THE SPALLATION NEUTRON SOURCE: A POWERFUL TOOL FOR MATERIALS RESEARCH *

T.E. Mason, T.A. Gabriel, R.K. Crawford, K.W. Herwig, F. Klose, and J.F. Ankner,
SNS Project, 701 Scarboro Rd. Oak Ridge, TN 37830

Abstract

The wavelengths and energies of thermal and cold neutrons are ideally matched to the length and energy scales in the materials that underpin technologies of the present and future: ranging from semiconductors to magnetic devices, composites to biomaterials and polymers. The Spallation Neutron Source (SNS) will use an accelerator to produce the most intense beams of neutrons in the world when it is complete at the end of 2005. The project is being built by a collaboration of six U.S. Department of Energy laboratories. It will serve a diverse community of users drawn from academia, industry, and government labs with interests in condensed matter physics, chemistry, engineering materials, biology, and beyond.

1 INTRODUCTION

With materials of ever increasing complexity becoming key elements of the technologies underpinning industrial and economic development there is an ongoing need for tools that reveal the microscopic origins of physical, electrical, magnetic, chemical, and biological properties. Neutron scattering is one such tool for the study of the structure and dynamics of materials[1]. Neutrons are well suited to this purpose for several reasons:

- Neutrons are electrically neutral leading to penetration depths of centimeters;
- Neutron cross sections exhibit no regular dependence on atomic number and are similar in magnitude across the periodic table giving rise to sensitivity to light elements in the presence of heavier ones;
- The range of momentum transfer available allows probing of a broad range of length scales (0.1 to $10^5 Å$) important in many different materials and applications;
- Thermal and cold neutrons cover a range of energies sufficient to probe a wide range of lattice or magnetic excitations;
- Neutrons have magnetic moments and are thus uniquely sensitive probes of magnetic interactions;
- Neutrons can be polarized, allowing the cross-sections(magnetic and nonmagnetic) to be separated;
- The simplicity of the magnetic and nuclear interactions make interpretation of results straightforward.

Advances in neutron scattering have, from its earliest days, been driven by the scientific opportunities presented by improved source performance and instrumentation optimized to take advantage of that performance. The Spallation Neutron Source represents a substantial advance in neutron source performance over any facility in the world and, together with improved instrumentation, will make possible measurements of structure and dynamics with unprecented intensity, resolution, and dynamic range. The accelerator complex that is the proton driver for the SNS is described elsewhere in these proceedings. What follows is a brief summary of the Experimental Facilities that will turn the protons into science.

2 SNS EXPERIMENTAL FACILITIES

2.1 Target Systems

The development of the SNS Target System, including preliminary design and research and development, is progressing as planned. A global overview of the target/instrument hall is shown in Fig. 1. The mercury-based target system, which will receive the short-pulsed, proton beam (2 MW, 1-GeV protons, 60 Hz, < 1.0 μs/pulse), will be located in the center of the bulk shielding. As shown in Fig. 1, the shielding is slightly left of center, with the maintenance

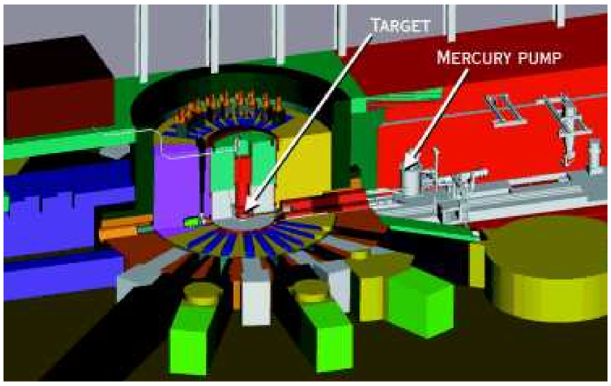

Figure 1: Cross-sectional view of the bulk shielding, shutters, instruments, maintenance cells, and mercury target.

cells to the right. The first maintenance cell will monitor and maintain the mercury process and pumping system. Additionally, because the system is designed to require only five days for replacement of the stainless steel

* Work supported by the U.S. Dept. of Energy under contract DE-AC05-00OR22725

(SS316L) target container and because the first maintenance cell will allow replacement every six weeks, a good availability of neutrons will be maintained. The remaining cells will be used for storage, maintenance, and shipping of various components such as shutters, the proton beam window, and the inner core plug that holds the moderators.

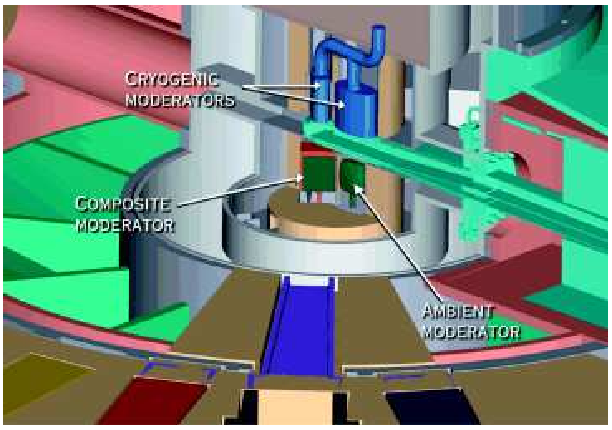

Figure 2: Cross-sectional view of the cryogenic, composite, and ambient moderators and the mercury target. The proton beam arrives from the upper left of the drawing.

A sliced section of the target, moderator, and reflector system is shown in Fig. 2 . Cryogenic moderators [supercritical light hydrogen (H2) @ 19 K] are located on the top of the target. The upstream bottom moderator will contain a composite of supercritical light hydrogen and light water. The purpose of this composite is to increase the number of neutrons in the 100 K range. Neutrons in this energy range can be used for a multitude of applications. Preliminary analysis indicates that this increase could approach the neutron yield expected from a liquid methane moderator. The downstream bottom moderator is ambient light water.

In support of the target design, we have focused our R&D program on the development of a mercury target system and have included research in thermal shock, thermal hydraulics, material damage and compatibility, and remote handling. All of our large R&D mercury loops are now operational. The use of these loops will yield valuable information on thermal hydraulics, remote handling, and operator requirements and training. The enclosure structure and part of the mercury loop structure are shown in Fig. 3. This structure is a prototypical mercury loop that will be similar to the one used in the actual SNS facility. The target end is located in the left side of the enclosure. The motor and sump pump can be seen on the right side. The system, which holds about 20 metric tons of mercury, became operational on October 31, 1999, and reached its design requirements shortly after startup. At the maximum pump speed of 600 rpm, the mercury flows at a rate of 30 l/s.

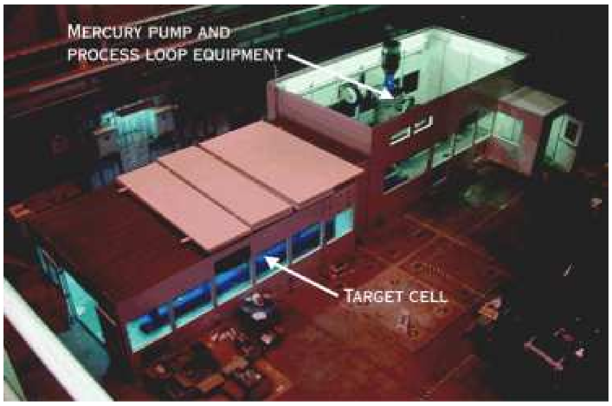

Figure 3: Target test facility showing the actual location of the target cell, mercury pump, and process loop equipment. In the actual facility the proton beam would be coming from the left side.

2.2 Instrument Systems

When SNS is complete and operating at 2 MW, it will offer unprecedented performance for neutron-scattering research, with more than an order of magnitude higher flux than any existing facility. Fig. 4 shows the layout of the SNS accelerator complex, experimental facilities, and support facilities. To realize the potential this offers for research in chemistry, condensed matter physics, materials science and engineering, and biology, a world-class suite of instruments is being developed that makes optimal use of the SNS beams and that is suited to the needs of users across a broad range of disciplines. The mechanisms by which instruments are built and operated will be responsive to varying degrees of experience, from new graduate students and first-time neutron users to experienced users with an interest in instrument design. As a DOE user facility, the SNS construction budget includes funds for an initial suite of instruments that will be available to users through a peer-reviewed proposal system. These instruments are being selected in consultation with the user community, following advice from our Instrument Oversight

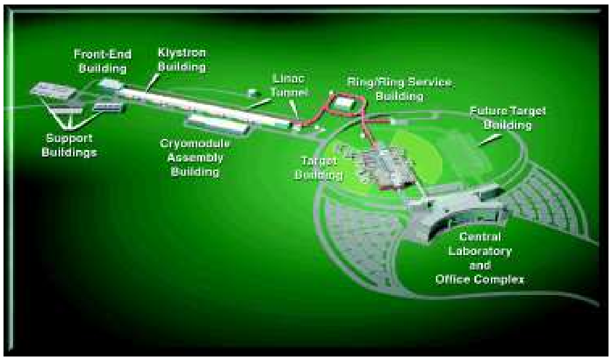

Figure 4: Spallation Neutron Source site plan showing the front end, linac, accumulator ring, target, instruments, and central lab/office and other support facilities.

Committee (IOC), and are being designed in consultation with prospective users through Instrument Advisory Teams (IATs). We expect that 75% of the beam time on this instrument suite will be available through the proposal system, with the remaining 25% for use by in-house scientific staff, for testing and calibration, for feasibility studies by users before submission of proposals, and for rapid response experiments that occur outside the regular proposal schedule.

In addition to providing a fast start on instruments for SNS users, the initial instrument suite will allow the development of core technologies such as choppers, data acquisition systems, and control software that will form the basis for similar systems in other instruments. These systems will be standardized where appropriate to simplify use and maintenance and to reduce costs. Full "target-to-detector" computer simulation is being developed to optimize and integrate target and instrument design. In many cases, the SNS will require instrument technologies beyond the current state of the art. Consequently, our construction budget for instruments is supplemented by a significant R&D program, which will allow development of new technologies that will form the basis for the initial instrument suite and provide room for growth. Although the current instrumentation budget allows for 10 or 11 best-in-class neutron-scattering instruments, a total of 24 can be accommodated on the high-power target station. Over time, new instruments will be built for the additional beam lines as part of the normal operating life of the SNS. However, to achieve full utilization of SNS, with the possibility of serving the focused research needs of groups willing to commit to building and operating neutron instruments, it is desirable to provide for instrumentation built by Instrument Development Teams (IDTs) that may or may not include SNS as a member. IDTs would provide at least partial funding for an instrument and would receive dedicated beam time in return for their financial commitment. For an instrument fully funded (including operation) by the IDT, up to 75% of beam time could be reserved for the IDT, with the remainder open to general users. The basic principles by which instruments are approved for SNS are the same, whichever mode of access is involved. The main criteria for instrument selection are the scientific program and the need for the unique capabilities of the SNS. The SNS is committed to seamless user access and instrument optimization across the facility. Instruments should be built on the beam line that best suits their requirements, and access for users should be uniform across the facility, independent of the funding source for the instrument. Guidelines for instrument team proposals that will facilitate fair and systematic evaluation are being developed in consultation with our advisory committees as well as the broader user community.

The instrument team proposal process will advance in two phases: an initial letter of intent followed by a detailed proposal. The letter of intent will broadly outline the proposal with sufficient detail for evaluating the scientific potential, funding mechanism(s), and management plan. An approved letter of intent would be followed by a more detailed proposal. The IOC, as well as expert review, will be involved at the appropriate stage. Similar guidelines would be followed for other (nonscattering) uses of the SNS facilities, with the modification that review would be by the Scientific Advisory Committee, supplemented by subject matter experts (because the IOC is a neutron-scattering expert panel). Such potential uses of the SNS would also be subject to the condition that they not compromise the neutron-scattering mission of the SNS and that the funding must be incremental to the project and cover all incurred costs. In addition to project-funded instruments (with an IAT) and totally externally funded instruments (with an IDT), there is a possibility for hybrid arrangements that would be negotiated on a case-by-case basis with the understanding that funding level and dedicated beam time are commensurate.

There are currently three instruments that have been recommended for construction as part of the SNS Project. These are shown in Fig. 5 together with other instruments under consideration and are described briefly below.

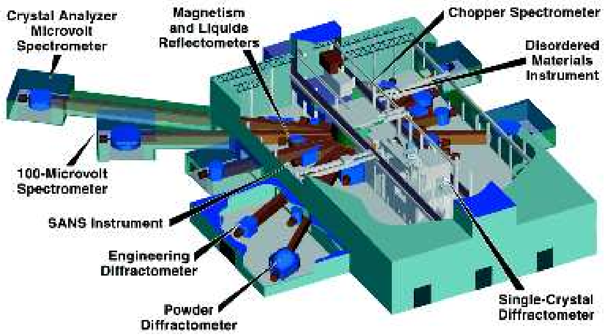

Figure 5: Schematic instrument suite for the SNS. The actual instrumentation will be determined in consultation with the user community.

High Resolution Backscattering Spectrometer A mechanism for achieving high energy resolution in inelastic scattering is to make use of Bragg scattering close to the backscattering condition to determine the final wavelength of neutrons scattered from the sample. With a pulsed source, time-of-flight is used to determine the incident neutron energy. [2, 3, 4] The SNS instrument is a near-backscattering, crystal-analyzer spectrometer designed to provide extremely high-energy resolution ($\hbar\omega = 2.2\mu$eV FWHM, elastic). The design requires a long initial guide section of 84 m from moderator to sample to achieve the timing resolution necessary to achieve the desired $\delta\omega$. The scattering chamber design is illustrated in Fig. 6. Neutrons focused onto the sample by the supermirror funnel scatter towards the analyzer crystals. The strained, perfect silicon (111) crystals reflect neutrons with a narrow distribution of energies centered at 2.082μeV onto the detectors. The design is optimized for quasi-elastic scattering but will provide 0.1% resolution in energy transfer $\hbar\omega$, up to $\hbar\omega = 18$ meV. This spectrometer will provide an unprecedented dynamic range near the elastic peak of $-258\mu eV < \hbar\omega < 258\mu eV$, about seven times that of comparable reactor-based instruments. For experiments that require the full dynamic range available at reactor-based instruments (or greater), we expect this spectrometer to have an effective count rate of 100 times that of the current best spectrometers.

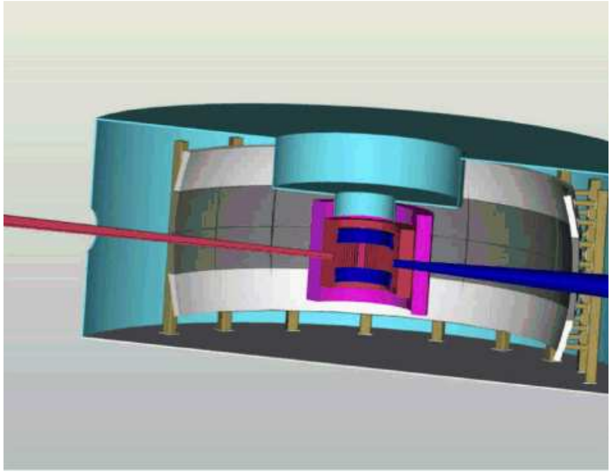

Figure 6: View of the scattering chamber of the backscattering spectrometer. With the analyzer crystals located 2.5 m from the sample, the chamber will have a diameter of approximately 6 m.

Reflectometers Neutron reflectometry is the study of elastic scattering from surfaces and interfaces at glancing angles. It provides structural information about surface and near surface atomic and magnetic order. [5] Two reflectometers are being considered for installation on a single beam line at SNS, one featuring an incident polarized beam for the study of magnetic materials and one with a horizontal sample surface to facilitate the study of liquids (see Fig. 7). Both instruments will use advanced neutron optics. Supermirror-coated microguide beam benders eliminate fast-neutron and gamma backgrounds. Tapered supermirror guides transport high flux to the sample position. The incident optics and bandwidth chopper system deliver ($\lambda > 2.5\mathring{A}$) neutrons to the sample at repetition rates of 60, 30, or 20 Hz. Running at 60 Hz, the instruments will be capable of measuring reflectivities of R $< 10^{-9}$, an order-of-magnitude improvement over the best existing instruments. Similar or greater improvements in data-collection rates have exciting implications for kinetic studies.

The polarized-beam reflectometer employs a vertical sample geometry to accommodate large superconducting magnets and other ancillary equipment. In addition to collecting data in reflection geometry, the instrument will have a detector bank at high angles for diffraction studies. Use of a Drabkin-flipper-type beam conditioning device and different polarizer, analyzer, and spin-flipper options are the objects of a vigorous R&D effort.

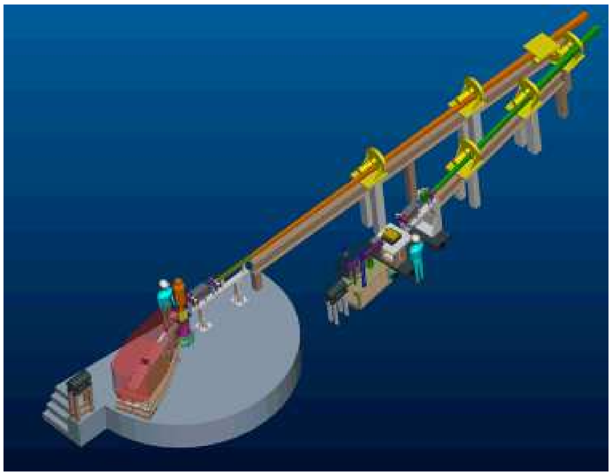

Figure 7: Three-dimensional representation of the reflectometry beamlines, viewed from the detectors looking towards the cryogenic moderator. On the left is the polarized beam reflectometer (vertical surface), on the right the liquids reflectometer (horizontal surface)

The liquids instrument features a novel design that uses the broad angular dispersion produced by the tapered guide. By sampling different incident angles (5-15) with beam-defining slits and using the relatively narrow wavelength bandwidth available at 60 Hz, we can efficiently cover a large range of momentum (hQ) transfer. Operation in this mode uses all of the source flux and combines the counting efficiency of a fixed-wavelength reflectometer with the wide Q coverage of a broadband instrument.

3 CONCLUSIONS

The Spallation Neutron Source will be the world's leading facility for studies of the structure and dynamics of materials using thermal and cold neutrons. It leverages state of the art accelerator technology, to deliver a high power (more than a factor of 12 times ISIS, currently the world's most intense pulsed spallation source), high reliability tool to physicists, chemists, biologists, and engineers. When it is fully instrumented it will support 1000-2000 users per year drawn from universities, industry, and government laboratories in the U.S. and abroad. Ultimately it will support two target stations, operating at different frequencies and power levels, doubling the capacity and more than doubling its scientific performance.

4 REFERENCES

[1] For a recent review see: MRS Bulletin, **24**, 1999.

[2] P.M. Gehring, D.A. Neumann, Physica B **241**, 64 (1997).

[3] B. Frick, A. Magerl, Y. Blanc, R. Rebesco, Physica B **234-236**, 1177 (1997).

[4] C.J. Carlile and M.A. Adams, Physica B **182**, 431 (1992).

[5] J.F. Ankner and G.P. Flecher, J. Magn. Magn. Mater. **200**, 741 (1999).