ELSEVIER

Journal of Nuclear Materials 318 (2003) 1–13

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Overview of the Spallation Neutron Source (SNS) with emphasis on target systems

Tony A. Gabriel *, John R. Haines, Thomas J. McManamy

Spallation Neutron Source, [1] 701 Scarboro Road, MS-6474, Oak Ridge, TN 37830, USA

Abstract

The status of the Spallation Neutron Source (SNS) is discussed. In addition, a more detailed overview is given of the Target Systems' part of the SNS with emphasis given to the technology issues that present the greatest scientific challenges. At present, SNS is within budget and schedule limits and excellent progress is being made on all fronts – design, fabrication, installation, and testing. First beam on the Hg target system is expected in December 2005. The project, as of June 2002, was 42% complete.

1. Introduction

In many areas of physics, chemistry, biology, materials, and nuclear engineering, it is extremely valuable to have a very intense source of neutrons so that the structure and functionality of materials can be studied. Discussions on all the Spallation Neutron Sources (SNS) under consideration or development are given in Refs. [1–3]. One facility under construction at ORNL for this purpose is the SNS. This facility will consist basically of three parts: (1) a high-energy and high-powered proton accelerator, (2) a target/moderator/reflector/shielding/shutter/utility assembly (Target Systems, TS), which converts part of the proton beam power to low-energy ($\lesssim 2$ eV) neutrons through spallation and delivers them to the third part, (3) the neutron scattering instruments. A parameter list is given in Table 1. A picture showing the overall facility is given in Fig. 1. LBNL is responsible for the front end, which is currently being shipped to ORNL for installation; LANL/JLAB, the linac (parts of the Drift Tube Linac (DTL) and klystrons have been shipped to ORNL for installation); BNL, the high-energy beam transport system and accumulator ring; ORNL, Target Systems and Conventional Facilities; and ANL, the neutron scattering instruments.

Shown in Figs. 2–6 are some recent photographs of the SNS site. Substantial progress has been made in the Conventional Facilities (CF) area. The photographs follow the progression of the proton beam as it makes its way to the Hg target located in the Target Building (TB). One beam dump, the ring extraction dump (7.5 kW passively cooled) is not shown, but will be located in front and to the right of the TB. Two major CF procurement packages, the General Contractor (GC) for the remaining part of the TB and the Central Laboratory and Office Building (CLO) packages, will be awarded later in 2002. These two packages are the only remaining major CF procurements to be awarded.

As in all state-of-the-art projects, there are technical difficulties that will be encountered. The SNS difficulties are twofold: (1) development of high-gradient super

---

* Corresponding author.

[1] The Spallation Neutron Source (SNS) is a collaboration of six US National Laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Thomas Jefferson National Accelerator Facility (TJNAF), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL). SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the US Department of Energy.

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0022-3115(03)00010-2

Table 1
SNS parameter's list

Start	October 1999
Finish	June 2006
Cost	\$1.4117B
Proton energy	1 GeV
Average beam power	$\leqslant 2$ MW
Repetition rate	60 Hz
Pulse width	<1 μs
Energy per pulse	<34 kJ

conducting (SC) cavities for the high-energy end of the Linac, and (2) cavitation induced erosion in the Target module. The technical issues have technical solutions, but even if the technical solutions fail, backups have been incorporated.

For example, an additional length has been added to the linac tunnel, which can be used to added SC cavities to get the proton energy up to 1 GeV. A preliminary solid target design has been developed which will fit into the mercury system envelope. Therefore, there are no showstoppers for the SNS. All difficulties can be handled within the cost and schedule available.

2. Accelerator components

The SNS is composed of several sequential accelerator systems with a resultant proton energy of ~1.0 GeV delivered to the neutron production Hg target (see Fig. 7).

Beginning the process is a cesium enhanced H^- ion source, the Front End (FE) system. The next accelerator unit is the Radio Frequency Quadrapole (RFQ), which accelerates the H^- beam to an energy of ~2.5 MeV. The last section of the FE system is the Medium Energy Beam Transport (MEBT). In the MEBT, the proper bunch structure of the beam is developed using buncher cavities to match the rotation frequency of the accumulator Ring.

After the front end, the H^- ions enter the first of four distinct accelerating structures within the Linac. The first two parts are a Drift Tube Linac (DTL) which accelerates the beam to ~87 MeV and a Coupled Cavity Linac (CCL) which accelerates the beam to ~187 MeV. The final two sections are Superconducting Radio Frequency (SRF) structures with a mechanical (relativistic) beta of 0.61 (~325 MeV) and 0.81 (~1.06 GeV).

At the injection region of the Ring, the H^- beam traverses thin carbon foils that strip the two electrons from the H^- ions and allow the resultant protons to be circulated and stored in the Ring. The beam structure produced back at the FE allows the protons to only occupy ~2/3 of the Ring's circumference. This pattern is required to give time for extraction. After ~1000 turns are accumulated in the Ring, a series of fast rise-time dipole elements (kickers) are triggered to extract the stored $\lesssim 2\times10^{14}$ protons circulating in the Ring for delivery to the Hg target.

Fig. 1. SNS configuration.

Fig. 2. Linac and helium refrigeration building.

Fig. 3. Linac Tune Beam Dump with Flight Tube attached (7.5 kW, passive cooling) and High Energy Beam Transport (HEBT) line to Accumulator Ring.

Fig. 4. Ring Injection Dump (200 kW, actively cooled). H^- that are not converted in the stripping foils to protons are accumulated here. Part of the Ring can be seen in the background.

Fig. 5. Ring on side of extraction to Target Building.

Fig. 6. Shielding monolith located in the Target Building (TB). The baseplate and lower liner will be installed soon. The liner will contain the shielding, shutter and the Hg Target System.

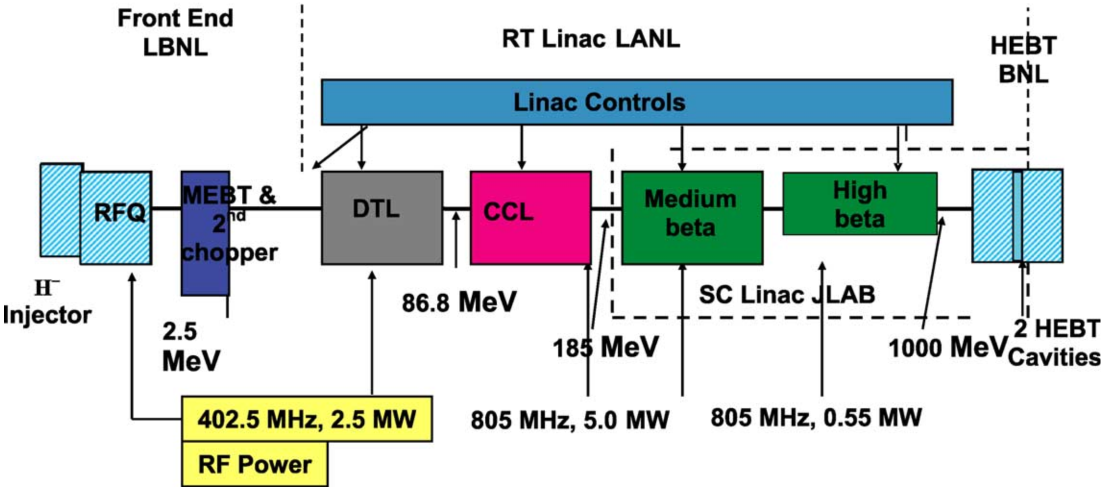

Fig. 7. The Accelerator Configuration will include a SuperConducting RF System.

3. Scope, requirements, design, procurement, and installation status of target systems

The scope of TS is to provide low-energy neutrons from high-energy spallation reactions for short-pulsed neutron scattering instruments and to develop three proton beam dumps, one for the linac and two for the storage ring (injection and extraction).

The first requirement for TS is to safely and reliably receive a proton beam in a flowing-mercury target with the characteristics defined in Table 1. As a second requirement, TS must be able to convert part of the proton beam power into short, high-intensity pulses of low-energy neutrons (both thermal and cold) which can be used by up to 24 neutron beam lines, and which meet the requirements of the neutron scattering instruments.

Building a TS for the SNS requires the development of a target, in this case a flowing-mercury target, which can give maximum neutron yield; a reflector/moderator assembly to trap, reflect, and thermalize the neutrons; a vessel system to contain the reflector/moderator assembly and provide support and alignment for the start of the neutron guides; bulk shielding and shutter assemblies to shield the personnel from the neutrons and to allow the closing of the low energy neutron pathways so samples can be replaced in the neutron scattering instruments; utilities (light and heavy water, vacuum and He) to help with the cooling and functions of the various systems; remote handling to accommodate the change out of the target, inner reflector assembly, neutron guides and shutters, proton beam window, etc.; and Instruments and Controls for the majority of the subsystems mentioned above. Currently, the detailed design of the TS is almost complete and many procurements have been placed. A picture of the shielding monolith showing the various components as well as the Hg process loop is given in Fig. 8.

By June 30, 2003, all of TS detailed design will be complete. The installation of TS equipment has begun. The baseplate, which acts as a base for the vessel and part of the shielding has been placed. The bolts that will stabilize the liner, which contains the rest of the components, have been placed into concrete. The liner will be placed shortly. Heavy and light water tanks are ready for installation into the basement. Four tanks are used to separate the least from the most activated. Presented in Fig. 9 are the remote handling tools that will be used to replace the target module. The thru-the-window arms are in storage at the SNS. The incell servo manipulator arms and the 7.5 ton are currently being built.

Because a solid target may be needed, plans have been made to make sure it will fit within the framework laid out for the Hg system. A preliminary layout of this system is shown in Fig. 10. Because of the size of the system, components like the pumps, storage tanks, and the filter and ion exchange columns had to be placed in rooms in the basement. The only changes that have been done is to increase the ceiling thickness over the filters and ion exchange column room so as to reduce the radiation dose levels in the manipulator gallery.

A target design based on the PSI/SINQ Zircaloy rod target has been developed. Since a Zircaloy rod target reduces the neutron source brightness relative to mercury, the loop capacity will allow future use of tungsten targets, which will return the neutron brightness.

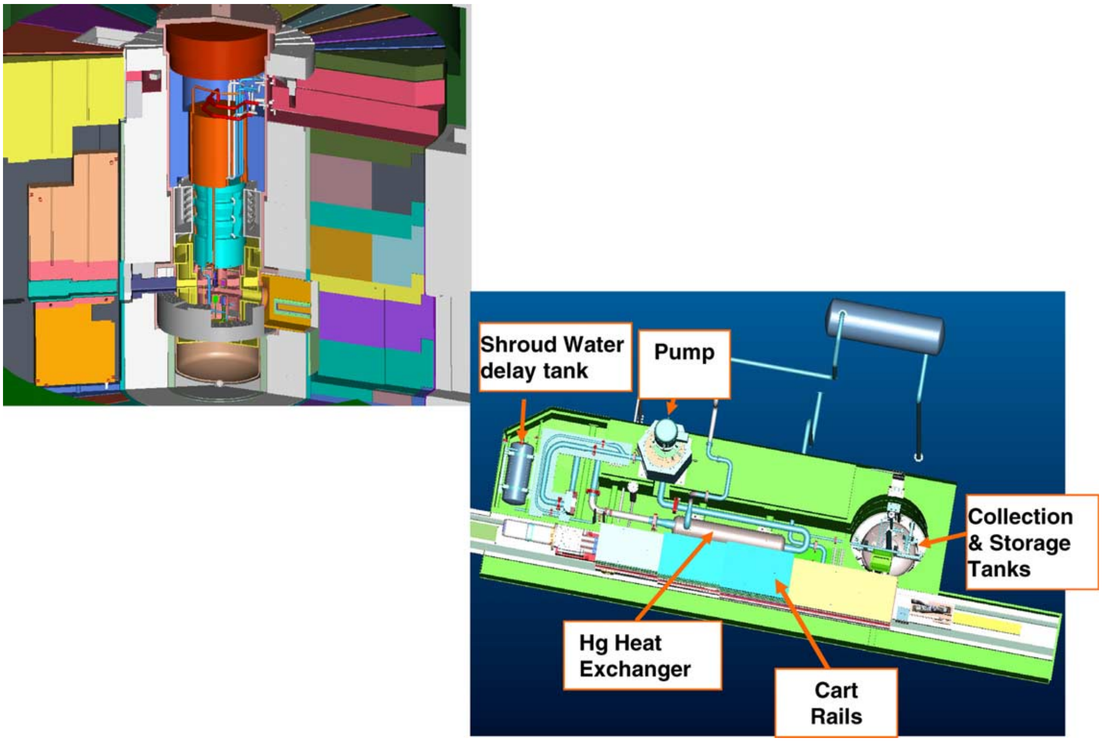

Fig. 8. Monolith region without Target Cart and Process Bay Equipment in Hot Cell with Target Cart extracted.

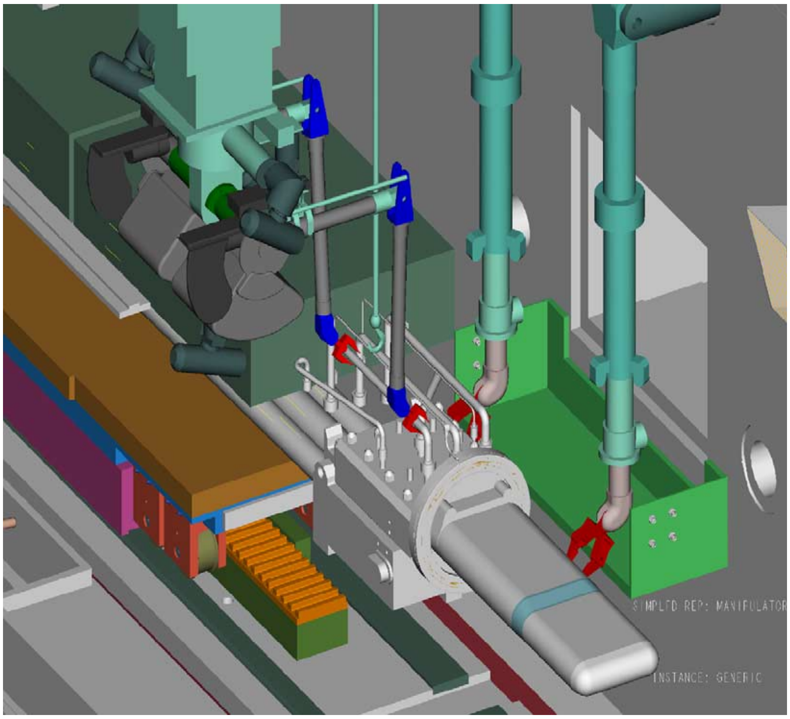

Fig. 9. The Remote Maintenance Systems for Target Systems will be best in the world.

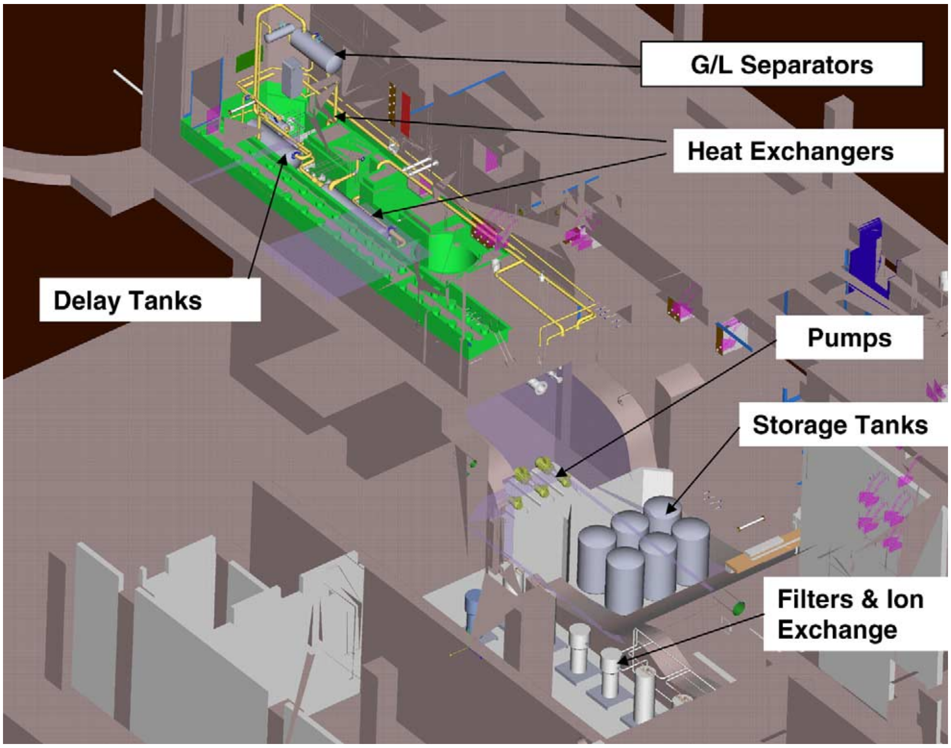

Fig. 10. Arrangement of D_2O loops in Target Building. The Targer Cart Assembly (TCA) (not shown) will be the same as for the Hg system. The entrance hole for the TCA is shown in the upper/left.

If the decision is made to go with the Hg target initially and it is found out it will not work with the current design or foreseen designs, an approach for switching out a Hg system for a solid system is being pursued. This effort encompasses both cost and schedule. If some design and other preparations are planned ahead, approximately 24 months are required to switch.

4. Target development R&D

Five areas have been defined as needing R&D to develop a successful TS [4,5]. These are (1) steady-state power handling, (2) remote handling and operation, (3) radiation damage, (4)material compatibility, and (5) thermal shock. Three major facilities (and numerous smaller test units) have been developed at ORNL to address the first four areas. These major facilities are shown in Fig. 11. The Target Test Facility (TTF) is a full-scale prototype Hg loop. The WTHL is the water thermal hydraulic loop for studying flow stability and recirculation zones. The MTHL is the mercury thermal hydraulic loop for studying heat transfer and erosion. Also shown in the picture is a cylindrical target that was used to study thermal strain levels in the container resulting from the pressure wave generated in the mercury by the short-pulsed proton beam. All of the issues defined in the R&D program have been addressed or solved, except for the erosion through cavitation induced pitting brought on by the thermal shock of the beam.

4.1. Pitting background

For several years, SNS researchers have been collaborating with researchers from the Weapons Neutron Research Facility (WNR) at the Los Alamos Neutron Science Center (LANSCE), European Spallation Source (ESS), Japan Neutron Source (JNS), Japanese Atomic Research Institute (JAERI), and High Energy Accelerator Research Organization (KEK), and Brookhaven National Laboratory (BNL)/Alternating Gradient Syn-

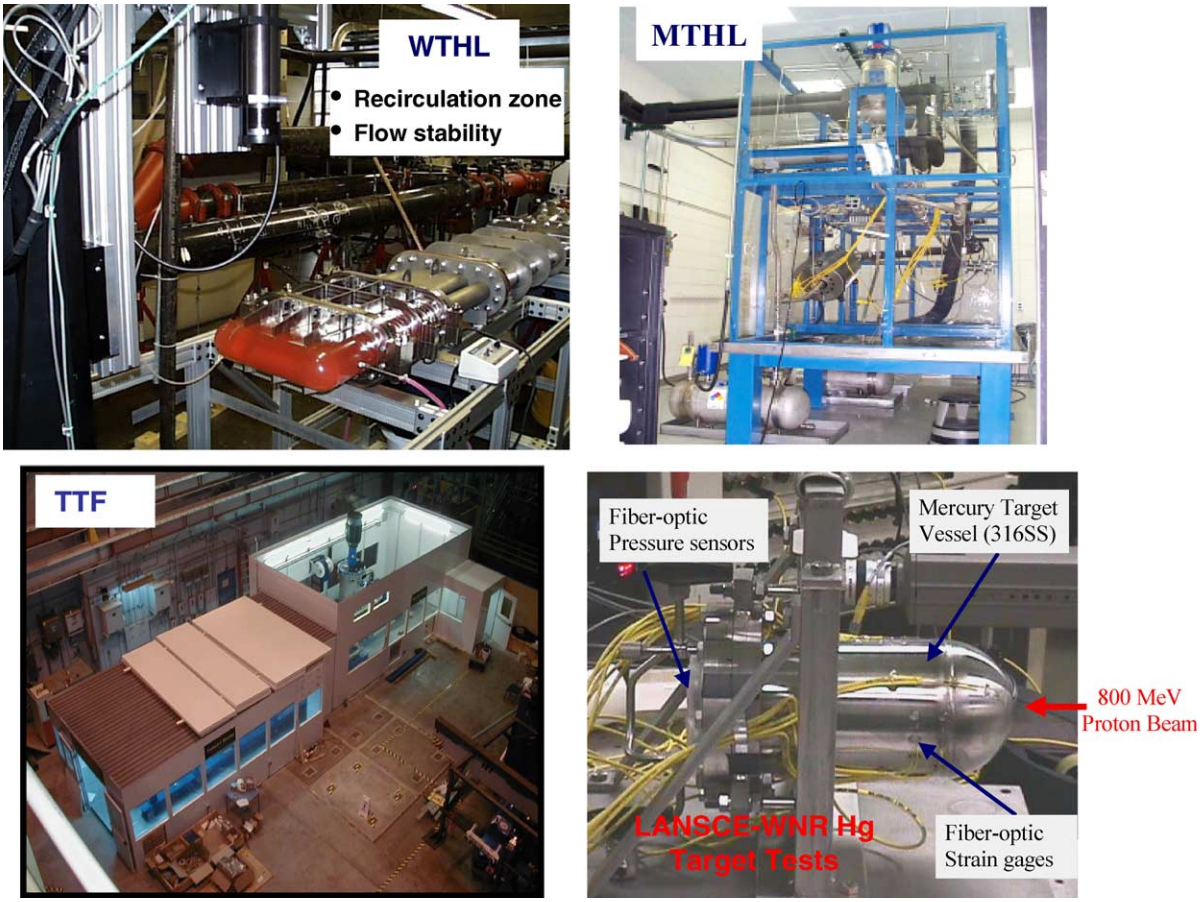

Fig. 11. Mercury Target development has three major facilities at ORNL and utilizes the Accelerator Facilities at LANL/WNR and BNL/AGS.

chrotron (AGS) personnel to study issues associated with using mercury as the target material for the SNS. Mercury was selected as the target material for the SNS because of its favorable neutron-production characteristics and potential to handle the high-proton-beam power (2 MW) that is planned for this facility. An important issue identified for liquid-metal targets in pulsed sources is their ability to withstand the rapid pressure increase when the pulsed proton beam irradiates them. Although a WNR pulse contains much less energy than a pulse from the 2-MW SNS, focusing the WNR proton beam in the Blue Room down to a size of about 20 mm in diameter will allow us to reasonably simulate the beam intensity in smaller target containers, and therefore, the pressure increase expected for the SNS. Previous tests with an array of target shapes, diagnostics, and instrumentation measured the vessel strain to ensure that the target can sustain the dynamic pressure loads. Besides providing data that are helping the SNS team to design and analyze the actual SNS target, these tests successfully demonstrated that a newly developed fiber-optic-based strain-measurement system could function in this demanding radiological environment.

4.2. Understanding pitting in irradiated targets

Tests conducted during 2001 were designed to examine whether the pressure pulse caused pitting damage to the stainless-steel container for the mercury. The pitting phenomenon was first identified as a potential concern by a team of researchers at the Japan Atomic Energy Research Institute [6], where they observed pitting of stainless-steel surfaces that were in contact with mercury subjected to large, mechanically induced

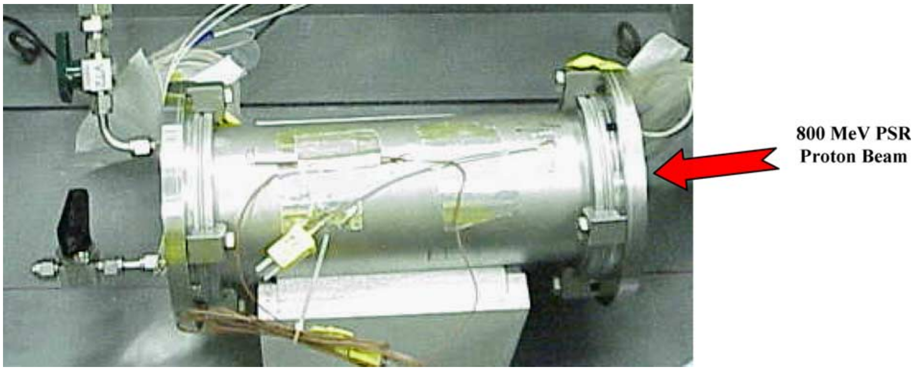

Fig. 12. Large Effects (LE) target used for the July 2001 mercury-target-pitting tests in the Blue Room at WNR. Thin diaphragms were used in these tests to achieve large strains.

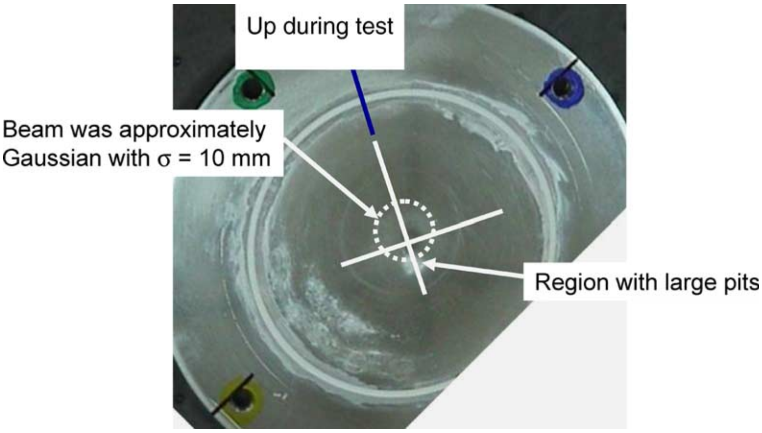

Fig. 13. This thin diaphragm flange was exposed to mercury in the July 2001 tests in the Blue Room at WNR. The cross marks the center of the diaphragm and the circle indicates the one sigma boundary of the approximately Gaussian-shaped beam. Large pits were clustered in a region symmetric to the center of the beam relative to the center of the diaphragm. This shift may be caused by the radial focusing of the pressure wave.

pressure pulses. As such, the need exists to discern whether the surfaces of mercury-target vessels become pitted with comparable beam-induced pressure pulses. This issue could not be resolved from examinations of targets previously irradiated at WNR because these targets were not inspected before irradiation and the roughness of the surfaces was too great to distinguish between beam-induced pits and other imperfections in the surface of the materials.

Because of the urgency to complete the SNS target design, two experiments were conducted in 2001 to study the pitting issue – in July and December. One of the two targets used in July 2001 is shown in Fig. 12. This type of cylindrically shaped target is referred to as a 'large-effect' (LE) target and was first used in the strain measurements to obtain an easily measured 'large' strain in the thin diaphragms that were incorporated in the end plates/flanges.

All four of the diaphragms tested in July 2001 were fabricated from 316-type stainless steel in the annealed condition. Three of four were used directly in the LE targets, whereas the fourth was treated with a surface-hardening technique. This treated diaphragm was used on the rear (proton-beam exit) end of one of the two LE targets.

A photograph of the mercury-facing surface of one of the untreated diaphragms is shown in Fig. 13. As shown in the photo, large pits, visible to the naked eye, are distributed over a region that is about 5 mm in diameter and centered about 10 mm directly below the center of the diaphragm. Using activation analysis techniques, it could be shown that the beam was centered approximately 5 mm directly above the center of the diaphragm. This 180° shift between the beam and the pit region may be due to radial focusing of the pressure wave and its reflection off of the sidewalls of the cylinder.

Micrographs of the surface of one of the untreated diaphragms before and after exposure to 200 nearly full-current pulses from the Proton Storage Ring (PSR) are shown in Fig. 14. Evidence for pitting is obvious in these images. In carefully examining the diaphragm surfaces, two categories or types of pits were observed: (1) large (~100-μm-diameter) pits that appeared in a cluster near the center of the diaphragm, as shown in Fig. 14, and (2) randomly distributed, small pits (~10-μm). Large and small pits occurred on both the front (beam entrance) and rear (beam exit) of the untreated diaphragms. Although some of the large pits clustered near the center of the diaphragm were found on the surface-hardened diaphragm, dramatically fewer randomly distributed pits could be detected at the resolution used to perform the inspections (~5 μm). Based on the July 2001 test results, it was concluded that mitigating this pitting damage is required to ensure that the mercury target can achieve an acceptable lifetime at the SNS. With this in mind, the December 2001 tests were dedicated to further examine the pitting phenomenon and to look at possible elimination, or at least reduction, of the pitting problem.

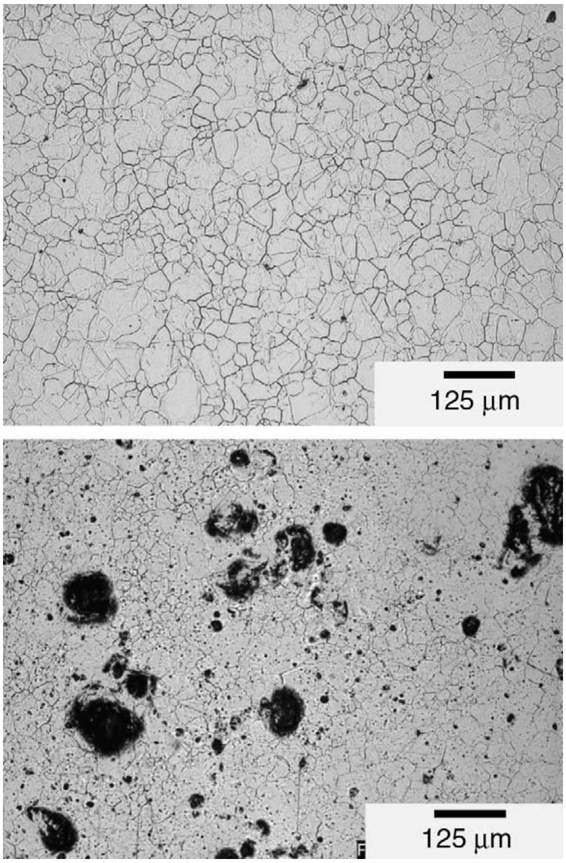

Fig. 14. This image shows micrographs of a stainless-steel diaphragm from one LE target used in the July 2001 mercury-target-pitting tests: (a) a typical region before beam exposure and (b) a section near the center of the diaphragm containing large pits that were formed by exposure to 200 pulses in the Blue Room at WNR. These large pits had diameters of up to approximately 100 μm. Small, randomly distributed pits were also found on the bare surface of the three annealed stainless-steel specimens. Large pits were found, to a lesser extent, on the one diaphragm that was treated with a hardening process, and dramatically fewer small, randomly distributed pits were detected.

Six mercury targets were tested in December 2001. Four of these targets used different shapes or different diaphragm materials and were exposed to 200 beam pulses. Most notably, a target was used with a rectangular cross section in an attempt to eliminate the postulated radial focusing of the pressure wave. Also, diaphragms were tested with increased thickness in an attempt to reduce the large stresses. Two targets were also tested with only 20 pulses to determine whether future experiments might be possible at this reduced fluence level. Finally, a lead–bismuth target, with geometry and materials essentially the same as that used in July 2001, was exposed to the WNR beam for 200 pulses. This experiment was done in collaboration with the LANSCE team working on the lead–bismuth target design for the Advanced Accelerator Applications program. One of the target container faces from the December 2001 tests showed no pitting after 200 pulses. The face was ‘thick’ and composed of 20% cold worked SS316 and hardened by the kolsterizing process. This is a promising result, but the surface hardening treatment is only 33 μm thick and there is no data concerning its lifetime during long irradiations. About 200 pulses may

Table 2
Second and third round of pitting tests conducted at LANSCE/WNR in December 2001 and June/July 2002

Purpose of the December 2001 Test (6 SNS targets, 1 rectangular, 5 cylindrical):
Determine whether large stresses and/or radial focusing led to large pits near center of flanges
Examine more cavitation damage resistant material options
Examine impact of small Hg region simulating target coolant passage (rectangular shaped)
Confirm whether methods to simplify future screening tests are acceptable
Fewer beam pulses
Configurations with multiple specimens available
Purpose of the June/July 2002 Test:
Nearly all targets are prototypical, i.e., rectangular (total targets: 22; over 70 surfaces polished and examined)
These tests looked for cavitation thresholds (3, 1, 0.3 MW), mitigation methods (air gaps, bubbles, etc.), and materials, which might be more cavitation resistant
Provide data for final decision of initial SNS target type (Hg or solid)
The data for the decision will be October 2002

Table 3
Proposed instruments

Twelve instruments have been approved by the SNS Experimental Facilities Advisory Committee
Five are being funded within the project:
High-resolution backscattering spectrometer
Vertical Surface (Magnetism) reflectometer
Horizontal Surface (Liquids) reflectometer
Extended Q-range small-angle diffractometer
Third generation powder diffractometer
Three more instruments are being funded by Instrument Development Teams (IDTs):
ARCS Wide-angle thermal chopper spectrometer (Brent Fultz, Caltech)
CNCS Cold neutron chopper spectrometer with 10-100 meV resolution (Paul Sokol, Penn State)
Engineering materials diffractometer (Canada)

Table 4
Proposed instruments

Funding not yet secured for remaining approved instruments
Fundamental physics beamline (under ORNL LDRD funding a proposal is being developed)
High-pressure diffractometer
Disordered materials diffractometer
High-resolution thermal chopper spectrometer
Single crystal diffractometer
Other instruments are in the discussion stage
Spin-echo spectrometer
Hybrid polarized neutron inelastic spectrometer
Chemical spectroscopy instrument
Protein crystallography

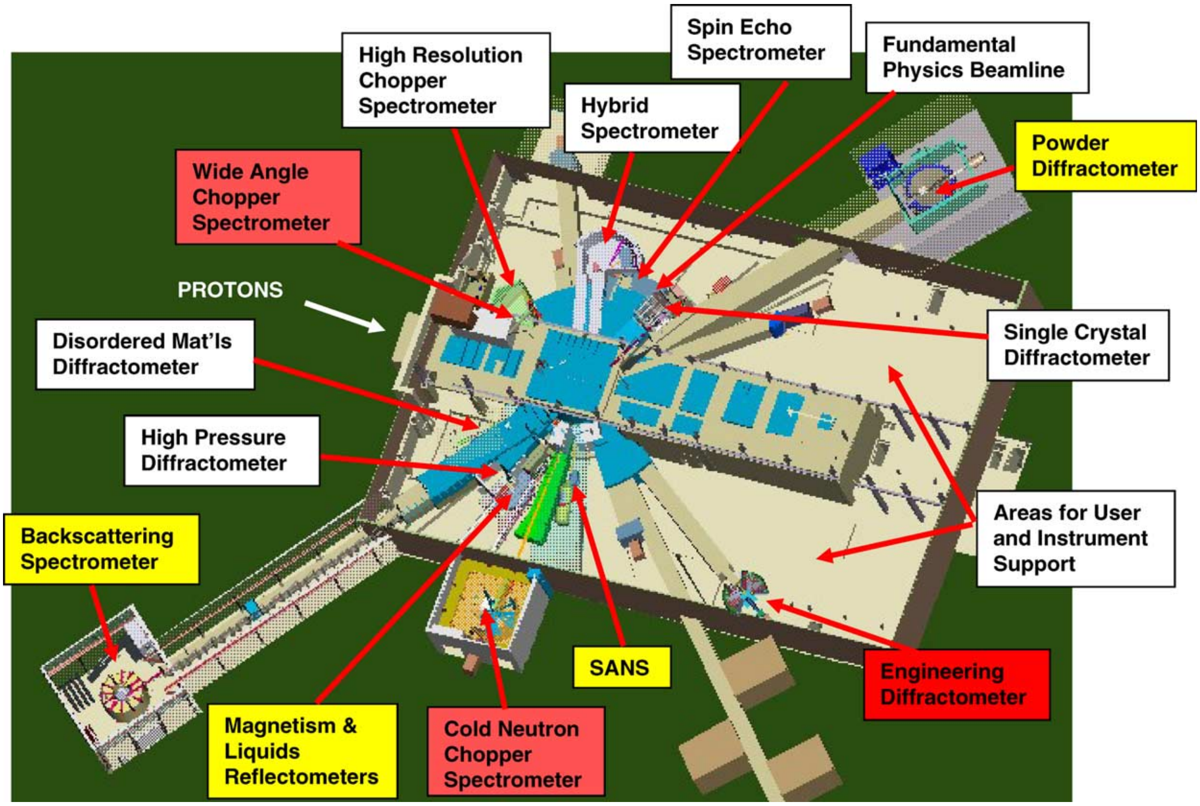

Fig. 15. Instrument layout in the Target Building.

not be enough cycles to start this erosion process on this type of surface. The mercury target container lifetime has to be 1250 h or ~300 million pulses.

Using the data obtained from the 2001 tests and new insights into the physics of pressure wave propagation and cavitation, additional tests have been carried out in 2002 to assess possible solutions that are, geometry, mitigation methods, and materials. The analysis of this data has just started. Table 2 gives the purposes of the 2001/2002 tests.

Since extrapolation to a reasonable lifetime is necessary, several out of beam prototype cavitation apparatuses are being developed to simulate cavitation-induced erosion at $\sim 10^6$ pulses. Most of these tests are based on the Split Hopkins Pressure Bar (SHPB) concept adjusted to operate at ~1 Hz. Another concept is based on the Lithotripter, which is used to breakup kidney stones. A rapid discharge of the Lithotripter in a water bath can generate in proper time at a focal point strain level comparable to those in the Hg containers (~20 MPa). A small capsule containing mercury and sample material at the focal point has been popped with $\geqslant 1000$ pulses. The capsule has been opened and inspected. Pitting has occurred and the detailed post inspection is underway. The post inspection will determine if the damage is 'prototypical'. The other apparatuses (several are based on the SHPB concept) are under development and results are expected shortly.

5. Instrument systems

The instruments are the hearts of the SNS and five have been funded within the Project. See Tables 3 and 4 for the overall status of the instruments. Additional detectors have been approved and three of these instruments have obtained funding through the efforts of Instrument Development Teams (IDT). Five more instruments are approved, but funding has not yet been obtained. The project anticipates more IDT funding shortly and also expects that some of this funding will be international like the funding for the Engineering Materials Diffractometer. A layout of 24 instruments is shown in Fig. 15 and gives the locations of many of the instruments given in Tables 3 and 4.

References

[1] K.N. Clausen, 'The European Spallation Source (ESS) Project', ICANS-XV 15th Meeting of the International

Collaboration on Advanced Neutron Sources, Proceedings vol. 1, 6–9 November 2000, Tsukuba, Japan.

[2] Y. Oyama, S. Ikeda, JAERI-KEK Joint Project Team, 'Status of Spallation Neutron Source Program in High Intensity Proton Accelerator Project', ICANS-XV 15th Meeting of the International Collaboration on Advanced Neutron Sources, Proceedings vol. 1, 6–9 November 2000, Tsukuba, Japan.

[3] T.E. Mason, T.A. Gabriel, R.K. Crawford, K.W. Herwig, F. Klose, J.F. Ankner, 'The Spallation Neutron Source: A powerful tool for materials research', in: 20th International Linac Conference, 21–25 August 2000, Monterey, California, published on the LANL e-print server.

[4] T.A. Gabriel, 'An Overview of the SNS', Published in the proceedings of the 'Golden Anniversary' of Nuclear Engineering at North Carolina State, Raleigh, NC, 2–4 December 2000.

[5] This section on pitting has been taken mostly from J.R. Haines et al., SNS Mercury Target Development, TSR-221, July 2002, and includes a few updates.

[6] K. Kikuchi et al., R&D on Mercury Target Pitting issues, these Proceedings. doi:10.1016/S0022-3115(03)00016-3.