST FACILITIES AND THE CAPABILITIES AT ORNL, DETERMINE IF A NEW FACILITY COULD CLOSE THESE GAPS, AND AT WHAT ESTIMATED COST AND SCHEDULE

This task will focus on modifications to existing facilities at SNS that could be made to address the needs identified in Task 2 and the design options studied in Task 3. A schedule for the resulting concept will be developed and a cost estimate completed. Areas to be addressed include the location or possible locations for such a facility, the proton beam optics required to transport the proton beam, the possibility of using existing utilities for the facility, and the location or locations of the experiment room(s).

Deliverable for Task 4—Briefing at the FAA Technical Center. A final report will be delivered after the briefing, providing the opportunity to address questions raised during the briefing in the final report.

3. FINDINGS

The study effort began in May 2013. The team focused on investigating current SEE test practices (Task 1) and determining the capabilities and limitations of world-leading SEE test facilities (Task 2) for several months. Publications were researched, standards were compiled, and websites were explored. More than 100 papers, standards, and related documents were collected, and more than two dozen relevant websites were identified. The team communicated with AVSI member and Honeywell employee Laura Dominik, an acknowledged expert in SEE phenomena and testing.

In addition, unrelated trips by SNS staff provided the opportunity for the principal investigator (PI) to visit and tour two of the most important SEE test facilities:

1. The ICE House at LANSCE Weapons Neutron Research (WNR) facility in Los Alamos, New Mexico [9 and 10].

2. The ChipIR instrument at the ISIS TS-2 SNS at Rutherford Appleton Laboratory in Didcot, Oxfordshire, UK [6 and 7].

In November 2013, a status meeting was held at the FAA William J. Hughes Technical Center [11]. The meeting was characterized by productive discussion that was useful to the SNS team. The requirements/needs/wish-list features for a new SEE test facility were better understood; that clarity was necessary to progress on concepts for a facility at SNS. However, some design goal parameters remain ambiguously defined. The industry and regulators are in a state of continuing evolution regarding the testing capability required to meet future standards. For example, the need for protons/pions/muons vs. pure neutron irradiation could not be established at the time of the meeting. Participants in the meeting expressed a desire for test facility flexibility.

3.1 TASK 1—INVESTIGATE CURRENT SEE TEST PRACTICES IN AVIATION

A broad range of industries with interest in SEE testing were identified. In the case of aviation, HE neutrons (10 MeV and up) and protons (100 MeV and up) have been most responsible for SEE in electronics at commercial flight altitudes. Devices with dimensions of 150 nm and below also have a significant SEE sensitivity to neutrons in the range of 1–10 MeV. Devices containing boron as a dopant or in a glassivation layer become very sensitive to thermal neutrons (reaction: $B^{10} + n \rightarrow Li^7 + \alpha$).

Atmospheric neutron flux depends on altitude and latitude. Integral flux for neutrons at 10 MeV and above at 40,000 ft and 45° latitude is reported as 6000 $n/cm^2/h$ [3]. The HE neutrons are moderated and thermalize with hydrogenous materials (e.g., cargo, fuel, passengers, and plastics) and are absorbed by neutron poisons like boron if they are present.

3.1.1 Standards Specific to Avionics

Two International Electrotechnical Commission (IEC) standards specific to avionics were noted as particularly useful for SEE avionic testing and our study: IEC International Standards 62396-1 [12] and 62396-2 [13]. Figure 1 shows the atmospheric neutron spectrum at 40,000 ft, based on measurements and models, over the range from 1 kiloelectron-volt to 3 GeV. The IEC standard 62396-1 states that neutrons with energies greater than 10 MeV are the dominant cause of SEE for sensitive devices with geometric features larger than 150 nm; however, for devices with feature sizes ≤150 nm, the contribution of neutrons with energies between 1 and 10 MeV may be significant. What was learned from current practice is that integral flux values are typically reported for energies above 10 MeV, but the importance of lower-energy neutrons is recognized particularly because the industry trend is toward feature sizes much smaller than 150 nm. Lower-energy neutrons in aircraft are addressed in IEC Technical Specification 62396-5 [14].

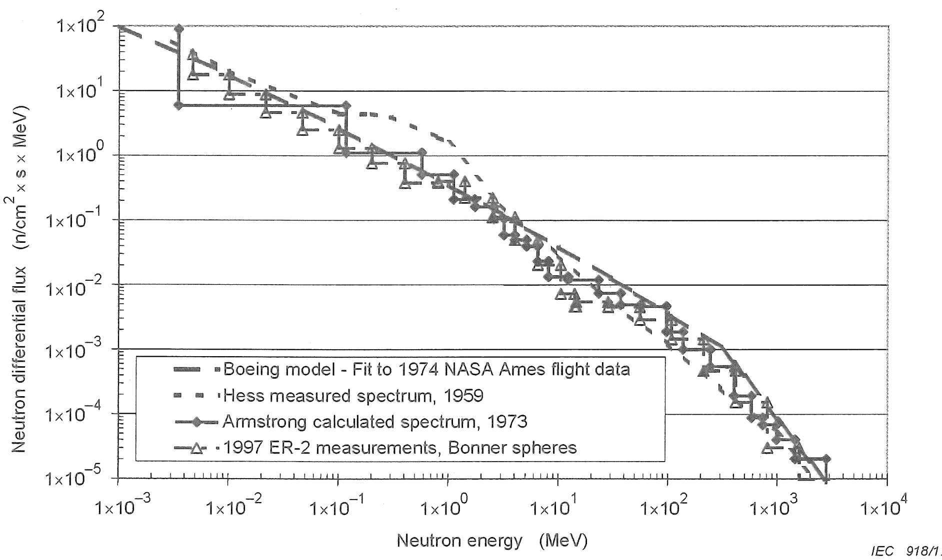


Figure 1. Energy spectrum of atmospheric neutrons at 40,000 ft (12,160 m), latitude 45 [12]

Current testing practice is dominated by component testing, with radiation imposed on relatively small areas typical of IC chip sizes. The dominance of component testing is due to current research demands from industry, limited test time at suitable sources, and facility capabilities.

3.1.2 Facilities

Identified irradiation source types for SEE testing include:

- Mono-energetic proton sources
- Quasi mono-energetic neutron sources
- Heavy ion sources (space applications)
- Laser sources (photoelectric effects)
- Neutron generators (deuterium-tritium sources)

- Real-time measurements at ground and at mountain top
- Spallation neutron sources

The spallation neutron sources have several advantageous features that make them particularly desirable. Perhaps most important is that they can produce a neutron spectrum that is prototypic to radiation found in the atmosphere. Figure 2 shows the ground elevation differential flux (New York City, scaled) along with those obtained from two HE spallation sources: the ICE House at the WNR Facility at LANSCE and the TRIUMF Neutron Irradiation Facility in Vancouver. The ICE House spectrum matches the ground spectrum particularly well from approximately 20 to 600 MeV. Heavy ions have a minor impact on aircraft at typical commercial vehicle altitudes; they are better suited to spacecraft SEE testing. Ground and mountaintop testing is simply limited in test throughput, as flux levels are less than that of aircraft at altitude.

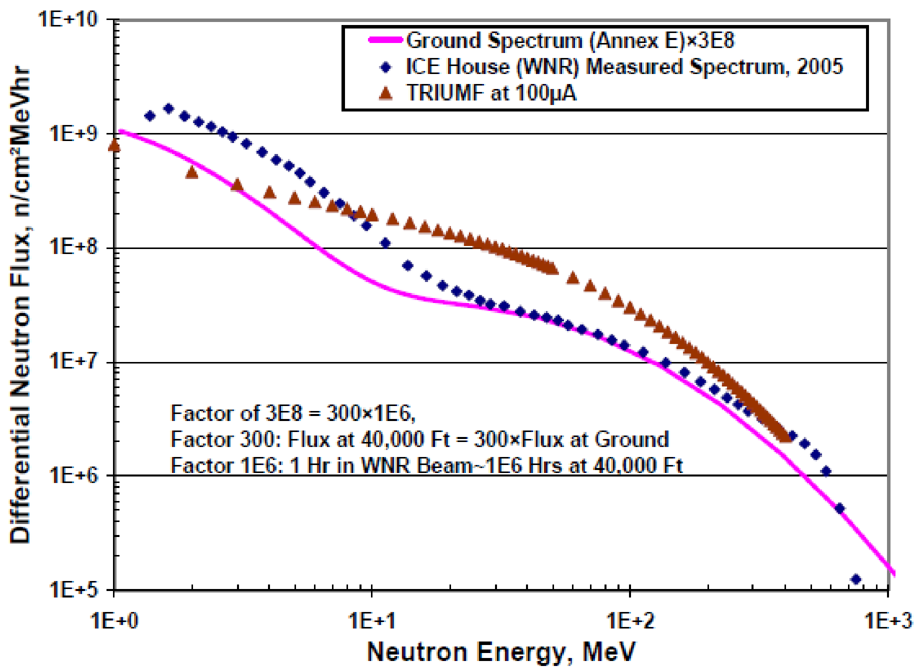


Figure 2. Comparison of Los Alamos and TRIUMF neutron beam spectra with terrestrial spectrum [15]

If moderating material is placed in an HE neutron BL, flux of thermal energy neutrons can be enhanced to account for lower-energy neutrons encountered inside aircraft from HE interactions with fuel, passengers, and plastics. Thermal neutrons have a higher probability of interacting with certain isotopes, such as boron-10; its use in semiconductors increases their vulnerability to upset events [16].

It is possible to obtain large-area beams at the ICE House, but according to facility staff, there has been little demand for them. Most users request a 1–3 in. diameter beam (adjustable by collimation) for component testing. It is possible to irradiate larger systems by removing collimation and placing equipment further away from the beam port.

High neutron flux levels are essential for performing accelerated testing. The ICE House neutron flux (integrated neutron flux above 1 MeV is ~ 10^6 n/cm^2/s) is approximately a million times higher than the flux of neutrons produced by cosmic rays, depending on altitude [15]. One hour of exposure in the ICE House beam is equivalent to more than 100 years of exposure at aircraft altitudes. Because SEE events are somewhat rare, high acceleration is needed for fundamental investigation of components or reliability demonstrations of avionic systems.

Typical ICE House users test with one to a few days of beam time and bring their own DAQ hardware for monitoring equipment under irradiation. The neutron spectrum and fluence on equipment is monitored by LANSCE staff, and the data are provided to the users. A number of tested components can be irradiated simultaneously by stacking and aligning them in the BL (see figure. 3). Successive neutron attenuation of HE neutrons in such a setup is not large; it is accounted for by algorithms provided by LANSCE staff. Increasing distance must also be accounted for. Alignment is achieved by use of a double-ended laser that is set on fiducial markings on the fission chamber at the beam outlet (for spectrum characterization) and the beam dump at the far end of the test room. For inch-scale components, this technique has been sufficient.

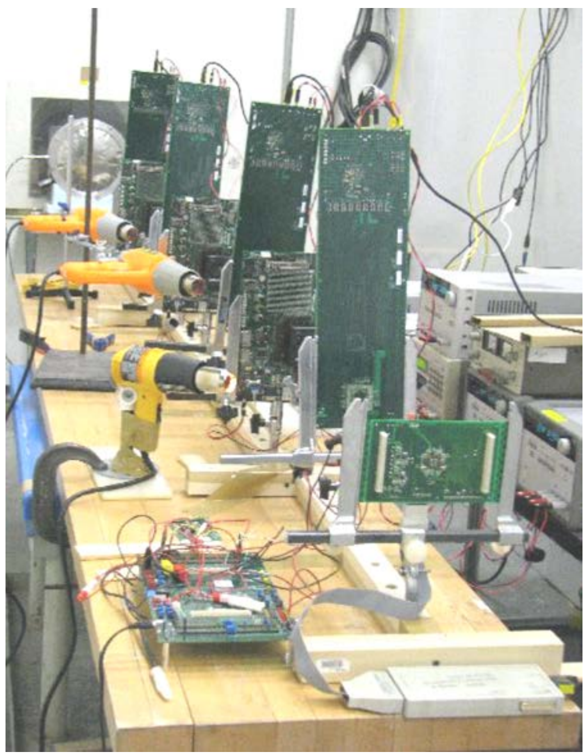


Figure 3. Circuit boards with components aligned for neutron irradiation at the ICE House [2]

The ICE House offers fairly large test rooms; once users have taken the proper safety training, they are free to operate the neutron shutter and to access their hardware as needed. Aside from beam size collimation, the beam condition is coupled to other users of the spallation target at the WNR. Any unique operating requirements must be negotiated with LANSCE staff with consideration for other users. Since 2012, a second test area at the WNR has been configured and dedicated for SEE testing. With the two ICE Houses now operating, the annual number of available test hours is reported as approximately 3000 each [17].

TRIUMF offers both component and system test capabilities in separate areas:

> High energy neutron beams are produced by 450 MeV protons stopping in a water-cooled aluminum beam dump on one of the high-intensity proton lines. The neutron beam of dimensions 5 cm × 12 cm and fluxes of 3×10^6 n/cm^2/s (>10 MeV) is accessed vertically by a long narrow slot in the surrounding steel shielding. The presence of the water moderator means that a significant flux of thermal neutrons (~25% of the high energy flux) is also present. While this arrangement is frequently used for small component and device testing, the access is limited for larger systems and the flux is too great for high-level system testing [18].

The access for components, noted as being awkward, is by way of a 5 × 15 cm vertical channel, requiring that test components be lowered into place by a pulley system. A system test capability has been developed at TRIUMF with a large-area neutron beam generated by protons on a lead absorber in another area. The neutron beam size is 80 × 80 cm^2, with a maximum flux 10^7 higher than the sea level flux for neutrons of 10 MeV or higher. It can be varied from more than 50,000 n/cm^2/s to less than 1000 n/cm^2/s by changing the proton current or the distance to the test point. Two proton beam energies are possible—either 500 or 116 MeV. Wender reported that there are 3000 hours per year available for component testing and 800 hours per year available for system testing at TRIUMF [10].

ChipIR at the ISIS TS-2 SNS is now in commission [6–8]. Located at the Rutherford Appleton Laboratory in the UK, ChipIR was purpose-built for SEE testing of avionics and ground-based electronics systems and components. A typical instrument on an SNS for scattering science uses thermal/cold neutrons; the TS-2 source was designed for such instruments. Modifications to the ChipIR BL are designed for maximizing HE neutrons to the sample equipment. Simulations predict that the neutron spectrum will be a good match to atmospheric neutrons from cosmic rays at commercial aircraft altitudes and at ground level. Flux levels with small beams for components are expected to exceed the ICE House level (perhaps reaching 10^7 n/cm^2/s), and large systems will have more modest fluxes. Up to 1 × 1 m^2 systems can be irradiated. Spectrum tailoring is also possible.

The ChipIR facility was toured in August 2013, and a number of features and user accommodations were noted. These include movable equipment stages for components and systems, allowing remote alignment of equipment to beam; remotely controlled beam collimators; remotely controlled neutron beam filters; patch panels and cabling between the test enclosure and the DAQ room; an electromagnetically shielded DAQ room; quiet power supply for the DAQ room and test enclosure; quiet heating, ventilation, and air-conditioning for the DAQ room; and a private break room for ChipIR users. If it achieves its performance goals, ChipIR is poised to become the premier neutron SEE test facility in the world. ChipIR should have approximately 3000 annual operating hours.

Two other spallation source SEE test facilities are briefly noted here. The Atmospheric-like Neutrons from the thIck TArget facility at the Svedberg Laboratory in Sweden uses a 180 MeV proton beam incident on a tungsten target [19]. The Research Center for Nuclear Physics at Osaka University uses a proton beam with incident energies up to 392 MeV [20 and 21].

3.2 TASK 2—DETERMINE THE CAPABILITIES OF WORLD LEADING SEE TEST FACILITIES. DETERMINE THE SHORTCOMINGS OF THESE FACILITIES BY WORKING WITH THE AVSI AFE 72 WORKING GROUP

Some Task 2 findings overlap with the Task 1 scope and are reported in section 3.1. Based on discussions with the FAA and with AVSI member Laura Dominik, a primary issue is the lack of available test time at suitable facilities to satisfy the anticipated increase in need that will result from new FAA regulations mandating testing of avionics systems. Motivation for a new test facility at the SNS is further described by Dominik et al. [22]:

> The WNR ICE House facility is seen as being oversubscribed and underfunded, and access to it is seen as sometimes being difficult or unreliable:
>
> C. Existing Limitations at WNR
>
> Government and customer specifications increasingly require assessments of the single event effects probability in electronics from atmospheric neutrons. The accelerator that best simulates this neutron spectrum is the WNR facility at Los Alamos, but it is underfunded and oversubscribed [16]. As the demand for this facility in terms of hours of neutron beam time has consistently increased over the past ten years, accessibility to this facility has become a problem for the variety of industries and companies that want to use it for testing their new electronics in a simulated neutron environment.
>
> In 2004, because of security issues at LANL, the entire laboratory was shutdown to visits from outside users for many months. In 2005, there were indications that due to cost cutting pressures, the entire LANSCE operation may be curtailed by about a factor of 50%. Since 2005, access to LANSCE is available only via a yearly proposal and follow-on LANSCE time allocation. If an industry need for LANSCE beam time is identified, it conceivably could take an investigator 18 months to get the beam time. Such delays cannot be tolerated in fast paced industries [22].

Note: The article from which this quotation was taken was published before the opening of the second ICE House at WNR in 2012, which effectively doubled the potential operating hours. In CY 2012, LANSCE reported 2845 hours of beam delivered to WNR [17]; it is unknown how much of that was available to users of the ICE House, which requires beam sent to WNR target 4. By comparison, in CY 2011, LANSCE reported the WNR received 1062 hours of beam [23]. In CY 2010, 2635 hours were delivered to WNR target 4 [24]. The longer term outlook for WNR operating hours is difficult to predict. The accelerator began operations in 1972. The

LANSCE-LINAC Risk Mitigation project will replace obsolete and end-of-life equipment at LANSCE and will provide new capabilities [17].

Regardless, a presentation provided by Gary Horan of the FAA to the SNS (included in appendix A) further highlights these reasons for the need for additional test facilities:

- Increasing demand for SEE testing of components
- System-level testing for robustness and mitigation verification
- HE (solar storm) testing
- Thermal neutron testing

Boron is again being used in IC manufacturing, increasing vulnerabilities to thermal neutrons. The FAA, AVSI, and IEC foresee an increasing need for testing systems and components with thermal neutrons. The demand will depend on the specific test goals of the experimenter. The ability to add thermal neutrons to an HE (atmospheric-like) spectrum can be accommodated by placement of a water or polyethylene (PE) volume and thermalizing reflector in the HE BL at close proximity to the target. Thermalizing neutrons comes at some expense to the HE flux. It is conceivable that such a moderator could be moved in and out of use on demand.

3.3 TASK 3—WHAT IS REQUIRED FOR A FUTURE SYSTEM TEST FACILITY TO SATISFY ANTICIPATED NEEDS

The HE neutrons of energies 1 MeV and up are largely responsible for SEE because of their abundance in the atmosphere and their penetrability. The neutron flux intensity varies greatly with altitude and latitude, with peak fluxes reached at 60,000 ft and 90° latitude. The spectral shape of the neutron flux field is fairly constant, exhibiting approximately a 1/E dependence up to 300 MeV and a $1/E^2$ dependence above 300 MeV, extending to multiple tens of GeV. The conditions at 40,000 ft altitude and 45° latitude are commonly adopted as a reference cosmic-ray-induced flux field for electronics exposure, as this is the region most often frequented by commercial flights. At this altitude and latitude, approximately half of the peak flux values are achieved with integrated neutron fluxes of 1.55 $n/cm^2/s$ and 2.44 $n/cm^2/s$ above 10 MeV and 1 MeV, respectively [12].

Solar flare events can substantially increase the atmospheric particle fields; for example, two orders of magnitude of increase in the neutron flux was reported for the solar flare that occurred on February 23, 1956. The spectral differences in the neutron fields are minor (in the 1–1000 MeV range that makes up the bulk of the neutron flux intensity), as shown by data from the QinetiQ Atmospheric Radiation Model database, shown in figure 4 [25 and 26]. At energies above 1 GeV, the falloff for the solar flare is more pronounced because the incoming solar protons have a considerably softer energy spectrum compared to cosmic particles [15 and 27]. The spectral differences between cosmic source atmospheric radiation and the solar flare source are inconsequential to SEE; the danger of solar flares lies in the increase of the flux intensity. Providing higher flux at a test facility is more important than closely matching the solar spectrum.

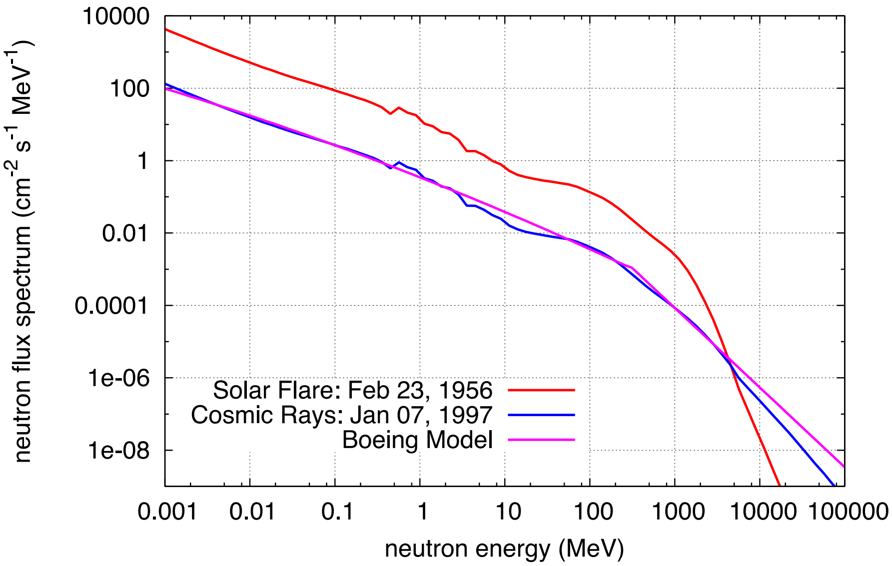


Figure 4. Comparison of neutron flux spectra for regular cosmic ray and solar flare enhanced conditions of January 7, 1997 and February 23, 1956 [25]

To conduct electronics testing within a reasonable experiment time, it is desirable to accelerate the SEE rate by increasing the flux intensity. Acceleration is limited by the fact that, depending on the sensitivity of the particular electronics under investigation at a certain flux level, the frequency of the irradiation effects rises to a point at which undesirable interference effects of two or more events come into play and cloud the experimental results. As present-day SEE irradiation facilities allow acceleration factors of about 10^6, we decided for the study phase of our work to limit the study to a peak of >10 MeV neutron fluxes of 10^7 n/cm^2/s. As the acceptable level of acceleration depends on the radiation sensitivity of the components, the irradiation facility must provide means of tuning the flux intensity.

The ICE irradiation facilities at Los Alamos National Laboratory demonstrate that an 800 MeV proton beam incident on a compact tungsten target generates a neutron source with a spectrum closely matching the atmospheric neutron spectrum if viewed at 30° with regard to the incident proton beam (see figure 2). Simulations were performed with Monte Carlo N-Particle Transport Code for the SNS 1.0 GeV proton beam to assess the angular dependence of neutron emission from a tungsten target of 5 cm diameter [28]. Figure 5 compares the 1.0 GeV results with the The Boeing Company model atmospheric neutron spectrum [12]. The calculations were completed at 1 kW proton beam power. In the energy range of 10 to 600 MeV, the spallation spectrum at a 30° emission angle describes the Boeing model spectrum shape very well; for lower energies, the spallation spectrum overpredicts the Boeing model; and for energies above 600 MeV, the spallation spectrum underpredicts the model.

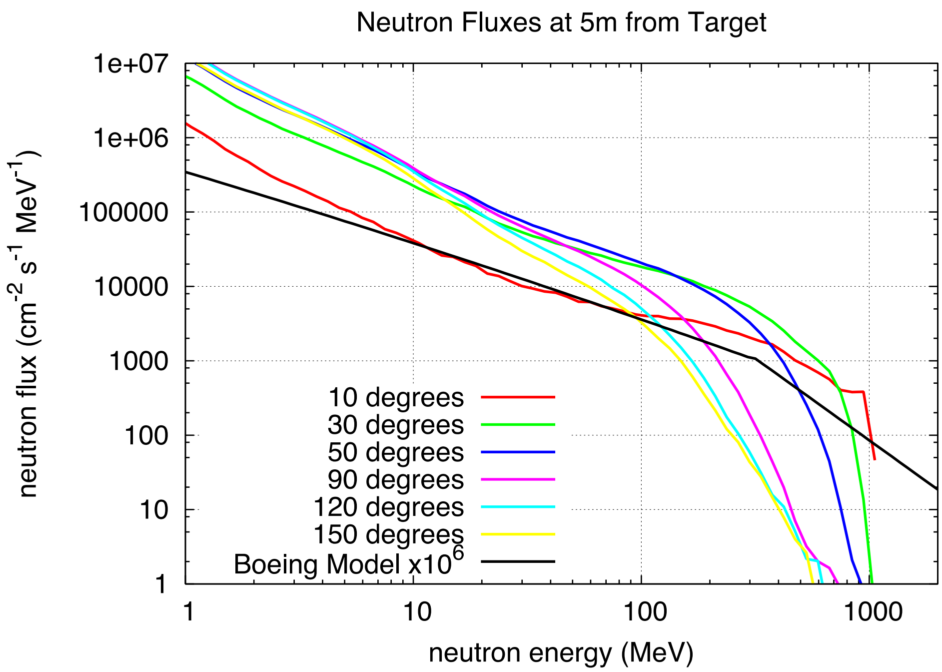
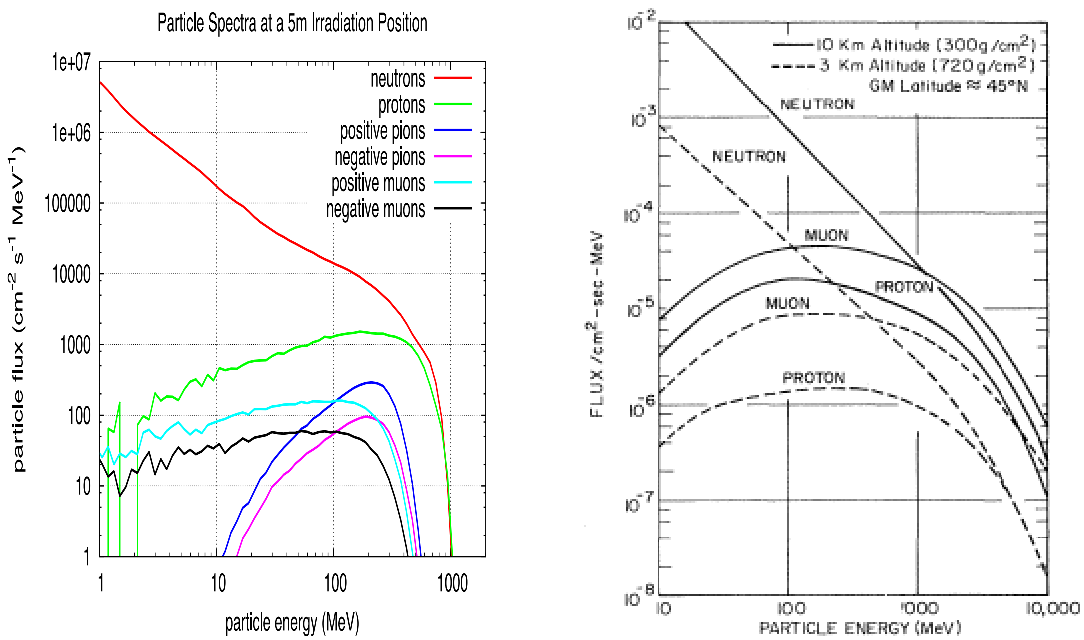


Figure 5. Angular neutron and proton emissions due to a proton beam of 1.0 GeV energy and 1 kW power incident on a 5 cm diameter tungsten target compared with the Boeing model atmospheric neutron spectrum

Particles in the atmosphere other than neutrons can contribute to SEE, as is discussed in IEC International Standard 62396-1 [12]. Proton fluxes are reported to be equal to neutron fluxes above 300 MeV and to drop to the 10% level below 300 MeV. Because SEE caused by HE protons are similar to neutron induced SEE, their contribution can be included in neutron irradiation experiments by further scaling up the HE neutron flux by 20%–30%.

In the past, other atmospheric particle contributions to SEE, like those from pions and muons, were considered negligible. However, the impact of pions and muons on SEE appears to be an area of continued investigation.

Secondary protons and pions are also produced in proton-induced spallation reactions in tungsten. Figure 6 shows the calculated proton, pion, and muon fluxes at 30° emissions from a 5 cm diameter tungsten target compared with the neutron emission on a per proton basis. Muons are produced through pion decay in flight; as a consequence, the pion and muon mix changes with distance from the target. Based on Ziegler and Lanford, the muon fluxes at spallation targets are approximately an order of magnitude lower than those in the atmosphere [29].



(a) (b)

Figure 6. The (a) angular neutron and particle emissions due to a proton beam of 1.0 GeV energy and 1 kW power incident on a 5 cm diameter tungsten target, and (b) atmospheric particle spectra [29]

When moderating materials containing hydrogen/carbon are present, large quantities of moderated and thermalized neutrons can build up in airliners. These can harm electronics as a result of absorption in neutron poisons, such as B-10, that are occasionally present as trace isotopes in IC insulation. The thermal flux in an airliner may vary greatly based on the presence of hydrogenous moderator materials, such as fuel or passengers. The IEC Technical Standard 62396-5 summarizes the current research on thermal neutron flux (below 1 eV) in commercial airliners to be at levels approximately 0.2–2 times the HE neutron flux (above 10 MeV) [14]. Considering this range, a reasonable choice for a testing beam is to have equal numbers of thermal neutrons and more than 10 MeV neutrons, keeping in mind that locations with double the thermal flux may exist on airplanes.

The thermal component in the neutron spectrum can be generated with a spallation source by placing hydrogenous materials at the target. Figure 7 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.

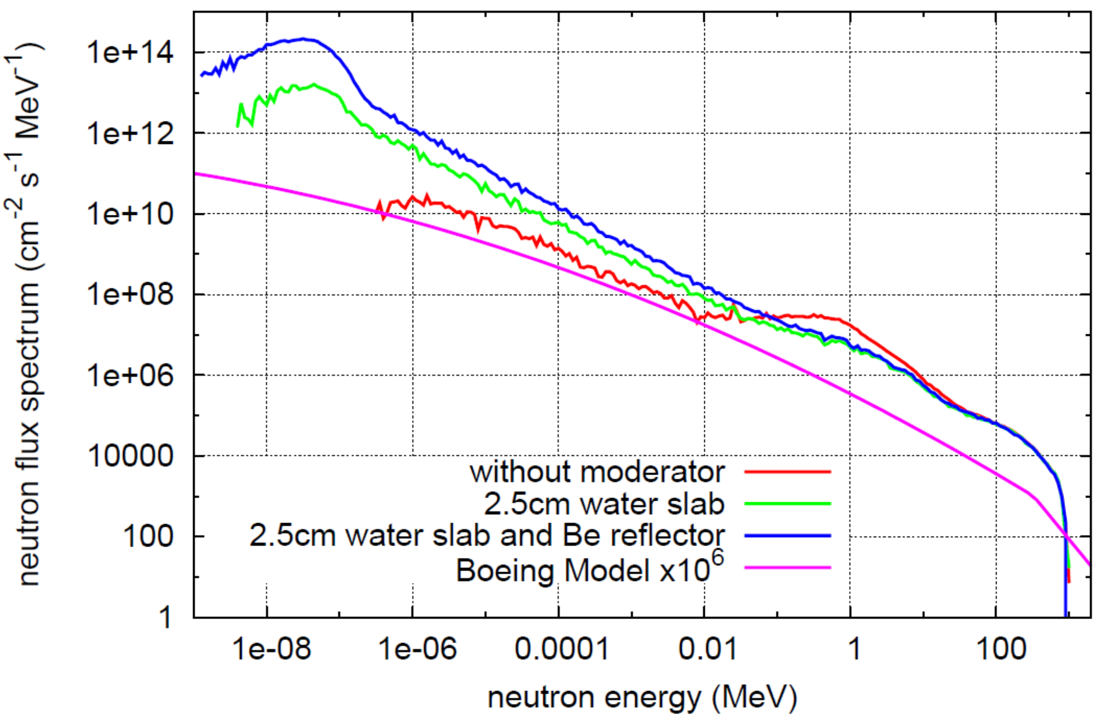


Figure 7. Neutron spectrum at 30° from a 1kW 1 GeV proton beam incident on a bare tungsten target, from a 2.5-cm water slab at the tungsten target, and from a 2.5-cm water slab at a reflector surrounded by beryllium, to a 30-cm radius at a tungsten target

A 30° takeoff angle from a GeV proton beam incident on a tungsten target seems to be the most economical method of generating an atmospheric neutron spectrum. However, the neutron beam from the SNS water moderator emitted into BL-8 provides a spectrum and intensities above 10 MeV that come very close to the ideal (assumed irradiation position at 9 m distance from target), even though BL-8 is at a 49° angle. Below 10 MeV, though, the differences are pronounced, as shown in figure 8. This beam is generated by viewing the water moderator located below the mercury target, meaning that spallation neutrons from the target must undergo another scattering event to contribute to the neutron beam. By filtering this beam with 2 cm PE and 12 cm of aluminum, the spectral shape for energies below 10 MeV can be significantly improved at a cost to overall intensity. Simulations indicate that integral fluxes (filtered) above 10 MeV of 5.4×10^6 n/cm^2/s are achievable with SNS being driven at 2 megawatt (MW), compared with 6×10^6 n/cm^2/s obtainable at a 5 m distance from a tungsten target powered by a 1 kW proton beam. The charged particle contribution in an SNS neutron BL is low because the neutron beam is generated by a secondary scattering source.

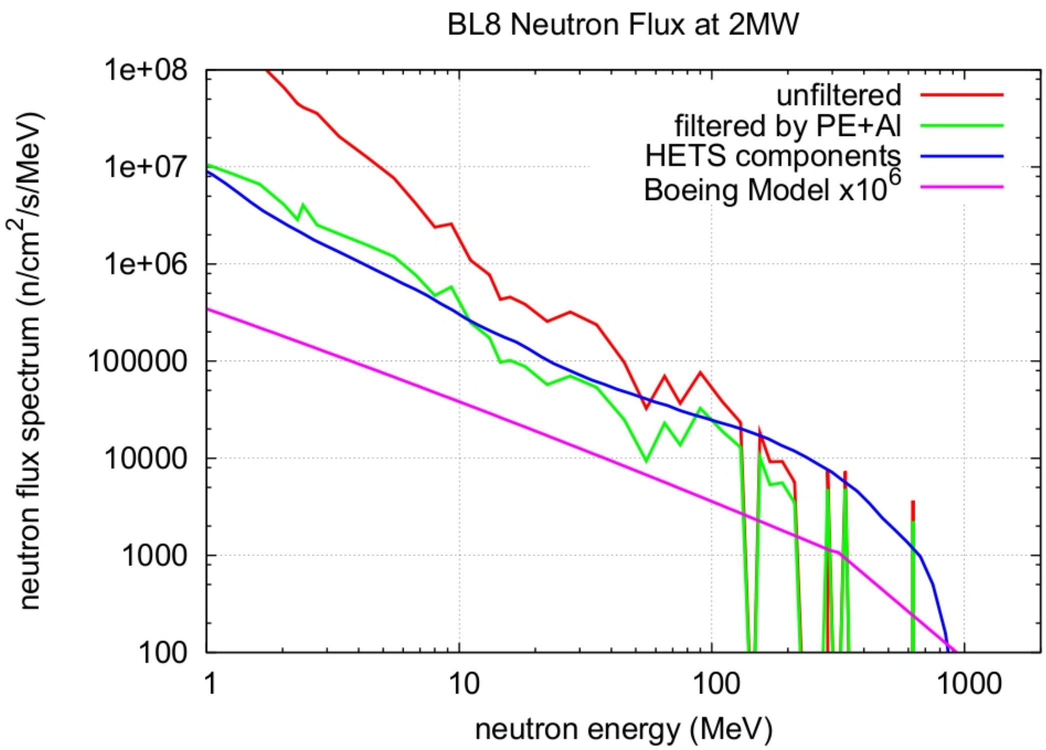


Figure 8. The HE neutron flux spectra at SNS BL-8 at 9 m distance from the moderator compared to the Boeing model and an HETS

The SEE testing is an area of constant change, driven in part by rapid developments in electronics in terms of new chip innovations and improvements in technologies striving for even smaller chip designs, and in part by changes in testing standards being established to qualify electronics for use in avionics. A facility for SEE testing should be planned with enough flexibility to cope with these ongoing developments.

An irradiation facility testing aviation electronics for SEE should mimic the atmospheric radiation field caused by cosmic ray exposure as closely as possible. It might be possible to test electronics components with sources that are mono-energetic and of different radiation types, and to then piece together the sensitivity to radiation of all their individual contributions. However, testing of active systems involving multiple components and their interactions, perhaps even including SEE mitigation strategies, implies that the whole system should be simultaneously exposed in its entirety to all types of radiation present in the environment in which it functions. This means that the radiation field must be large enough to expose the complete system, be homogenous over the system, and include all components of radiation in the broad spectral bands to which the exposed system would be sensitive in its working environment. If a system exhibits radiation self-shielding effects because of its mass or composition, it might even require a multidirectional radiation field, which would be expensive to establish.

For diagnostic purposes, it may be desirable to selectively turn features of the radiation field off and on (e.g., to eliminate the thermal neutron component, suppress the 1–10 MeV neutron component, or even disregard charged particle contributions). Furthermore, it may be advantageous to be able to flexibly expose only parts of a system to radiation by allowing variable beam collimation and system positioning.

3.4 TASK 4—FACILITY OPTIONS AT THE SNS

At the inception of this study, it was envisioned that a SEE test facility could be situated at or near the SNS RID, which is rated to accept approximately 100 kW of unstripped H^{-} beam. Actual power delivered to the RID depends on the operating power and injection stripping foil efficiency. Regardless, as the construction of the RID is not suited to reconfiguration, adding an HE neutron irradiation area into the RID would be difficult. The accelerator tunnel region upstream of the RID and downstream of the injection foil equipment is congested with equipment (e.g., magnets and beam diagnostics) that is critical to SNS operation (see figure 9). Redirection of part or all of the RID beam to a new target nearby and locating test space appears to be difficult and poses risks to primary accelerator operation. The operation of a SEE testing area using the RID beam would be coupled to SNS primary operation so that independent control of power on target and neutron intensity would require beam attenuators and collimation that would generate spurious radiation fields. Overall, using the RID beam for this purpose is not an attractive option.

Figure 9. Beam transport to the RID, which is off to the right. (the stripping foil equipment is behind the stairs; this is the highest dose rate region of the accelerator)

A broad look at test facility options produced a list of roughly ten prospects. These have been reduced to three, which offer varied degrees of performance and functionality; cost; and estimated time to completion. They are presented briefly here and described in detail in sections 4–6.

The HETS would provide the maximum test capacity and irradiation flexibility. A dedicated target station would be constructed for HE neutron research and testing. It would use approximately 1 kW of proton beam power on a gas-cooled tungsten target and would have two irradiation test areas capable of high-neutron flux for components, or modest flux over a large spot size (up to $1 \times 2\ m^2$) for system testing. The proton beam would be taken from the end of the accelerator HEBT section using laser stripping techniques. This is established technology in this power range and is finely controllable. A new proton beam tunnel and transport line would have to be constructed to the HETS location, which is foreseen as being situated between the RID building and the water tower. The HETS would be fully featured for users' broad flexibility by offering the capability to add thermal neutrons, tailor the neutron spectrum with filters, vary incident beam size, and align test pieces remotely without re-entry to the test enclosure.

A facility installed on the SNS target station, fashioned after the ChipIR instrument at ISIS TS-2, is envisioned at BL-8; both A and B channels would be required, thus occupying space for two neutron scattering instruments. This BL faces the ambient water moderator and could provide neutron flux at more than $10^6\ n/cm^2/s$ at a 9 m distance without modification of the neutron optical path. A higher flux might be achievable with reasonable specialization of that BL's core vessel insert. It could also provide thermal neutrons and large irradiation spot sizes for system testing, although it would be smaller than at the HETS facility. As in the HETS, the test enclosure would require unusually thick enclosure shielding (ca. 1.5 m high-density concrete), that along with external constraints from neighboring instruments would limit the enclosure's inside dimensions. These factors are also the reason both A and B channels are needed because the available space could not accommodate a second BL-8 neutron instrument. Nevertheless, this is the least-expensive option of the three and could be available in about 3.5 years after approval and funding. It has the advantage of using the existing utilities and infrastructure, and its construction would have virtually no impact on SNS operation. The BL-10 is also an attractive location from a technical standpoint. These presently open BLs are highly desirable locations for proposed (but yet unfunded) neutron scattering instruments and obtaining one of them for a SEE test facility will come only with very persuasive and timely arguments to SNS leadership and the DOE BES.

A mid-cost option suitable for system irradiation could be built that would have little neutron spectrum tailoring capability. This option would also use laser-stripped beam extracted from the end of the accelerator HEBT and would be sent to a new tunnel/cave facility that would house an uncooled tungsten target. Shielding blocks arranged around the target and cave walls would allow for positioning of avionic systems fairly close to the target for HE neutron exposure. Approximately 100 milliwatt (mW) proton power on target would be needed for fluxes suitable for system testing at close target distances (approximately 1 m). The flux intensity over the system would vary by as much as 30% over an area of $1m^2$ and would not be comparable to what could be achievable with the other two options. The new tunnel/cave could be designed so that it could be reconfigured in the future and built out to a HETS option.

Construction and operation activities for any SEE facility cannot present a risk to SNS operations.

4. THE HETS

4.1 CONCEPT—FACILITY DESCRIPTION

A complete and flexible SEE irradiation station is proposed around a green field dedicated target station that would require only a kW-level proton beam incident on a tungsten target. The required beam can be extracted from the SNS beam transport line by laser stripping, a proven technology that was developed at SNS a few years ago [5]. The target station, HETS, would house two independent HE irradiation test areas and would allow for placing additional beam ports for other applications if required.

A computer aided design (CAD) model of the proposed HETS facility positioned on the SNS site is shown in figure 10. The building plan area is approximately 100 × 100 ft^2 and 50 ft in height. The proton tunnel would be underground and part of the HETS building below grade level. Access would be by North Perimeter Drive, which is presently a gravel-paved road on the edge of the SNS site boundary.

Figure. 10. The CAD model of the HETS superimposed on an aerial photograph of the Oak Ridge SNS site

Sectional views of the target facility design are shown in figure 11. Both test enclosures will be capable of either system or component testing, making it possible for two user groups to work simultaneously. Separated DAQ rooms are planned.

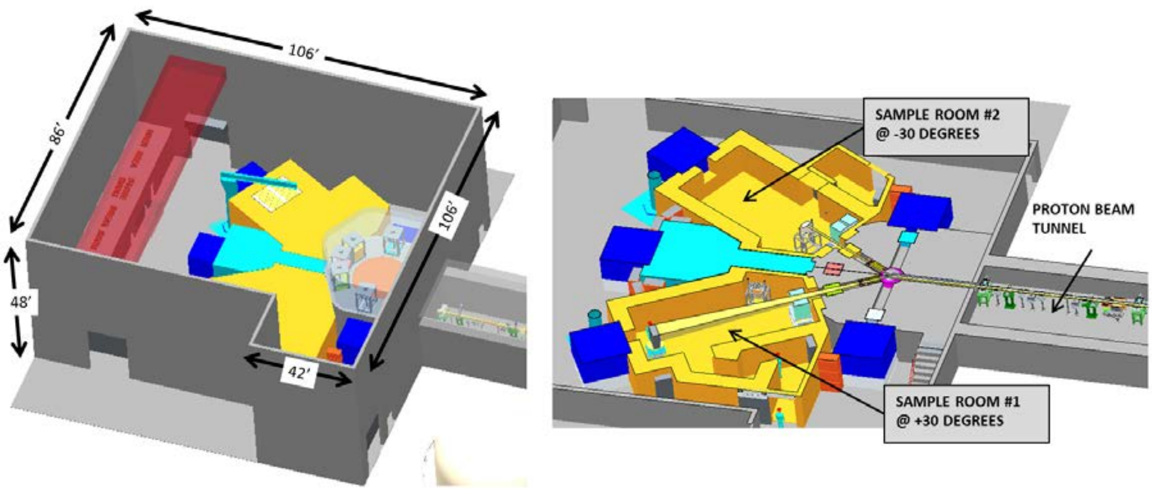


Figure 11. The HETS target station layout

The HETS will deliver peak neutron fluxes above 10 MeV neutron energy of 10^7 n/cm^2/s for component irradiation and 10^4 n/cm^2/s for system irradiation. The absolute normalized neutron flux spectra are shown in figure 12. Assuming that the component irradiation area is positioned at 5 m distance from the target, a peak proton beam power of 1350 W is necessary.

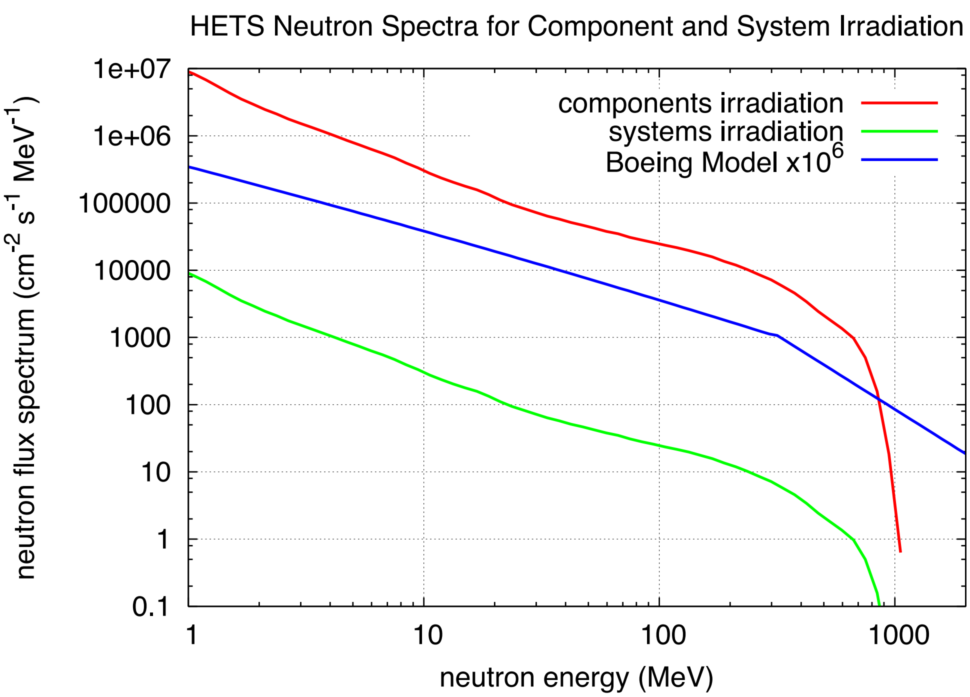


Figure 12. The HETS neutron spectra at the component and system test positions

A work breakdown structure (WBS) was developed to help define project scope and organize cost estimates. The WBS for HETS is shown in figure 13. Sections 4.1.1–4.1.6 (Accelerator Systems, Target Systems, Neutron Test Systems, Conventional Facilities, Integrated Controls, and research and development [R&D]) describe the WBS Level 2 elements. Project management is covered in the cost estimate as a percentage of all other costs.

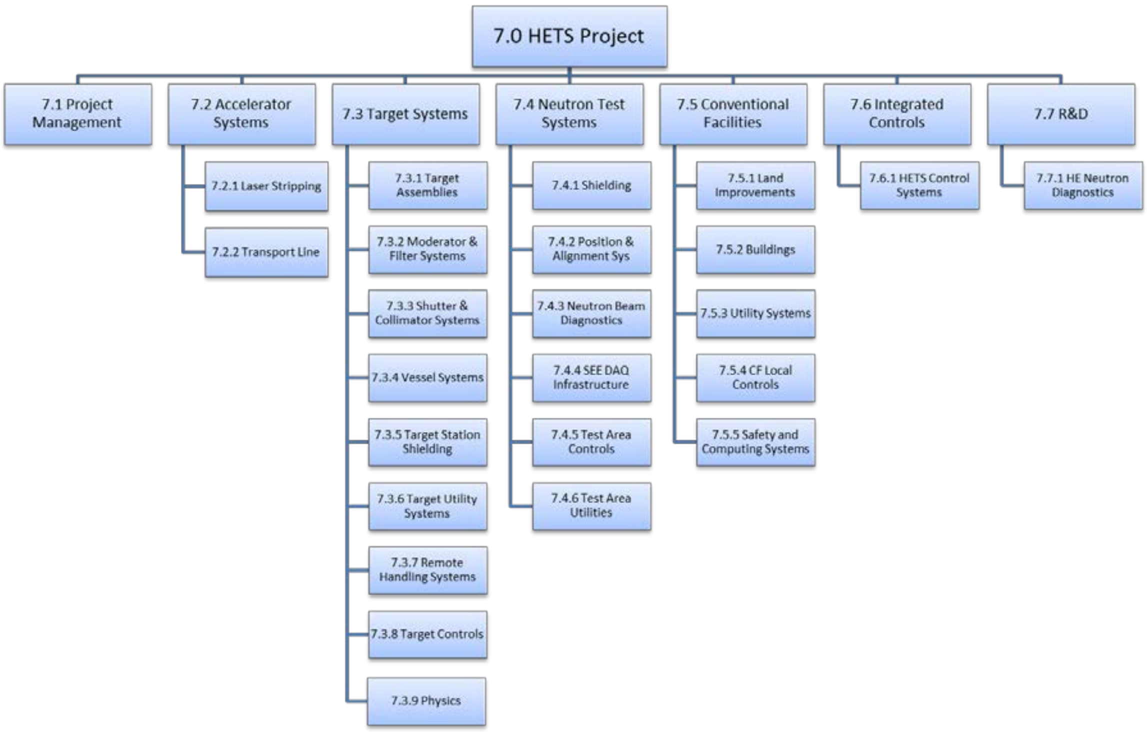


Figure 13. The HETS project WBS

4.1.1 Accelerator Systems (WBS 7.2)

It is proposed that the kW-level proton beam be extracted from the main SNS H^- beam between where it is transported from the linear accelerator to the beam compression ring (see figure 14).

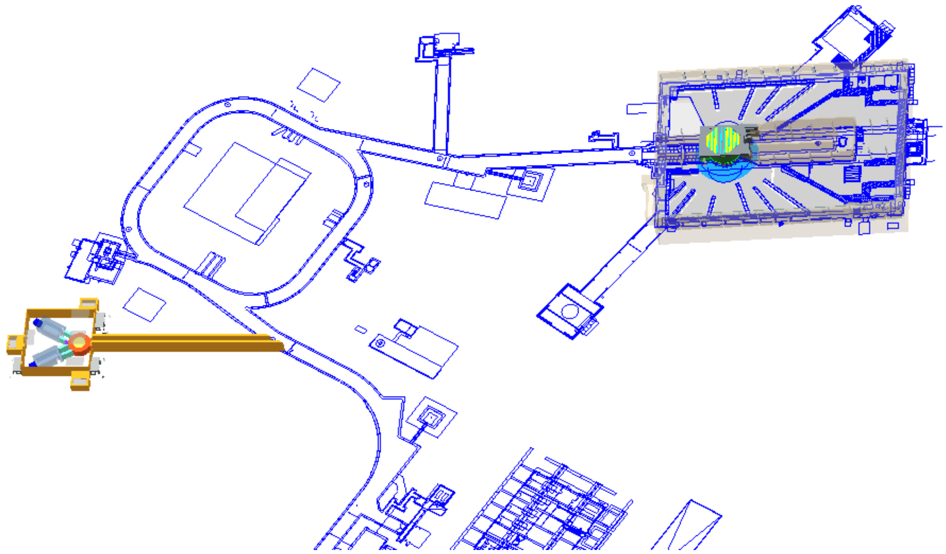


Figure 14. Location of beam extraction from main SNS H$^-$ beam for HETS

Figure 15 shows the setup for beam splitting using the laser stripping technique introduced earlier. Right before entering the last dipole magnet in the HEBT section, the H$^-$ beam is exposed to a high-intensity laser beam, which causes one electron to strip off from the H$^-$ particles. A fraction of beam is stripped from H$^-$ to H^0, the latter drifting straight through the dipole magnet that separates the neutral and charged beam fractions. The straightly propagating H^0 beam is then passed through a thin foil to strip the remaining electron to convert the H^0 beam into an H$^+$ (proton) beam. The once again charged beam is then bent by another dipole magnet to a trajectory toward HETS. Quadrupole magnets in regular spacing along the proton BL keep the beam focused.

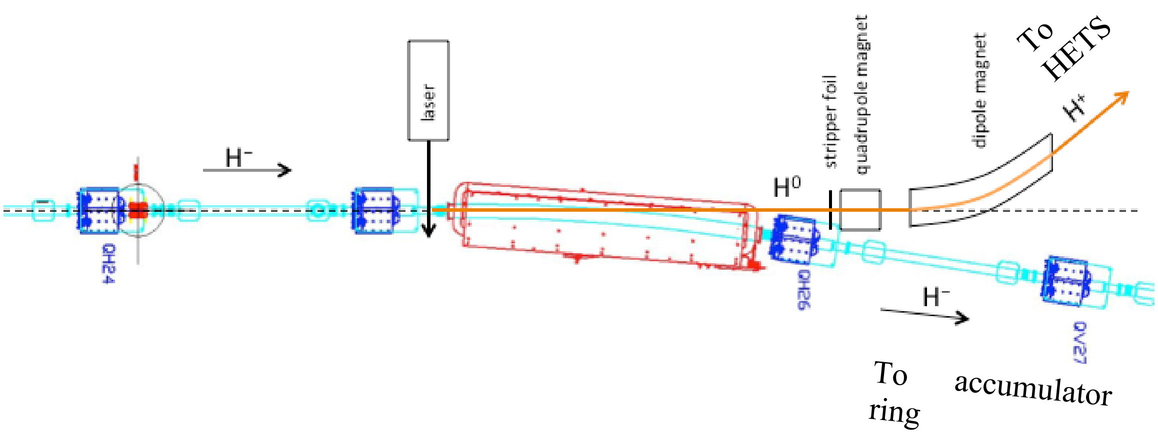


Figure 15. Laser stripping and beam separation of the kW-level beam sent to HETS

The laser stripping system will be capable of producing H^+ beams with as much as 4 kW of power. Beam position monitors and wire scanners will track the H^+ beam from separation to the target; a beam current monitor will measure the intensity of the proton current delivered to the target.

A new underground tunnel (3 m high, 4 m wide, and approximately 70 m long) will house the BL connecting the SNS tunnel and HETS. Its estimated construction cost is summarized in section 4.1.4, Conventional Facilities Scope (WBS 7.5).

All the support equipment and utilities for the HETS proton BL (water pumps, power supplies, and control racks) will be housed in the HETS building.

4.1.2 Target Systems (WBS 7.3)

The target station is a shielding monolith with a tungsten target at its center. The target monolith has to attenuate the radiation field generated by the proton beam impact to meet the DOE limits and Oak Ridge National Laboratory (ORNL) policies for radiation protection. Penetrations through the shielding monolith—the BLs—allow the extraction of neutron beams into well-shielded experimental areas. The target systems include:

- A proton delivery beam pipe, including a proton beam window
- A compact, helium-cooled tungsten target
- A target helium cooling loop
- Insertable moderators for thermal neutron production
- A core vessel as containment for the high-radiation area
- Two neutron BLs for HE particle extraction with optics components
- Monolith shielding
- Shutters for all BLs
- Selectable charged particle deflectors and neutron filters for tailoring spectra
- Target instrumentation, utilities, and controls (those not assigned to integrated controls)

Furthermore, WBS 7.3 covers project efforts on physics (except for accelerator physics), an essential project element for optimizing neutron performance and defining design requirements for the neutron source, test areas, and shielding.

The target monolith consists of stacked steel structures interspersed with PE at a volume ratio of steel to PE of 9/1. In its center, the monolith houses a core vessel of 0.6 m diameter and 0.5 m height; the core vessel contains the target and moderators and acts as containment for the high-radiation area.

The target, a tungsten rod of 50 mm diameter and 200 mm length, is helium-cooled within an aluminum vessel.

Two BLs penetrate the shielding monolith in the horizontal plane, viewing the target at 30° with regard to the proton beam axis (see figure 11). The best match with an atmospheric neutron and proton spectrum is obtained at this emission angle. The moderators are sized so that, in the inserted/filled condition, they provide about as much thermal flux intensity as HE flux intensity.

The neutron BL openings are tailored to allow the extraction of a 1 × 2 m^2 beam at a 14 m distance from the moderator.

The moderators will either be slabs of PE that can be remotely manipulated or thin aluminum vessels that can be filled with water through a pump and valve system. The moderators will be placed close to the target to give maximum exposure to neutrons from the target. A 30-cm thick reflective layer of beryllium will be wrapped around the target and the moderator, leaving a direct view of the target and the moderator.

The solid cylindrical tungsten target will be cooled by a closed loop of helium gas flow (2 bar 2 mm flow gap, 200 m/s gas flow) through an annular flow around the target cylinder (see figure 16). Neutronics and heat removal calculations have been performed to validate this condition. The neutronics evaluation showed that at a proton beam power of 2.3 kW, the heat deposited in the target would be approximately 1 kW. Peak temperatures in the target of 130°C would be easily manageable (see figure 17).

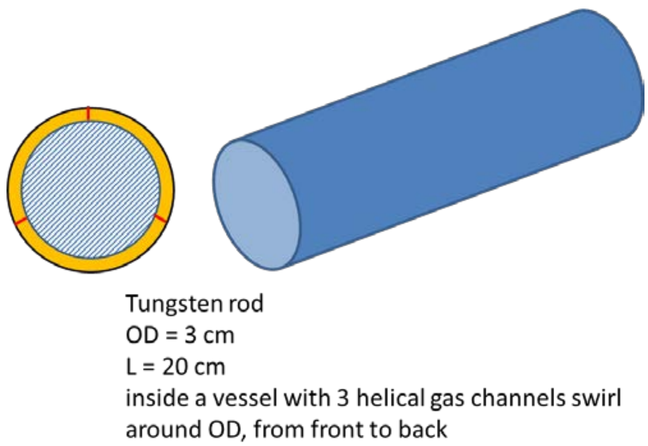
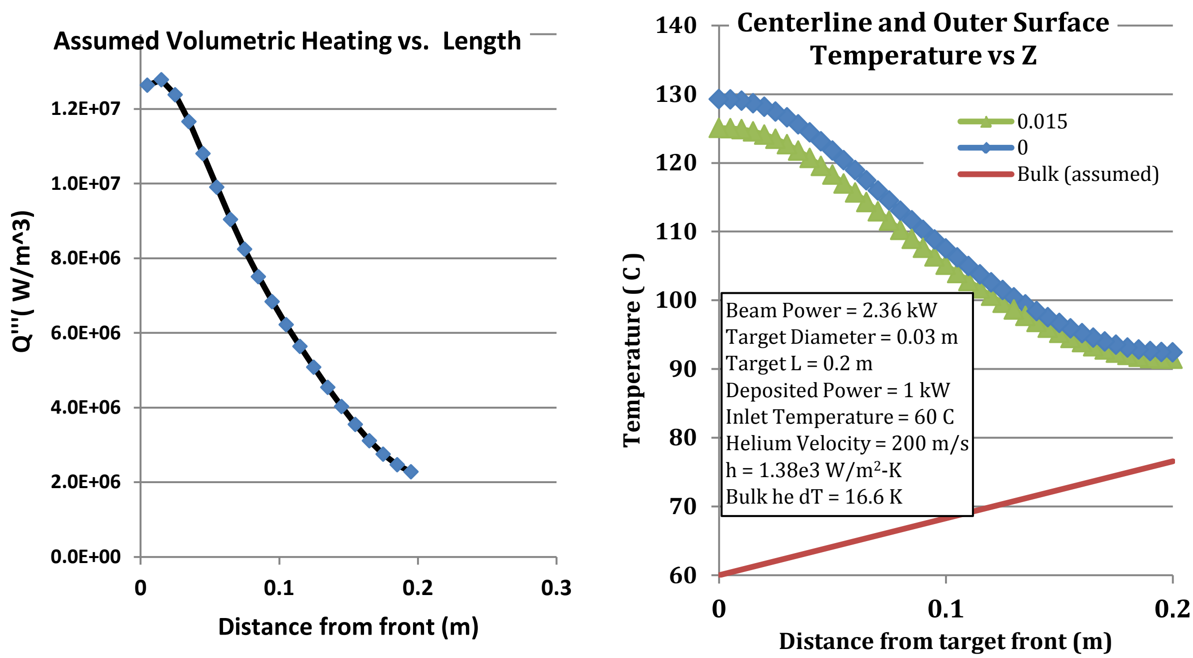


Figure 16. Tungsten target with annular flow gap



(a) (b)

Figure 17. The (a) target axial heat distribution and (b) resulting tungsten centerline and outer surface temperatures, assuming 2.3 kW proton beam power incident on the tungsten target

The BLs contain a number of beam shaping elements housed in the monolith. These components are listed beginning from the outside of the target core vessel outward in table 1.

Table 1. Beam-shaping components integrated into the HE BL

Component	Function	Radial location (cm)
Intensity dialer	Variable collimator to vary the neutron flux at the test location by restricting the view of the target	30–50
Charged particle filter	Dipole magnet of 1 Tesla	60–140
Spectrum modifier	Slabs of materials on translation stages acting as transmission filters to act as spectrum modifiers	150–180
Shutter/coarse collimator	Vertically moving shutter with four positions of collimators of varying sizes	190–290
Structure/testing area wall	Shield testing area against particles scattering from the coarse collimator and target monolith; beam diagnostics placed in wall depth	300–380
Beam diagnostics	Detectors for reporting delivered beam intensities	350–380
Fine collimator	Sets of vertically and horizontally movable jaws for fine beam size definition	390–490
Component test position	Component testing	500+

An intensity dialer is an instrument for decoupling the neutron flux level delivered into the testing area from the proton beam intensity delivered to the target. It is required when two or more simultaneous tests need different irradiation conditions. The intensity dialer will be a set of 0.20 m thick tungsten jaws that move horizontally and define the viewed area of the target/moderator system. The maximum beam attenuation of a factor of 100 will be achieved when the tungsten jaws are completely closed, which should be sufficient attenuation to perform component irradiation in one testing area that is receiving full beam intensity and system irradiation in a second testing area with a factor of 400–500 intensity reduction.

The charged particle filter will be used to eliminate the proton, charged pion, and muon contributions from the neutron beam when preferred by the users. A homogeneous magnetic field of approximately 1 Tesla can be applied across the BL over a length of 0.80 m, which will build sufficient transverse momentum to send the charged particles into the monolith shielding.

The spectrum modifier unit consists of plates of various materials, such as PE, boron-carbide, aluminum, copper, and tungsten. These materials have characteristic transmission functions that will be used as generic attenuators to filter the thermal and epithermal neutrons and to tune the spectral shape to better fit the atmospheric neutron spectrum.

A massive guillotine steel structure will integrate the functions of the BL shutter and coarse collimator. This device will make it possible to shut off the beam to one testing area while the second testing area is still served. Additionally, the coarse selection of beam size deep inside the monolith terminates the scattered beam fraction in the established shielding.

The fine collimator will fine-tune the beam size delivered to an experiment and allow for beam sizes from 1 mm^2 to 0.2×0.2 m^2. It will be built from two sets of 0.5-m thick steel jaws, providing adjustable slits in the vertical and horizontal directions. It will be possible to move the fine collimator completely out of the beam path for system testing.

4.1.3 Neutron Test Systems (WBS 7.4)

Neutron Test Systems are comprised of the test enclosure shielding; equipment to locate and remotely align user components and systems with the beam; neutron beam diagnostics; DAQ infrastructure (DAQ room, clean power, patch cabling, panels, etc.); test area controls; and utilities. Some controls are covered under integrated controls (e.g., personnel protection systems [PPS]).

The two testing stations receiving the 30° neutron beams will be identical. Each testing station will offer two irradiation positions—one for component testing and one for system testing—in a 9×3 m interior area. The position for component irradiation will be located approximately 5 m from the target, and the BL will provide above 10 MeV fluxes up to 10^7 n/cm^2/s in areas as large as 20×20 cm^2. The position for system irradiation will be located at the far-target position (14 m from the target). Figure 18 shows cross-sectional views of the proposed facility. At the system position, it will be possible to deliver peak above-10 MeV fluxes up to 1.3×10^6 n/cm^2/s over an area of 0.56×0.56 m^2 (propagation of component testing beam to the back of enclosure). Alternately, it will be possible to deliver a beam over an area of 1×2 m^2 with a peak above 10

MeV fluxes up to 2×10^5 n/cm^2/s. At these flux levels and beam dimensions, the peak integral in-beam neutron currents are equivalent for all irradiation conditions.

It will be possible to tune the neutron flux intensity in three ways: by the laser intensity in the H^- stripping process, by the intensity dialer (target-near collimator), and by the spectrum modifier unit. With this combination of features, the system should be capable of producing a broad range of flux intensity. Altering the laser intensity directly changes proton power on target; therefore, both test areas will be affected.

As a neutron beam enters a test area, real-time diagnostic equipment determines its flux intensity to have a means to tailor the beam to user requirements and to quantify the delivered fluence. The neutron beam monitoring and diagnostics are envisioned using a three-part approach. Neutron energy spectra and absolute intensity will be measured by activation foils and proton recoil telescopes during dedicated calibration periods, during which real-time detectors will be calibrated to provide scaling estimates for the established spectral distributions. Active calibration will be provided by a proton-recoil telescope of 1 cm^2 rastered across the active area [30]. For passive calibration and monitoring, the activation foil packets that are used will be assayed following irradiation [31]. For real-time monitoring, transistor arrays [32] and fission chambers [33] will be deployed.

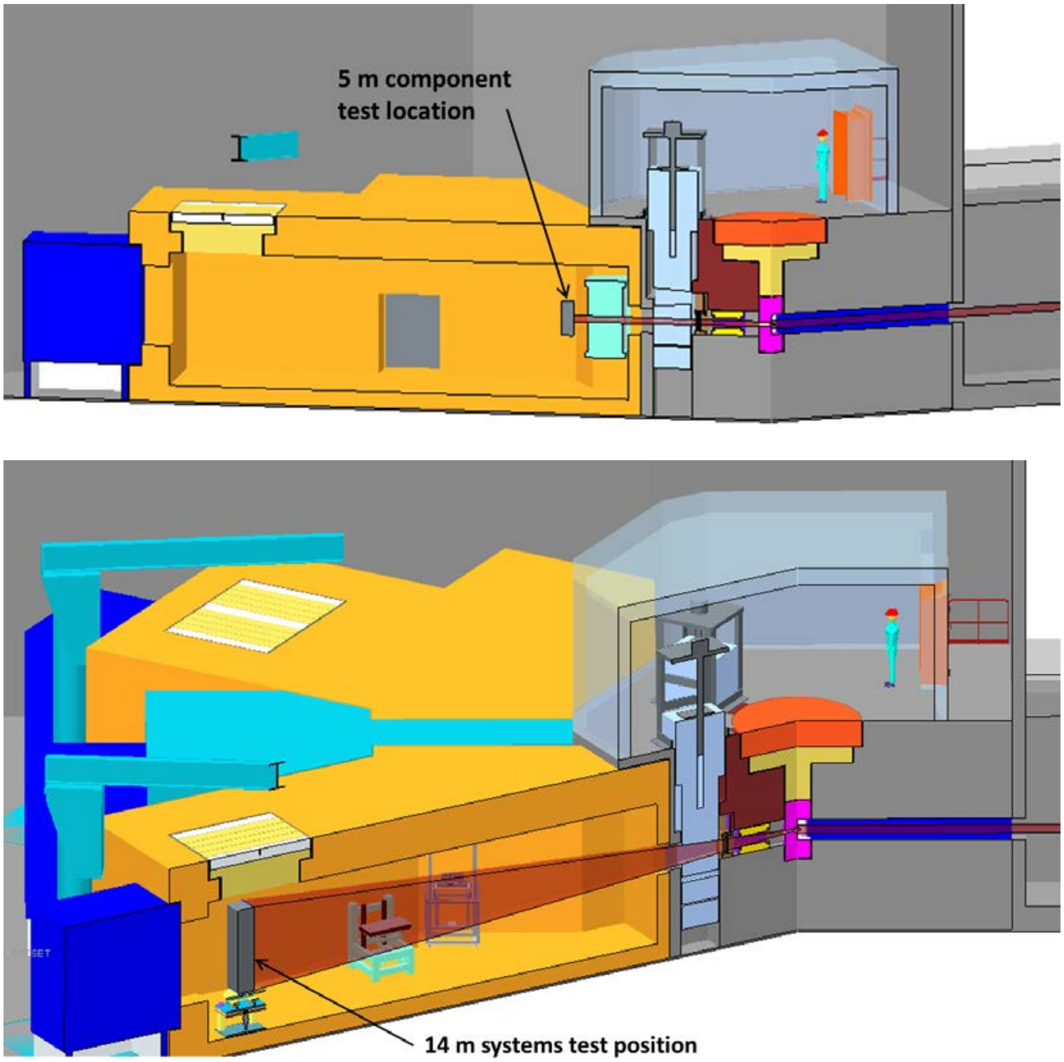


Figure 18. Sectional views of HETS target monolith and test enclosures

The test enclosure shielding will be designed to accept a HE neutron current of 4×10^8 n/s and neutron fluxes of 2×10^6 n/cm^2/s to the back of the enclosure. Assuming that the beam is scattered by interaction with the testing equipment, shielding walls and a ceiling of 2-m thick high-density concrete will be required to attenuate the dose rate to the limit of uncontrolled access of 0.25 mrem/h. The beamstop consists of 0.8 m steel with a cross sectional area of 1.2×2.2 m^2 encased in a 1.5-m thick layer of high-density concrete on the side and a 1.8-m layer of high-density concrete on the downstream side to achieve the same design goal as for the enclosure walls.

The testing stations will be equipped with several amenities for convenient and flexible experimental setup:

- A controlled temperature and humidity environment
- Electromagnetically shielded testing areas
- Low-noise power through independent grounding grids for each of the testing areas

- Translation stages at the component testing areas, including laser trackers and camera surveillance from different viewpoints for remote and flexible positioning of the electronics boards
- Remote control over beam optics components (collimators, filters, and shutters)
- DAQ patch panels for flexible and short electronic connections between the control room and testing areas without discriminating the shielding
- Cable feed-through options for direct electric connections between testing areas and the control room
- Crane access to the systems irradiation area through a hatch in the testing area enclosure and the HETS building crane

The testing areas will be accessed through the DAQ/control room area and labyrinths. Access control will be implemented through a PPS that senses the status of the main shutter and shuts the access door at beam permit. Prior to allowing beam permit, a protocol of enclosure search will be followed to make sure that the enclosure is emptied by all personnel. The PPS will force an automatic beam termination (either by shutter, by laser trip, or by main SNS beam trip) in case anybody breaks open the access doors or the radiation conditions exceed established limits.

All controls of the experimental areas will be brought together in the test area DAQ and control rooms. These rooms will also house the PPS panel, monitors for SNS and HETS beam status and surveillance cameras in the test areas, and monitors for the environmental conditions in the testing area. The test control room will provide computer access to all the neutron beam optics (collimators, filters, and shutter) and control the beam delivery to the experiment. The beam delivery system will record the online beam diagnostic data and provide running fluence tallies for experiment steering. The test area DAQ and control rooms will also provide space for user-provided DAQ equipment that can be hooked up with the electronics in the testing area through the feed-through and or patch panels.

4.1.4 Conventional Facilities (WBS 7.5)

The conventional facilities section of the WBS covers site land improvements; buildings (including the accelerator tunnel); cooling systems; electric power and other site utilities; facility-wide control systems; waste handling systems; maintenance systems; fire protection; business computing and all other needed support services to the accelerator; and target and experimental systems. The HETS facility will be integrated into and benefit from many established onsite SNS and ORNL systems.

The HETS building will be accessible by vehicle or by foot via the SNS North Perimeter Road. It will be an industrial building with an approximate 1000 ft^2 footprint and 50 ft height that will house the proton beam receiving line, the target monolith, and the test enclosures under one roof. In addition, it will provide space for the proton BL equipment (power supplies, cooling pumps, and control racks); a HETS systems control room; experiment staging and cooling-down areas; restrooms; and break rooms. A work laydown area for maintenance activities will be available.

Truck access bays for efficient transfer of testing equipment will be provided at both enclosure sides. Building cranes will cover the truck access bays, the enclosures, and the target monolith so that equipment and shielding blocks can be moved efficiently when needed. Secure storage space for equipment will be provided.

Because of its weight, the target monolith has to be secured by piles extending to the Chestnut Ridge bedrock. Excavating for the new tunnel segment and interfacing it with the existing SNS tunnel will be delicate because it will require digging into the HEBT earth berm, which is considered safety-relevant shielding during SNS operations.

Practically all of the utilities (including electrical power, water, cooling water, sewage, and communications lines) will be available through the nearby RID. Depending on requirements established in future project phases, conventional facilities could provide the utility systems:

- Tower cooling water
- Deionized cooling water
- Chilled water
- Building heating water
- Process water
- Sanitary waste
- Potable water
- Demineralized water
- Fire suppression
- Compressed air
- Vacuum
- Process gas distribution
- Natural gas

Buildings and systems will comply with industry standards and with federal and local regulations. Besides the above utilities, the building and beam transport tunnel will be equipped with communications lines (phone, internal, and external networks) and provide the hookups to all relevant control systems, which are addressed later.

4.1.5 Integrated Controls (WBS 7.6)

The HETS facility instrumentation and controls will be integrated into the site-wide SNS control system known as Experimental Physics and Industrial Control System [34] that monitors and controls nearly all accelerator, neutron source, and instrument systems. Machine parameters, such as delivered proton beam current and shutter positions, will be continuously logged. The SNS control system is centrally managed through the SNS control room, but control rooms that are close to subsystems are also used. Such will be the case with many HETS controls.

The neutron beam-relevant systems, such as collimators, filters, and shutters, will be bundled into the respective test area control systems.

From the point of view of radiation protection, the HETS site will be integrated into PPS. The network of active real-time radiation monitors (known as Chipmunks) will be extended to cover the HETS portion of the transport line, the target station, and the testing enclosure to mitigate off-normal and accidental excessive beam losses by terminating the beam within 2 seconds of triggering.

Radiological controls that will be implemented for the testing area include radiological area classifications and postings, radiological surveys, beam fault studies, radiological work control, and as-low-as-reasonably-achievable practices similar to those used for neutron BLs at SNS. The neutron BL shutters and access doors of the testing enclosures will be controlled by independent control sensors that will be integrated into the PPS system to respond to abnormal conditions, such as forced open access doors or elevated readings of radiation monitors.

4.1.6 The R&D (WBS 7.7)

The HETS, as presented here, is based almost exclusively on proven technologies. One area requiring development is HE neutron beam diagnostics. Because the diagnostic suite must provide vital information to experimenters, development work will be required to prove, qualify, and tune the systems for the needed accuracy.

4.2 COST

The cost of the HETS facility in fiscal year (FY) 2015 dollars was assessed using the described WBS structure; table 2 summarizes costs at the level three (L-3) WBS resolution. Overall, the cost comes to approximately $100 million. The L-3 costs were burdened with 30% contingency to cover uncertainties. No contingency was applied to R&D. Project Management (WBS 7.1) is estimated at 5% of project subtotal cost.

Table 2. The HETS facility cost estimate

WBS	**7.0**	**HIGH ENERGY TEST STATION**				**$99,187,207**
WBS	***7.1***	***Project Management***	5%		**$4,755,394**	
WBS	***7.2***	***Accelerator Systems***			**$8,682,960**	
		7.2.2	Laser Stripping	$734,084		
		7.2.3	Transport Line	$7,948,876		
WBS	***7.3***	***Target Systems***			**$22,672,239**	
		7.3.2	Target assemblies	$173,498		
		7.3.3	Moderator and Filter Systems	$72,519		
		7.3.4	Shutter and Collimator Systems	$2,392,615		
		7.3.5	Vessel Systems	$173,165		
		7.3.6	Target Station Shielding	$17,932,212		
		7.3.7	Target Utility Systems	$36,632		
		7.3.8	Remote Handling Systems	$171,288		
		7.3.9	Target Controls	$320,821		
		7.3.10	Physics	$1,399,489		
WBS	***7.4***	***Neutron Test Systems***			**$25,435,194**	
		7.4.2	Shielding	$23,696,365		
		7.4.3	Position and Alignment Systems	$329,004		
		7.4.4	Neutron Beam Diagnostics	$673,244		
		7.4.5	SEE DAQ Infrastructure	$336,596		
		7.4.6	Test Area Controls	$112,548		
		7.4.7	Test Area Utilities	$287,437		
WBS	***7.5***	***Conventional Systems***			**$36,118,700**	
		7.5.2	Land Improvements	$6,700,000		
		7.5.3	Buildings	$22,620,100		
		7.5.4	Utilities/Communications	$6,798,600		
WBS	***7.6***	***Integrated Controls***			**$267,583**	
		7.6.2	HETS Control Systems	$267,583		
WBS	***7.7***	***R & D***			**$1,287,470**	
		7.7.1	HE Neutron Diagnostics	$1,287,470		

The big cost items are shielding (making up 40% of the total cost), followed by buildings (22%), and the proton transport line equipment (8%).

4.3 TIME TO COMPLETE

It is estimated that it will take 5 years to complete HETS after award of the contract, including engineering design and construction. Commissioning would take at least an additional 6 months. Interference with SNS principal operations has not been considered in the construction time estimate; connection of the proton transport line and tunnel from the accelerator HEBT and construction around existing site utilities will require careful planning and coordination.

4.4 LICENSING AND SAFETY

Prior to operating HETS, safety and environmental evaluations must take place and be formally reviewed and approved. The SNS Final Safety Assessment Document (FSAD) will have to be modified to include HETS. The HETS will be a ~kilowatt power beam facility with a small footprint, and it is expected to fit into the environmental impact envelope of SNS. No unusual waste streams (beyond current SNS wastes) are anticipated during operations of HETS.

The tungsten target will accumulate an inventory of radionuclides, which must be reviewed. The expectation is that it can last the life of the facility. Using helium to cool it instead of water avoids loss of coolant accident scenarios in which moisture might lead to tungsten vaporization and dispersal from the site.

5. The SNS BL INSTRUMENT/TEST FACILITY

5.1 THE ChipIR SEE TEST INSTRUMENT AT THE ISIS TS-2 SNS

We visited the ChipIR instrument at ISIS late in its construction stage (August 2013). The instrument is now being commissioned. Our assessment was that it is poised to become the world’s leading site for SEE testing in terms of capabilities for electronic components and systems, neutron spectrum flexibility, DAQ infrastructure, and user accommodations. Using a BL on the TS-2 spallation source originally designed for cold and thermal neutrons, clever design modifications to the source’s beryllium reflector, and use of a special scattering neutron shutter should enable integral flux levels (above 10 MeV) on components approaching 10^7 n/cm^2/s and system irradiations up to 1×1 m^2 in size with HE flux up to 10^4 n/cm^2/s. Figure 19 shows a drawing and a photograph of ChipIR.

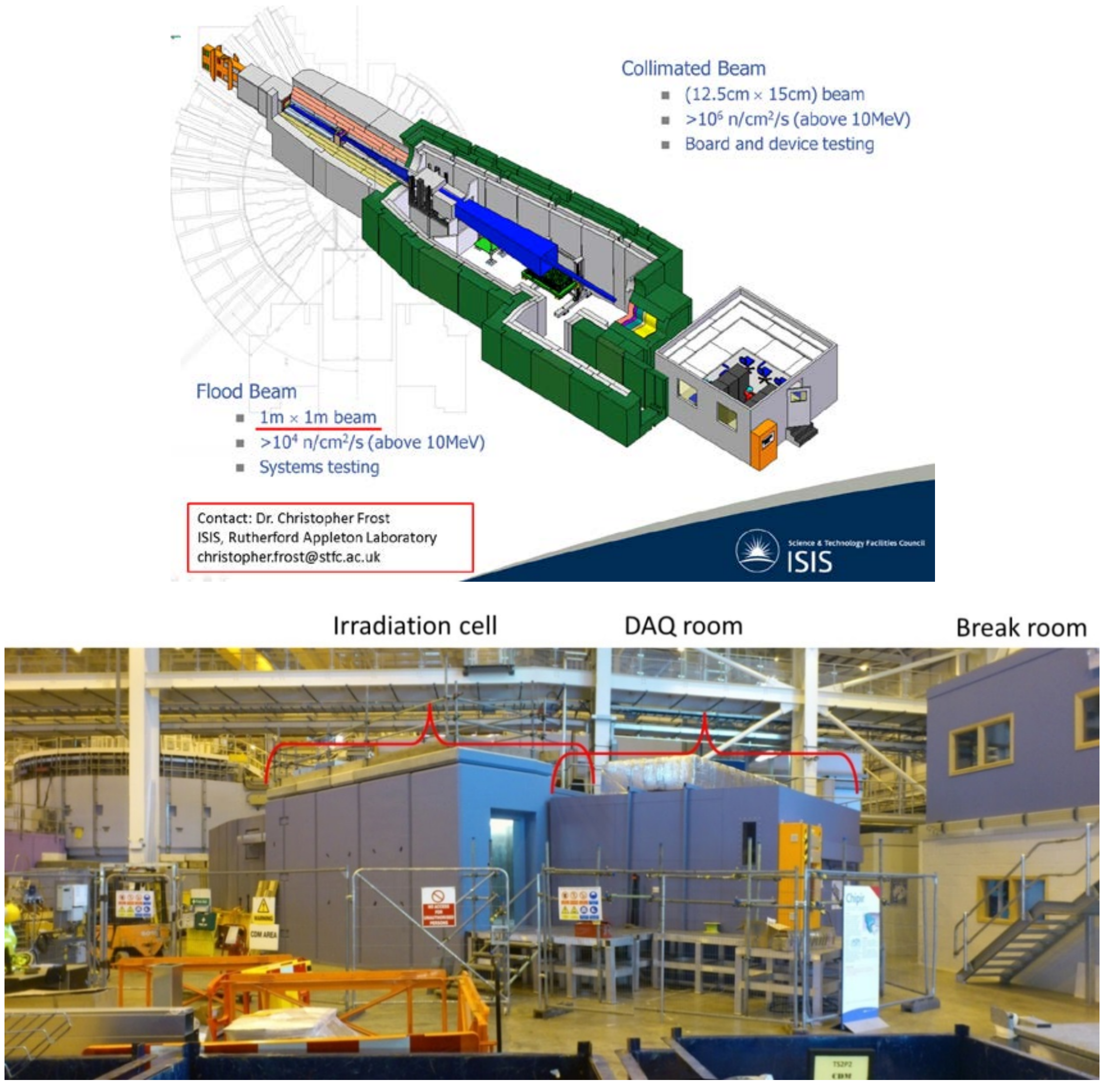
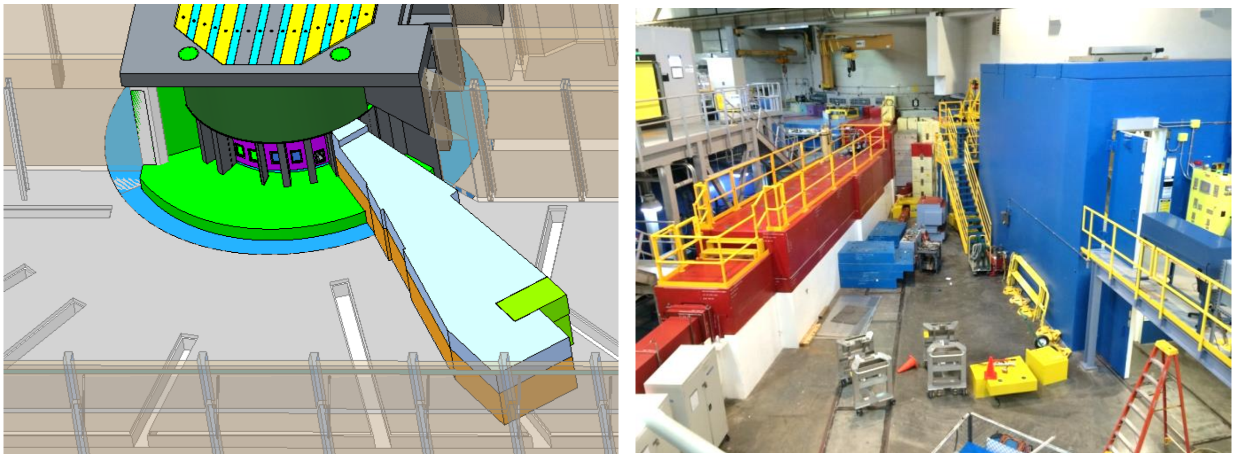


Figure 19. ChipIR at ISIS. Source: Drawing of ChipIR provided by Dr. Christopher Frost, Rutherford Appleton Laboratory

<u>5.2 A ChipIR AT THE SNS IN OAK RIDGE</u>

Technically, a similar SEE test facility can be built using an SNS BL. A more modest effort than for the HETS concept was put into developing a concept for a HE neutron instrument/test station to be located at SNS BL-8 and describing its potential performance capabilities. The BL-8 is a dual channel BL; it is currently unoccupied. It sits at 49° off the incident proton direction, which is not ideal but near enough to the optimum 30° angle to produce a high-energy spectrum comparable to a standard atmospheric spectrum. The adjacent BLs have been built, but the remaining space appears adequate if both channels are combined for a single instrument (see figure 20).



(a) (b)

Figure 20. The (a) SNS BL-8 HE neutron instrument concept, and (b) space between BL-7 and BL-9 as of July 2014

The BL-10 could also support an instrument for this mission. It has the advantage of having only one neighboring instrument, thus affording some additional lateral space. Another instrument has been proposed for this location, but it is not yet funded. Capabilities and costs would be similar to those for an instrument located at BL-8.

However, these presently open BLs are highly desirable locations for future 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 the DOE BES.

An initial characterization of the neutron beam at BL-8 is shown in figure 8. As the nominal BL optics point directly to the water moderator (bottom upstream moderator), the proportion of thermal to HE neutrons in the spectrum is approximately 50 and large with respect to atmospheric conditions. Some thermal neutrons could be filtered, though at the expense of the integrated HE flux. Nevertheless, initial results indicate that sufficiently high flux levels for SEE testing are achievable.

For component irradiations at 9 m from the moderator, 1.8×10^7 n/cm^2/s neutrons above 10 MeV would be available without filtering ($2. \times 10^8$ n/cm^2/s above 1 MeV); with filtering (2 cm PE and 12 cm aluminum), this falls to 5.4×10^6 and 2.1×10^7 n/cm^2/s, respectively. These values are based on 2 MW SNS operation, which is foreseen with accelerator upgrades associated with the proposed Second Target Station Project [35].

It would be necessary to benchmark measurements of the HE spectrum on the SNS BL to validate estimated flux values before beginning in-depth development of this design concept. Though neutronics simulations have been validated for thermal and cold neutrons at the SNS, and simulations are used with confidence for shielding of HE neutrons, fidelity for predicting performance of an HE source for an application such as a SEE test facility has not been verified. Nonstandard techniques must be applied to characterize the HE spectrum.

Preliminary design layouts of the instrument/test facility were prepared and are shown in figures 20(a) and 21. A BL-8 facility would require thick shielding, similar to HETS test enclosures.

Large area system irradiations would be completed at greater distances (approximately 24 m) from the source than at HETS, but some attenuation components would still be necessary to reduce flux to useful levels for testing systems (between approximately 10^2 and 10^4 n/cm^2/s). Unlike HETS, power on target cannot be reduced to serve this instrument's user requirements without affecting all scattering instruments. The BL-8 concept assumes a neutron shutter unique to SNS with two open positions—one for systems and one for components. In addition to having different openings, the systems position would include attenuating material. Further collimation equipment that is adjustable to the user's test needs is also envisioned downstream of the shutter.

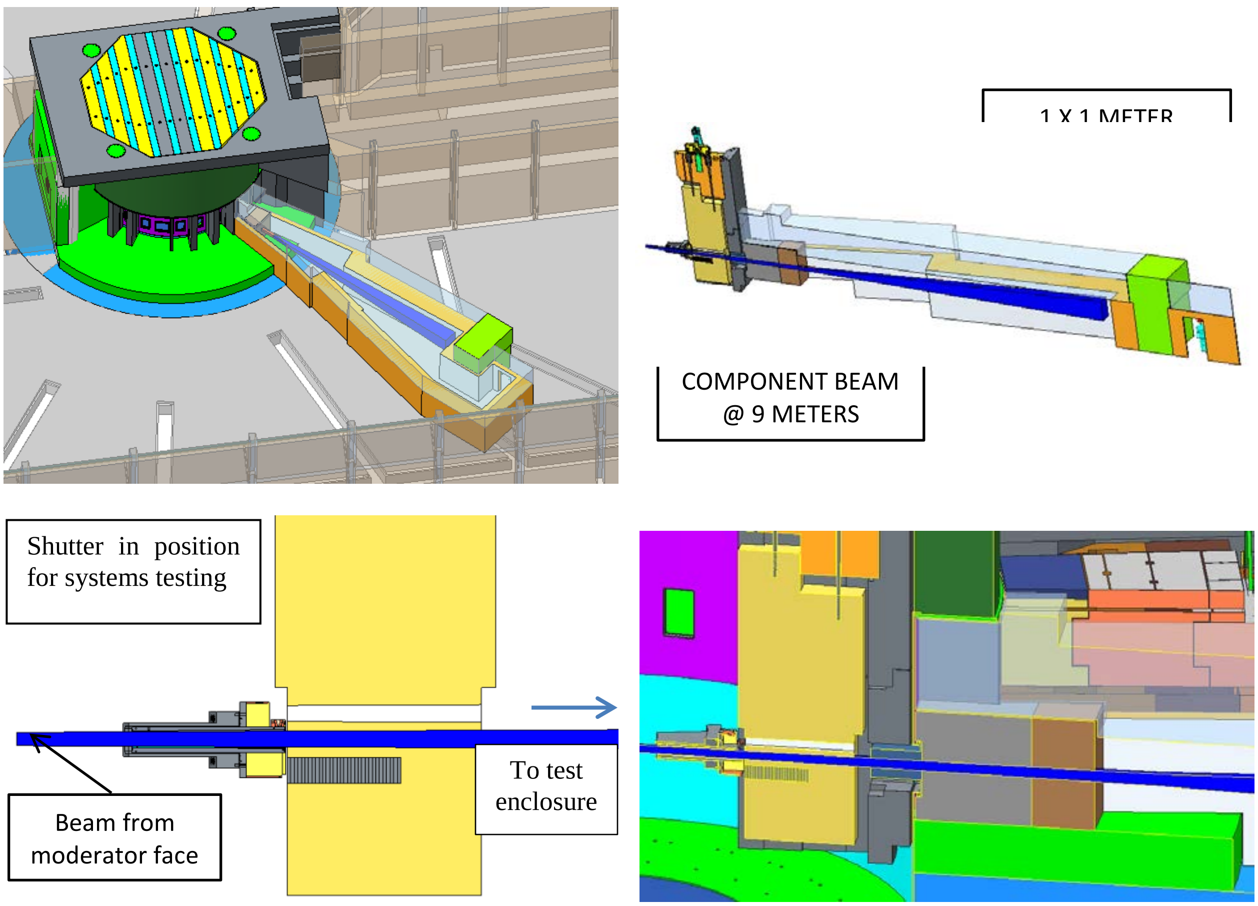


Figure 21. Views of a proposed BL-8 SEE test instrument

A suite of sample handling equipment, selectable beam filtering, beam diagnostic, and DAQ infrastructure similar to HETS is envisioned for the BL-8 option. However, it is recognized that limited space will constrain deployment of all features. For example, the limited space height and width available around the component test area (at the "chopper shelf") would provide less freedom for fine collimation equipment than would be available at a HETS. It is unlikely that a charged particle/pion deflector would be included, but a deflector would not be needed because the beam would be transmitted from scattering through the moderator rather than directly from the target. The substantial required shielding thickness would limit the overall interior height of the test enclosure as external height is limited in the instrument bay to allow for unrestricted crane operations.

Both -A and -B neutron channels would be necessary for a SEE test facility on BL-8. Illuminating a useful system beam spot size will require a special shutter with an opening larger than one of the dual-channel openings. The thick shielding required for the enclosure limits the available interior floor space because of restrictions on the extent of external walls. A facility designed around a single channel could not provide sufficient interior floor space to serve SEE activities.

5.3 COST

The estimated cost to complete a SEE test facility on BL-8 was prepared based on WBS structure and data prepared for the full-featured HETS option and is presented in table 3. The total estimated cost is \$14.7 million in FY 2015 dollars. There is no accelerator or conventional facilities cost in this estimate. The dominant contribution comes from test enclosure shielding; there is only one test enclosure. Estimated neutron shielding requirements and initial CAD modeling provided volumes for scaling shielding cost. A 50% contingency factor was applied to all WBS systems (except management) because the concept has not been as well developed as HETS.

Table 3. The SNS BL SEE instrument/test facility cost estimate

WBS	**8.0**	**BL HIGH ENERGY NEUTRON TEST INSTRUMENT**			**$ 14,705,216**
WBS	***8.1***	***Project Management***	5%		**$ 732,435**
WBS	***8.3***	***Neutron Source Systems***			**$ 3,041,936**
	8.3.3	Moderator and Filter Systems		$ 52,200	
	8.3.4	Shutter and Collimator Systems		$ 1,102,431	
	8.3.5	Vessel Systems		$ 27,131	
	8.3.6	Target Station Shielding		$ 364,269	
	8.3.8	Remote Handling Systems		$ 91,320	
	8.3.10	Physics		$ 1,404,585	
WBS	***8.4***	***Neutron Test Systems***			**$ 9,460,498**
	8.4.2	Shielding		$ 7,918,786	
	8.4.3	Position and Alignment Systems		$ 222,120	
	8.4.4	Neutron Beam Diagnostics		$ 776,820	
	8.4.5	SEE DAQ Infrastructure		$ 216,480	
	8.4.6	Test Area Controls		$ 129,863	
	8.4.7	Test Area Utilities		$ 196,429	
WBS	***8.6***	***Integrated Controls***			**$ 215,064**
	8.6.2	HETS Control Systems		$ 215,065	
WBS	***8.7***	***R & D***			**$ 1,287,470**
	8.7.1	HE Neutron Diagnostics		$ 1,287,470	

5.4 TIME TO COMPLETE

If approved and funded, it is estimated that engineering design and construction would take 3 years. An additional 6 months is anticipated for commissioning, after which the first users could begin to work. The potential for construction activities to interfere with primary SNS operations is minimal.

5.5 LICENSING AND SAFETY

A BL instrument/test facility should have no impact on existing SNS licensing or on the environment.

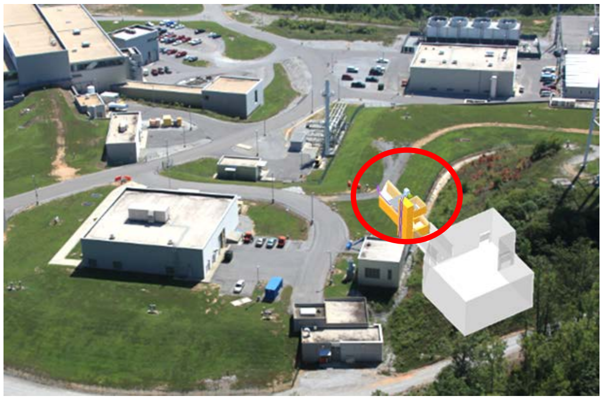
6. HIGH-ENERGY NEUTRON CAVE

6.1 FACILITY CONCEPT DESCRIPTION

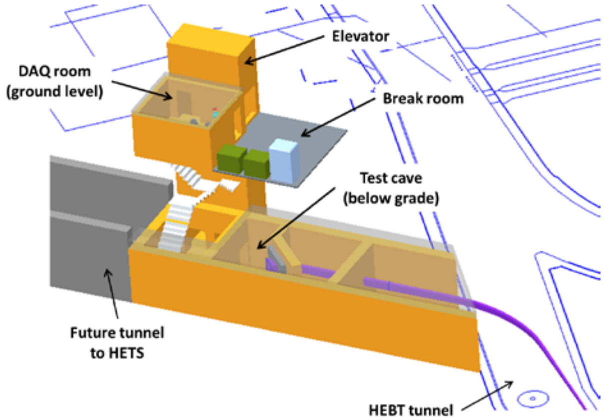
The title of the Work for Others SOW is "Definition of Capabilities Needed for a *System* Test Facility," and its content is clearly focused on avionic systems. The concepts presented in sections 4 and 5 (HETS and a SEE test instrument on an SNS BL) offer not only systems test capability but also comprehensive tools for component testing (i.e., individual ICs or similarly sized components). Component testing is understood to be vital to industrial and institutional research for the foreseeable future, a perspective reinforced in the project review meeting in November 2013 at the FAA William J. Hughes Technical Center [11]. High flux, flexibility to adjust the spectrum, and the ability to add ions are necessary component test capabilities. Flexibility in testing parameters will make it possible to investigate specific SEE vulnerabilities from particular types of radiation. Indeed, this report's title differs from the SOW in light of these facts to reflect the broader facility requirements.

For the limited scope of system testing, particularly for performing validation/verification tests, the bare need is to simultaneously expose all the system components to all the beam components, with above 10-MeV neutron fluxes up to approximately 10^4 n/cm^2/s, plus a 10%–20% proton component, and—when desired by the user—thermal neutrons at similar flux levels. These more limited and rigid requirements could be delivered by a neutron source setup that is simpler and costs less than HETS.

This third, more basic concept would be located off the end of the HEBT part of the SNS accelerator; it would consist of a shielded cave with a bare tungsten target fed by a GeV-energy proton beam. The systems to be tested would be exposed at close distance to the broad radiation field produced by the target in forward direction with respect to the incident proton beam. A thermal beam component would be included by placing a PE and beryllium reflector around the target. The physical setup would be similar to performing SEE testing with a (mono-energetic) neutron generator. It would require proton beam power of only some hundreds of mWs. For the moment, this proposed test instrument has been named the High-energy neutron cave (HENC) facility. Figure 22 shows the proposed location on the SNS site and a concept configuration.



(a)



(b)

Figure 22. The (a) HENC location on SNS site and (b) concept configuration

The cave would be situated in an accelerator tunnel spur with the same configuration as the initial tunnel section conceived for HETS. The intention is that this facility could be upgraded to the fully featured HETS at a later time if programmatic needs warrant it and funding becomes available. The tunnel is below ground, as is the entire SNS accelerator. The user DAQ, control room, and supporting areas would be located on ground level above the irradiation cave. Access to the cave would be by elevator or stairway.

There are some detriments to this concept. The HENC would not be suitable for component testing. Although fairly large systems could be irradiated, the flux uniformity would not be as good as with the other options. No capability to deflect charged particles away from the tested system would be possible. There would be limited ability to adjust the spectrum; the only mechanism would be moving a thermal moderator in and out of position.

6.1.1 Proton Transport

The below-watt-level proton beam would be produced in precisely the same way that the beam for the HETS would be produced, except that the stripping laser would require much less power. Instead of the 70-m long proton transport tunnel that would be needed for the HETS, the HENC would require only a 21-m long dead-end tunnel segment to house the irradiation cave.

Beam position monitors and wire scanners would track the H^+ beam from HEBT separation to the target, and a beam current monitor would measure the delivered proton current to target. The laser stripping system would be capable of producing H^+ beams of no more than 300 mW power.

All the support systems for H^- beam stripping and proton beam transport will probably have to be located in a new service building because available space in the ring service building is limited. If the support systems can be made to fit into the ring service building, then some cost savings may be possible, although cable lengths will be longer than if a new building is constructed.

6.1.2 Target and Irradiation Area

A tungsten target similar to the HETS target is suitable, but would, at most, be exposed to 50-mW heating at 300-mW proton beam power. No active cooling system is required for this level of heating. The target would be placed at the end of the proton beam pipe window. The system irradiation area receives a neutron beam centered at 45° off the incident proton beam. The above 10-MeV flux level can be tuned by the stripping laser intensity for up to 10^4 n/cm^2/s.

In a 30° wide sector between 30° and 60°, the spectral variation and intensity variation of the neutron flux field may be tolerably small and limited to the HE tail, as shown in simulation results presented in figure 23. System irradiation over an area 1-m wide and 1-m high at a 2-m distance is foreseen. The variation in the proton flux is larger; however, protons contribute, at most, 30% overall to the SEE.

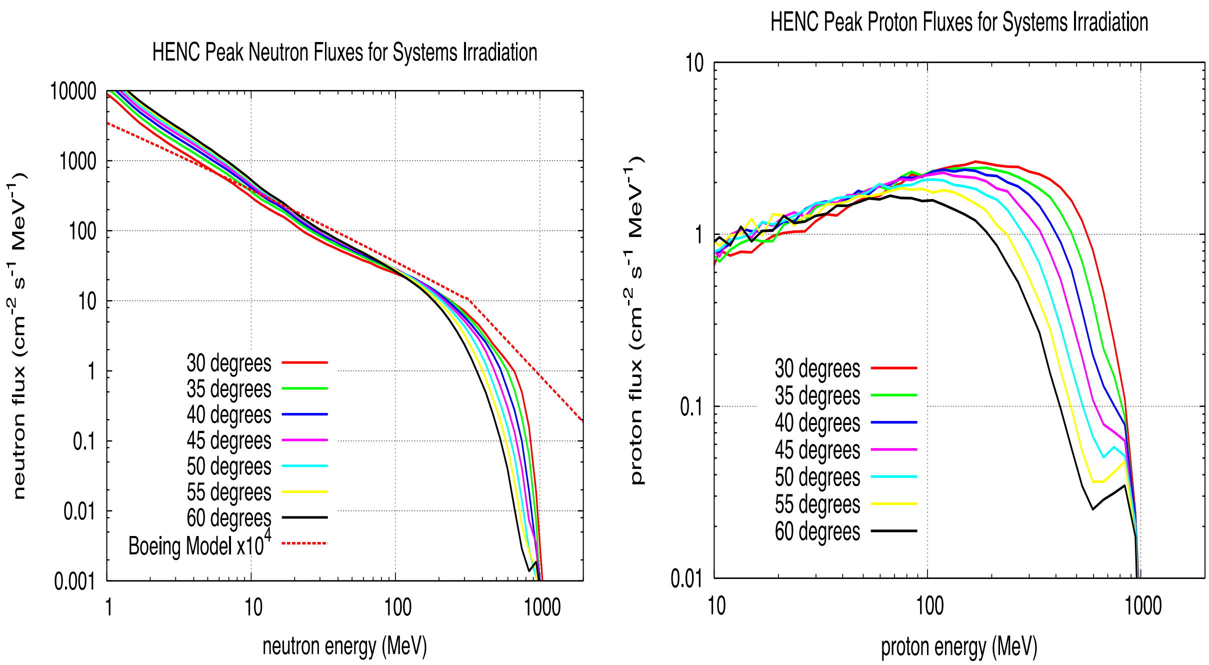
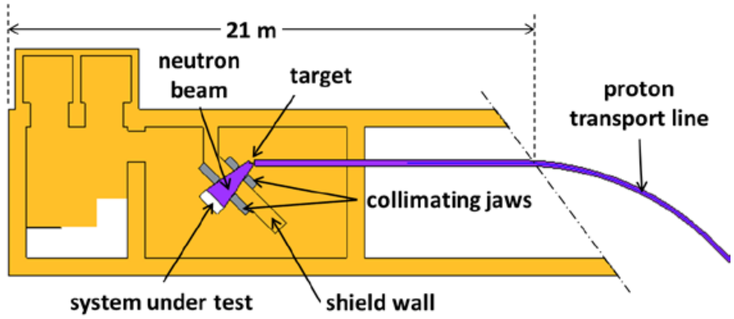
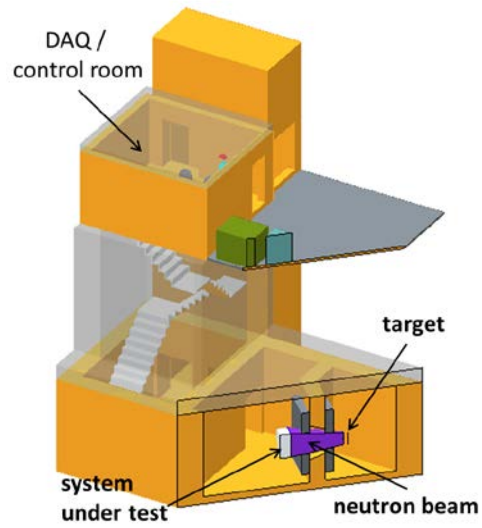


Figure 23. Angular variation of neutron and proton emission spectra from a tungsten target powered by a 0.1-W proton beam

The target and testing area would be staged in the tunnel (the cave) as shown in figure 24. 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 sides of the wall are proposed. This shielding configuration will allow some tailoring of the beam size to the needs of the experimenter and reduce radiation background. 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.



(a)



(b)

Figure 24. The HENC (a) tunnel-cave facility plan and (b) isometric sections

The facility shielding design must plan for an accident case in which the full SNS beam is delivered into the target. Having the DAQ and control room on the surface above a 5-m thick earth berm and using labyrinth-type access to the testing area will satisfy shielding requirements for this scenario. This shielding arrangement results in more distance between the DAQ equipment and the testing area than the HETS option, whose target is shielded by a complete monolith. Shorter distances would be better for data transmission fidelity, but would incur greater costs.

6.1.3 The DAQ and Control Room

The DAQ and control room would be located in a new building at ground level and would be accessible from the ring utility building access road. It would be equipped in a manner similar to the proposed arrangement for HETS. Access to the system irradiation area would be by elevator/stairway, both of which would be interlocked by SNS PPS. Local secure storage would be provided, and a truck bay for loading and unloading user equipment will be included. Break rooms and restrooms can be provided, but access to the SNS Experimental Hall and Central Lab and Office building is better than for HETS.

6.2 COST

The cost of the HENC facility in FY 2015 dollars was assessed by utilizing HETS cost spreadsheets and downscaling the WBS elements appropriately. The total project cost estimate comes to $30.2 million, as summarized in table 4. Contingency was increased to 50% on all L-2 WBS elements, except Conventional Facilities (7.5) and R&D (7.7), to cover uncertainties with this less-developed design concept. Contingency on conventional facilities is 40%; there is no contingency on R&D.

Table 4. The HENC facility cost estimate

WBS	**7.0**		**HIGH ENERGY NEUTRON CAVE**		**$ 30,278,669**
WBS	***7.1***	***Project Management***	5%		**$ 1,441,841**
WBS	***7.2***	***Accelerator Systems***			**$ 5,411,700**
		7.2.2	Laser Stripping	$ 847,020	
		7.2.3	Transport Line	$ 4,564,680	
WBS	***7.3***	***Target Systems***			**$ 2,764,978**
		7.3.2	Target assemblies	$ 110,880	
		7.3.3	Moderator and Filter Systems	$ 46,476	
		7.3.4	Shutter and Collimator Systems	$ -	
		7.3.5	Vessel Systems	$ 52,230	
		7.3.6	Target Station Shielding	$ 742,957	
		7.3.7	Target Utility Systems	$ -	
		7.3.8	Remote Handling Systems	$ 197,640	
		7.3.9	Target Controls	$ -	
		7.3.10	Physics	$ 1,614,795	
WBS	***7.4***	***Neutron Test Systems***			**$ 2,279,541**
		7.4.2	Shielding	$ 911,960	
		7.4.3	Position and Alignment Systems	$ 111,120	
		7.4.4	Neutron Beam Diagnostics	$ 747,900	
		7.4.5	SEE DAQ Infrastructure	$ 216,480	
		7.4.6	Test Area Controls	$ 95,651	
		7.4.7	Test Area Utilities	$ 196,429	
WBS	***7.5***	***Conventional Systems***			**$ 16,897,000**
		7.5.2	Land Improvements	$ 5,000,000	
		7.5.3	Buildings	$ 6,595,100	
		7.5.4	Utilities/Communications	$ 5,301,900	
WBS	***7.6***	***Integrated Controls***			**$ 196,139**
		7.6.2	HENC Control Systems	$ 196,139	
WBS	***7.7***	***R & D***			**$ 1,287,470**
		7.7.1	HE Neutron Diagnostics	$ 1,287,470	

6.3 TIME TO COMPLETE

The time to complete the HENC is expected to be more than 3 years, with an additional 6 months for commissioning. Construction interference with SNS operations has not been accounted for and could have significant impact on how long it might take for operations to begin.

6.4 LICENSING AND SAFETY

Prior to operating HENC, safety and environmental evaluations must take place and be formally reviewed and approved. Modification to the SNS FSAD is needed.

The HENC is a ~watt beam power facility with a small footprint, and it is expected to fit into the environmental impact envelope of SNS. No unusual waste streams (beyond current SNS wastes) are anticipated during operations of HENC.

7. SUMMARY

Authors and contributors to this study investigated SEE testing practices around the world and developed an understanding of future testing requirements through communication with the project sponsor, industry, literature searches, and facility tours. The SNS—with its 1.0 GeV protons (1.3 GeV with the Second Target Station upgrade), typical operation of 5000 hours per year, expertise in SNSs, user program infrastructure, and decades of useful future operational life—is ideally suited for hosting a world-class SEE test facility. A number of options at the SNS were considered, but the choices were reduced to three. The three proposed facilities offer different levels of functionality, performance, cost, and programmatic viability; all can address system testing needs.

Delivery and acceptance of this report serves as the final deliverable for the WFO study project. Advancing a SEE test facility at the SNS will require a strategic and sustained effort involving all stakeholders. The SNS staff stands ready to contribute.

7.1 THE PATH FORWARD

With the conclusion of this study, the authors hope for the pursuit of a SEE test facility at the SNS to be undertaken. Opportunities to provide outstandingly representative radiation conditions for testing avionics and ground-based computing systems and for fundamental SEE research are rare. The HE accelerators suitable for SNSs that can mimic the atmospheric radiation conditions are uncommon national assets. The SNS offers particularly good options for such facilities, and because it operates as a user facility for scientific research, it is well suited to hosting and supporting many visitors from industry and research institutes.

The three facility options described here 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 the best performing option, but also the most expensive and with the longest time to completion. It will have the most throughput capacity and have the greatest irradiation condition flexibility. Coordination of construction with SNS operations will present some challenges. A BL facility will perform 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 BL on the SNS is intense. If a BL cannot be assigned and funding is a limitation, the HENC option can perform as a system test facility, with minimal irradiation flexibility and poor component test functionality.

The SNS is a scientific user facility funded by the U.S. DOE BES and operated and managed by the Neutron Sciences Directorate (NScD) of ORNL. The NScD's primary mission is neutron scattering research. A HE neutron test facility for SEE applications differs from the standard scattering instrument normally supported by BES.

There are broad challenges in two critical areas for advancing a SEE test facility at SNS. First, communication with the sponsors and custodians of the SNS must be enhanced to make the case that this kind of test and research capability is urgently needed in the United States and that the SNS has excellent long-term potential to serve this national need. The SNS would be expanding its science mission beyond neutron scattering sciences. There is a precedent for this with regard to a Fundamental Neutron Physics Beam instrument funded by the DOE Nuclear Physics program. Strong communication with DOE BES will be needed along the way. Also, funding for construction and sustained operation of the facility must be secured (in addition to the BES current budgeting).

A strategy to address these challenges and advance a facility needs to be formed and executed. The stakeholder parties must all be involved: the FAA, avionics industries, the DOE, ORNL, and the SNS.

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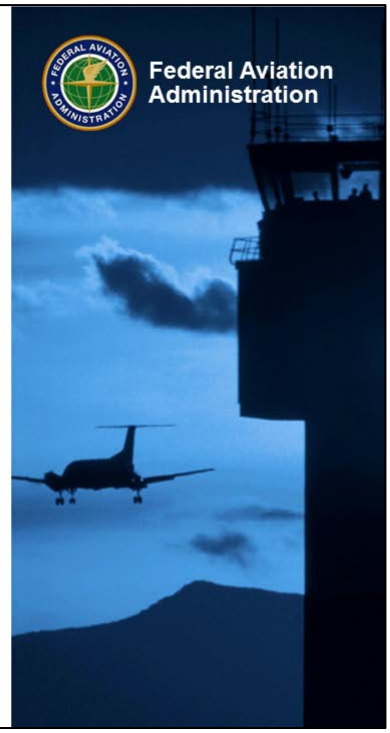
APPENDIX A—PRESENTATION “NEUTRON TEST FACILITY – INDUSTRY AND FEDERAL AVIATION ADMINISTRATION (FAA) VIEW” (G. HORAN, FAA)

Neutron Test Facility

Industry and FAA View



Presented to: SNS Managers

By: Gary Horan, ANE-111/AIR-120

Date: November 2013

Overview

- Atmospheric Radiation and Single Event Effects
- Standards and Regulatory Requirements
- Need for New Cosmic Ray Neutron Simulation Facility

Federal Aviation Administration 2

Atmospheric Radiation and Single Event Effects

- **Radiation effects recognized in recent years as safety concern for current and future silicon-based technologies**
  - Neutrons are mainly responsible for causing single event effects
  - Altitude and latitude are factors in the varying neutron flux
- **Single Event Effects (SEE)**
  - Disturbance of an active electronic device caused by energy deposited from the interaction with a single energetic particle
  - An event occurs when an ionization charge from the energy deposition exceeds the device critical charge
- **Resulting in:**
  - Corrupted data; including Hazardous Misleading Information
  - CPU halts and interrupts
  - Unplanned events; including system failure

Federal Aviation Administration 3

Technology Trends means Increased Risk

- **Increased soft error risk due to**
  - Smaller circuit dimensions and lower voltage
  - Typical charge found at storage nodes decreases
  - Takes less energy to disturb stored information
  - Stored bit values are more easily corrupted
- **Cannot extrapolate behavior of future IC technologies from older devices**
- **Dramatic increase in multiple cell upset for 90 nm parts**
- **Thermal radiation becoming more of an issue**

Federal Aviation Administration 4

AVSI

- **Aerospace Vehicle Systems Institute (AVSI)**
  - Cooperative of aerospace companies, FAA and DoD
- **Task Group 72 Charter - Mitigating Radiation Effects on Current and Future Avionics Systems**
- **Long Term Objective**
  - Develop approach for cost effective test method/simulation/analysis for device level failure rates
- **Key step**
  - Ensure availability of atmospheric radiation test facilities

Federal Aviation Administration 5

Reasons for Atmospheric Radiation Testing

Regulatory Authorities working in conjunction with Industry Groups

Regulatory Requirements

- EASA CM No.: EASA CM – SWCEH – 001 Issue: 01. Requires SEU analysis and its inclusion into the safety process
- EASA CRI
- FAA Issue Papers – Safety Impact of the FADEC's Susceptibility to Atmospheric Neutrons
- EASA and FAA plan to issue additional guidance in 2014

Industry Standards Development

- SAE S-18 & Eurocae WG-63
- ARP4761A / ED-135 – due in 2013 will address SEE – Supported by AVSI AFE72
- AIR6219 / ER-008 – SEE Safety Analysis – being drafted by S-18/WG-63/AVSI AFE72

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Current Industry Standards

- **IEC62396-1** Process Management for Avionics – Atmospheric Radiation Effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment (2012)
- **IEC62396-2** – Guidelines for single event effects testing for avionics systems (2012)
- **IEC/TS62396-3 –** Guidelines to optimize avionics system design to reduce single event effects rates (2008)
- **IEC/TS62396-4 –** Guidelines for designing with high voltage aircraft electronics and potential single event effects (2008)
- **IEC/TS62396-5 –** Guidelines for assessing thermal neutron fluxes and effects in avionics systems (2008)
- **JEDEC Standard, JESD89A,** "Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices", 2006.
- **JEDEC Standard, JESD89-3,** *Test Method for Beam Accelerated Soft Error Rate*

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Proposed Additional Standards

- **Addition of SEE topic to ARP4761A – Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment**
  - AIR 6219 Development of Atmospheric Neutron Single Event Effects Analysis for use in Safety Assessments
- **IEC62396-6 Extreme Space Weather**
- **IEC62396-7 Process for Incorporating Radiation Analysis into System Design Process**
- **Update to JEDEC Standard, JESD89-3, Test Method for Beam Accelerated Soft Error Rate**

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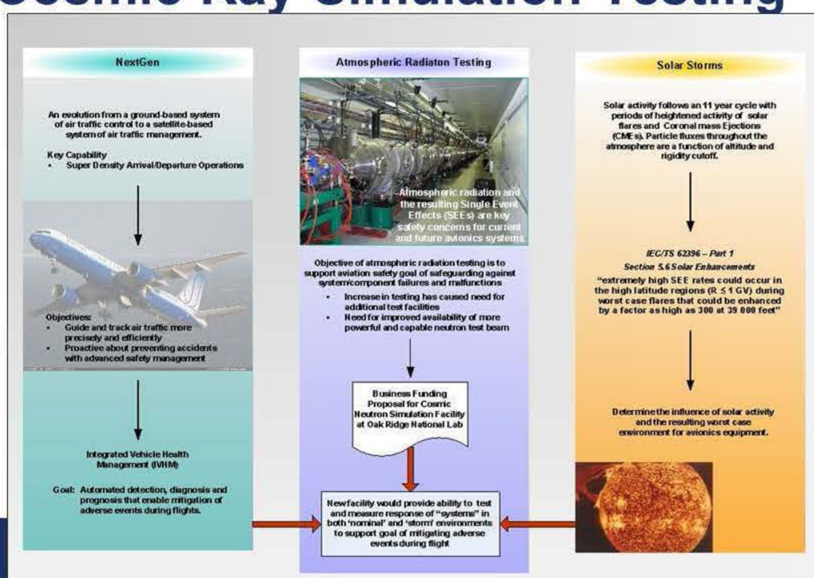
Need for Cosmic Ray Neutron Simulation Facility

- **Additional facilities needed to meet**
  - Increasing demand for SEE testing on components
  - System level testing for robustness and mitigation verification
  - High energy (solar storm) testing
  - Thermal neutron testing
- **Oak Ridge National Laboratory (ORNL)**
  - Incorporates neutron beam for testing microelectronics within Spallation Neutron Source facility
  - World's most intense pulsed accelerator-based neutron source
  - Flux level >50 times higher than that at Weapons Neutron Research (WNR)
  - Proton testing for polar routes

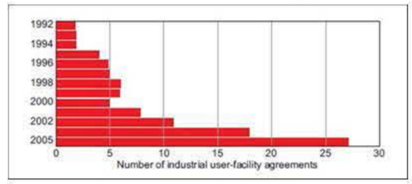
Federal Aviation Administration

NextGen, Solar Storms and Cosmic Ray Simulation Testing

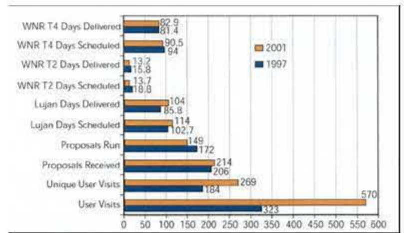


Current Status of SEE Testing

- **Demand for test facilities continues to increase**
  - Los Alamos National Laboratory is recognized as providing most accurate accelerated neutron test beam; new beam has been added in 2012
  - More companies and industries are testing their components and systems
  - Technology trends show parts becoming more susceptible to SEE



•Use of the ICE House at Los Alamos



Comparison 1997 versus 2001 run cycle for WNR and Lujan Center at Los Alamos

Los Alamos becoming oversubscribed

Federal Aviation Administration 11

Benefits

- **Cosmic Ray Neutron Simulation Facility will provide**
  - Additional capacity to meet current and future test needs for avionics and other safety/reliability critical industries
  - More timely access
    - Current beam time availability impacting program development schedules
    - Overcomes Over subscription at Los Alamos
  - Improved availability of more powerful and capable test beams
  - Device and system level testing
    - System level testing allows for robustness and mitigation verification
  - High energy and thermal testing

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