

OVERVIEW OF THE TARGET SYSTEMS
FOR THE SPALLATION NEUTRON SOURCE*

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ABSTRACT

The technologies that are being utilized to design and build the target systems for a state-of-the-art accelerator-based neutron source, the Spallation Neutron Source (SNS), are discussed. Emphasis is given to the technology issues that present the greatest challenges. The present facility configuration, ongoing analysis, and planned research and development program are also described.

I. INTRODUCTION

The conceptual design for a next-generation, accelerator-based, pulsed neutron source, which will be used primarily for neutron scattering research, is being prepared by an Oak Ridge National Laboratory (ORNL) led team for the Department of Energy. This facility, named the Spallation Neutron Source (SNS), consists of two parts: (1) a high energy (1 GeV) and high power (1 MW) proton accelerator that releases the protons in pulses of less than 1 μ s duration, and (2) a target system which converts the protons to low energy (≤ 2 eV) neutrons and delivers them to an array of neutron scattering instruments. This paper deals with the second part: i.e., the design and development of the SNS Target Systems and their most challenging issues. It should be noted that the Target Systems also include three beam dumps located at key positions along the accelerator beam line; however, these components will not be addressed in this paper.

The overall configuration of the key subsystems within the Target Systems are described below, followed by a discussion of the key design and performance issues and the R&D programs in place to investigate these issues. More detailed discussions of specific systems, technologies, or R&D efforts are presented elsewhere.¹⁻¹³

II. TARGET STATION CONFIGURATION

The SNS target and experimental systems are located in a single building as shown in Fig. 1. The target is positioned within a shielding structure that is approximately 12 m in diameter. The proton beam enters the target and the neutrons resulting from spallation and subsequent nuclear reactions are moderated and transported through 18 neutron beam tubes projecting horizontally around the target. Neutron scattering instruments will be positioned at the exits of these beam tubes.

The majority of the 50 m x 75 m target building is reserved for the scattering instruments located on the neutron beam lines, however, remote handling hot cells projecting from the back of the shielding are provided for handling the activated target, moderator, and reflector components. This region also contains utilities used for the target. Another cell for utility systems is located beneath the main floor level.

The target facility can be segregated into four areas for discussion:

- target assembly including the mercury process loop,
- moderators,
- reflectors,
- neutron beam transport system

A. Target Assembly Configuration

The reference design for the SNS incorporates mercury as its target material. A liquid target was selected for SNS over a water cooled solid target primarily because (1) increased power handling capability is possible with a liquid target, and (2) the liquid target material is not

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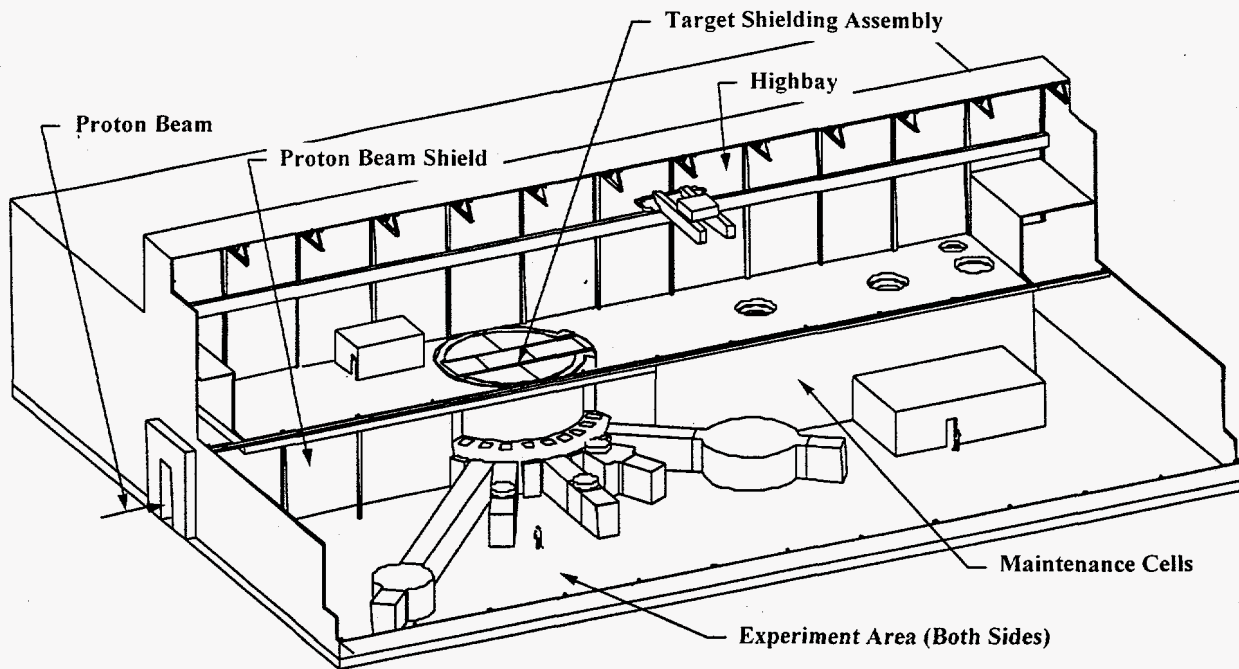


Fig. 1. Cutaway view of target building

damaged by the irradiation process and therefore lasts the entire lifetime of the facility. Previous efforts by the European Spallation Source (ESS) team have been used extensively in developing the SNS mercury target station.¹⁴

The overall configuration for the target, moderator, reflector, and neutron beam tubes (portion near the target only) is shown in Fig. 2. The Target Module consists of the mercury target, constructed from a stainless steel vessel that is self-cooled by the mercury flowing through

various passages within the vessel, and a water-cooled shroud that surrounds the target vessel.

The mercury target vessel, shown in Fig. 3, has a width of approximately 400 mm, a height of 100 mm, and a length of 650 mm. The mercury is contained within a structure made from 316-type stainless steel. Mercury enters from the back side (side opposite from the proton beam window) of the target, flows along the two side walls to the front surface, and returns through a 206 mm by 80 mm rectangular passage in the middle of the target.

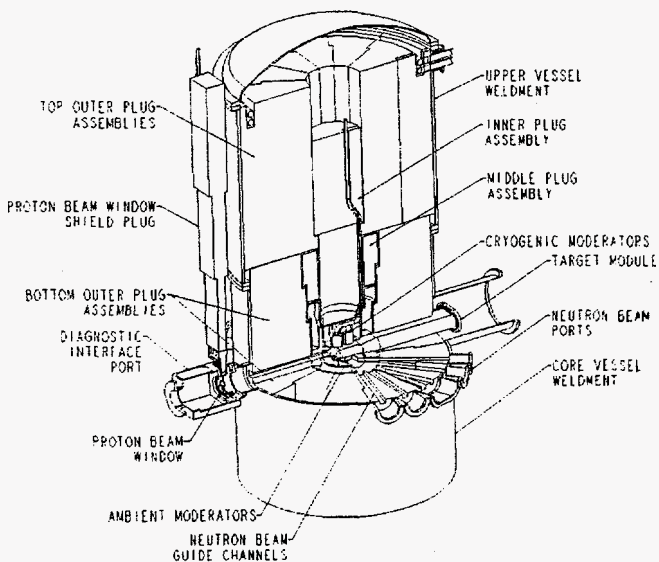


Fig. 2. SNS target, moderator, and reflector region

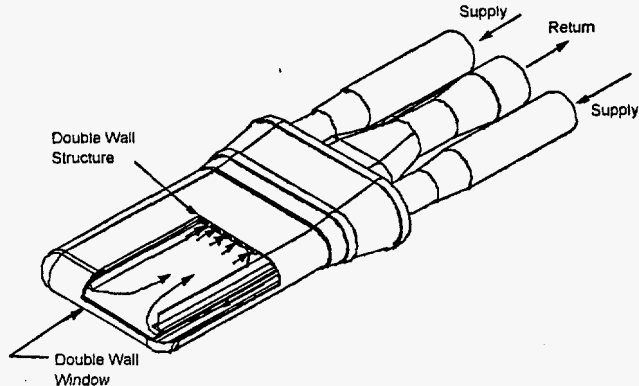


Fig. 3. SNS target vessel

mercury are achieved with separate flow streams. This approach is judged to be more reliable and efficient (minimal pressure drop and pumping power) than using the bulk mercury to cool the target window. Also, the duplex structure used for the window has significant structural advantages that help to sustain other loads. Besides serving as flow guides, the baffle plates used to separate the inlet and outlet flow streams are also important for maintaining the structural stability of the target.

The shroud (mercury spill container), which is a water-cooled duplex structure made from austenitic, 316-type, stainless steel, is provided around the mercury target to guide the mercury to a dump tank in the event of a failure of the target container structure.

The mercury process equipment located in the maintenance cells behind the target is shown in Fig. 4. The mercury target and the water-cooled shroud, which are subject to intense interactions with the proton beam, must be replaced on a regular basis. All major liquid target system components, except the assembly holding the target vessel and shroud, are located on the floor of the target service cell. The mercury contained in the target system is drained to the dump tank prior to retracting the target assembly.

The heat deposited in the mercury target is transported away in the flowing mercury loop to a primary heat

exchanger. The primary heat exchanger is a shell and tube type with mercury flowing in the tube side and the secondary coolant, i.e., demineralized water, flowing in the shell side. The tubes in this heat exchanger are a special, double-walled type that reduces the probability of a mercury leak into the intermediate loop.

In addition to this primary heat exchanger, the mercury-flow loop also includes piping, valves, fittings, pumps, expansion tanks, and mercury processing equipment. The secondary (water) loop transports the heat to a secondary heat exchanger located in the floor below the target service cell. The tertiary flow stream utilizes process water.

The mercury dump tank is located below all other components in the mercury system thus ensuring that most of the mercury can be drained to the dump tank even in a passive situation (failure of the electric power system). A gas purge system is also utilized under normal circumstances to provide more complete removal of the mercury from the target systems to the dump tank. The capacity of the dump tank is approximately 2 m³, which is slightly larger than the mercury inventory in the remainder of the system. The tank is actively cooled with a gas stream to remove the nuclear afterheat in the mercury; but, calculations have shown that passive cooling will work due to dilution resulting from the large volume of mercury.

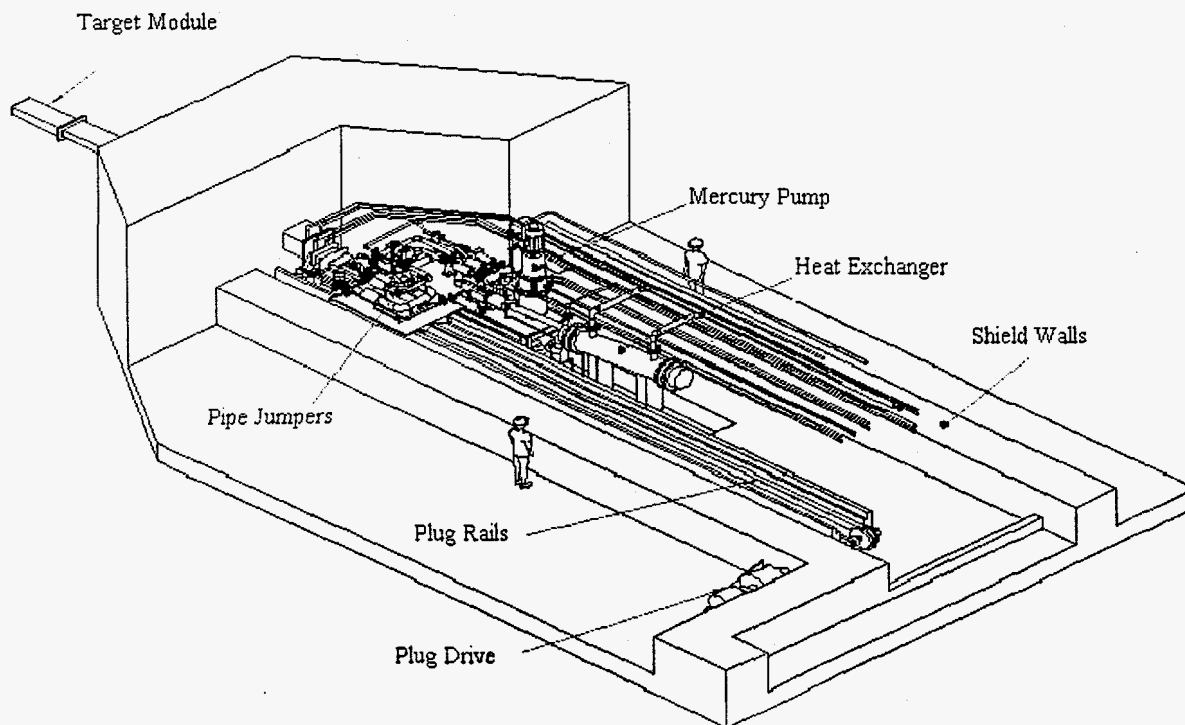


Fig. 4. Overall layout of mercury process loop

B. Moderators

Figure 2 shows the array of moderators planned for SNS. There are two light water moderators located below the target and two cryogenic moderators located above the target. All four moderators are arranged in wing geometry. The moderator vessels are made from aluminum alloy-6061.

Both ambient moderator vessels have a thickness of 50 mm and are decoupled and poisoned to give high temporal resolution of the neutron flux. These moderators are approximately 120-mm wide and 150-mm high. The overall heat load in the ambient moderators is estimated to be 4 kW (2 kW per moderator). This heat load results in an overall temperature rise of less than 1 K for a nominal flow rate of 2 L/s.

The two cryogenic moderators use supercritical-hydrogen that is circulated at a pressure of 1.5 MPa and a temperature of less than 20 K. Operation in the supercritical state was chosen for these moderators because it improves the cooling operation, eliminates phase change (boiling) concerns, and adds flexibility in operation. The hydrogen is maintained in the supercritical state in all parts of the loop during normal operation. Only one of these moderators is decoupled and poisoned.

C. Reflector Systems

The reflector is constructed from an array of plugs as identified in Fig. 2. This configuration is based on replacing the target horizontally and the moderators and reflector plugs vertically. The lower assembly of reflector plugs and moderators is contained within a vessel that has a diameter of 3.5 m. This size was selected so that shielding located outside this vessel will not require active water cooling. The vessel allows for operation with a contained helium atmosphere or at a rough vacuum.

The inner plug, shown in Fig. 2, contains the moderators surrounded by an assembly of reflector components. This plug will be removed and replaced as one unit. The lower section of the inner plug is constructed from a stainless-steel shell filled with stainless steel clad lead pins and cooled with heavy water. Decouplers made from cadmium surround the neutron beam paths. The most likely reason for replacement is expected to be a change in the moderator requirements to support the scattering instrument needs.

The middle plug assembly supports the inner plug and rests on the bottom of the core vessel. It is also a heavy water cooled steel shell filled with lead pins. Twelve bottom outer plugs fill the remainder of the lower vessel.

These are also heavy water cooled stainless steel shells. Designs are being evaluated for casting these with recycled lead or having a combination of lead and iron. The lead region will extend for a minimum of 1-m radius from the center of the target and 1 m above and below.

D. Neutron Beam Transport System

The neutron beam transport system provides the paths for moderated neutrons to travel through the bulk shielding to the scattering instruments. This system consists of 18 beam lines looking at the four moderators as shown in Figs. 1 and 2. Each viewed moderator face illuminates three beam lines, one normal to the face and two at plus or minus 13.75 degrees. The upper and lower forward moderators have two viewed faces and the two rear moderators each have one viewed face for a total of six viewed faces. This arrangement allows a 70-degree arc for the proton beam entrance region and a similar 70-degree arc for the remote maintenance systems at the rear of the target.

A neutron beam shutter concept similar to the ISIS and IPNS vertical shutter design is planned. The shutters are in the form of stepped rectangular slabs. In the open position a hole in the shutter aligns with the neutron beam flight path. The shutter is lowered approximately 500 mm to close. This puts approximately 2 m of shielding in the neutron flight path. The neutron beam lines require shielding outside of the bulk target shield. This shield is both for personnel protection and also to reduce the background noise in instruments.

III. PERFORMANCE EVALUATIONS

The power-handling performance of the target assembly and neutronic performance of the integrated target, moderator, and reflector systems have provided important guidance in defining the designs described above. These performance evaluations are described in detail elsewhere and are only briefly mentioned in this paper.^{3, 6-7}

A. Power-Handling Performance

The mercury target and its enclosing structure must be designed to sustain the time-averaged power loads as well as the nearly instantaneous power deposition during single pulses. These time-averaged and single-pulse loads are defined in Table 1. Since about 60% of the proton beam power is deposited in the target, the thermal-hydraulic system for the target is designed to remove a time-averaged power of 0.6 MW corresponding to a proton beam power of 1 MW. Since the pulse frequency is 60 Hz, the amount of energy deposited in the target during a single pulse is 10 kJ.

Table 1. Heat loads on the SNS mercury target

Parameter	Value
Energy of protons (GeV)	1
Pulse duration (μ s)	~ 0.5
Pulse frequency (Hz)	60
<u>Time-Averaged Loads</u>	
Beam current (mA)	1
Total proton beam power (MW)	1
Peak current density on target (A/m^2)	0.18
Peak beam power flux on target (MW/m^2)	180
Peak volumetric heating rate in Hg (MW/m^3)	640
Peak volumetric heating rate in window structure (MW/m^3)	340
<u>Nominal Loads During a Single Pulse</u>	
Peak energy density in mercury (MJ/m^3)	10.7
Peak energy density in window structure (MJ/m^3)	5.6

The power deposited in the target must be transported away without excessive mercury or stainless steel vessel temperatures or stresses. This transport is achieved using two separate mercury flow streams; one to transport the heat deposited in the mercury contained in regions interior to the vessel, and one to cool the stainless steel vessel structure. Three-dimensional computational fluid dynamics simulations of the target main flow and the cooling jacket were performed to predict the temperature, velocity, and pressure distributions in the target.⁷ Results for the reference design case, which has a time-averaged proton beam power of 1 MW, are summarized in Table 2. It should be noted that it is assumed in these analyses that the mercury "thermally wets" the stainless steel by the mercury. The liquid metal heat transfer literature contains many cases where this is achieved, but unfortunately there are also some cases where "wetting" does not occur and the resulting convective heat transfer is very poor. This issue is being addressed in the SNS target R&D program and will be discussed further in Section IV.

In the main mercury target flow stream, mercury enters the target through the two side channels at 80°C with a combined flow rate of 146 kg/s. The resulting bulk (volume averaged) temperature rise in the mercury is 30°C. The power deposited in the bulk mercury is effectively transported from the target with reasonable flow rates, operating pressures (< 0.3 MPa in the target), and pumping power (< 5 kW). The maximum temperature in the bulk mercury is less than 160°C even in the recirculation zone located near the flow baffles because the heating rate for the specified parabolic profile is relatively low in this region.

The transient response of the mercury target under the intense pulsed loads, referred to as thermal shock, and the effect this has on the lifetime of the target vessel is a key subject of the R&D program. The SNS activities in this area are discussed in Section IV.

Table 2. Design and performance parameters for the mercury target and its stainless steel vessel

Parameter	Value
<u>Bulk Mercury Flow Loop</u>	
Mass flow (kg/s)	146
Inlet temperature (°C)	80
Outlet temperature (°C)	110
Peak Hg temperature (°C)	152
<u>Target Window</u>	
Configuration	Double wall/duplex
Coolant	Mercury
Mass flow (kg/s)	14
Inlet temperature (°C)	80
Outlet temperature (°C)	< 110
Window/vessel material	316-type stainless steel
Peak temp of window (°C)	133

B. Neutronic Performance

The neutronic behavior of the target system has been investigated using Monte Carlo techniques to track the progress of various subatomic particles as they proceed through the target. For the analysis performed to support the SNS target design, the codes HETC95¹⁵ and MCNP¹⁶ were used. The codes were coupled in order to provide the proper source for the low-energy MCNP calculations. Various parameters were calculated to measure the neutronic performance of the target, moderator, and reflector designs. Results of these studies were used as key input for the following design studies:

- target material selection
- reflector material selection
- selections of moderator type and configuration
- definition of the overall layout of the target, moderator, and reflector systems
- determination of the need to provide neutron poisons and/or decouplers in the moderator and reflector systems
- evaluation of the benefits of using a pre-moderator for the cryogenic moderators

These studies are described elsewhere, but it is especially noteworthy that results of the neutronic evaluations performed for the target material selection studies showed that a Hg target is neutronicallly better than

W or Ta, especially at the higher (> 1 MW) power levels where the solid targets need more cooling water.¹⁷

IV. KEY ISSUES AND R&D ACTIVITIES

R&D efforts are being conducted to ensure that the mercury target can remove the single-pulse (~ 17 kJ) and time-averaged power (~ 1 MW) loads while maintaining its austenitic stainless steel container within its temperature (< 200°C) and stress limits. Materials irradiation and compatibility tests are also being conducted to verify that the target meets or exceeds its minimum lifetime, experimental availability, and neutron flux requirements. These issues and the R&D activities already under way or planned are discussed below.

A. Power-Handling Issues

1. Time-Averaged Power Handling. Testing and analyses are required to establish that the mercury target system can transport the time-averaged; i.e., quasi-steady state, power deposited by the beam. Where appropriate and feasible, the effects of short pulse transient loads caused by thermal-shock induced cavitation of the mercury will be simulated using acoustic transducer systems.

Thermal wetting in the cooling jacket flow stream and the effect of hot spots due to localized recirculation zones in the bulk mercury flow are the specific issues that will be resolved in the Thermal Hydraulic Tests and Analysis program. This program is divided into four elements including: (1) computational fluid dynamics (CFD) simulation of the target, (2) flow distribution tests using water as a surrogate fluid, (3) mercury thermal hydraulic parameter tests, and (4) full-scale mercury loop tests. These elements are briefly described below:

- CFD – Predictions of the thermal and fluid dynamics performance of the liquid metal target will be made using a commercially available CFD code. The code will be modified and validated to accommodate the unique features of the SNS mercury target.
- Flow Distribution Tests with Water – A full scale “mercury target” mock-up will be built and tested on a flow loop using water as a surrogate fluid to benchmark the CFD code and study flow distributions, pressure drops, etc. for the SNS target configuration.
- Mercury Thermal-Hydraulic Loop (MTHL) – A small-scale mercury loop will be constructed and used to examine thermal-hydraulic parameters such as heat transfer coefficients and friction

factors for mercury at the SNS target conditions with special consideration to wetting versus non-wetting effects.

- Target Test Facility (TTF) – A full-scale mercury loop will be built and operated to benchmark the CFD model and perform tests to confirm the performance of the mercury processing equipment. Construction and operation of this facility is a joint effort with the remote handling development program.

2. Thermal Shock. The interaction of the energetic proton beam with the mercury target leads to extremely high heating rates in the target during the beam pulse. Although the resulting temperature rise is only a few K, the rate of temperature rise is enormous (~ 10⁷ K/s) during the very brief beam pulse (~ 0.5 μs). The resulting compression of the mercury will lead to the production of pressure waves in the mercury that will interact with the walls of the mercury target and the bulk flow field. Concerns exist in two main areas: (1) impact of the effects of the combination of thermal shock of the wall due to its direct heating from the proton beam and the loads transferred from the mercury compression waves, and (2) impact of the compression-rarefaction, wave-induced effects such as fluid surging and potential cavitation.

The thermal shock tests and analyses program is aimed at confirming the preliminary conclusion that thermal shock pressures and their resulting stresses and effects on the flow field are within tolerable limits at a proton beam energy per pulse of 17 kJ (1 MW at 60 Hz). These efforts are divided into five elements including: (1) pressure pulse and cavitation tests, (2) accelerator target experiments, (3) benchmark model analyses of thermal shock in the mercury target, (4) evaluation of the cyclic shock loads, and (5) thermal shock mitigation tests and analyses (only if found to be required).

Although initial results indicate that the stresses in the target vessel are below the yield strength for annealed 316-type stainless steel, more detailed analyses and testing are needed to gain a better understanding of this phenomenon.⁷ Furthermore, thermal shock stresses must be examined in combination with stresses due to other loads, and the dynamic (short duration) and cyclic (more than 10⁸ cycles per month) nature of these stresses must be appropriately considered along with the effects of irradiation.

Mercury target tests are under way at Los Alamos National Laboratory's Los Alamos Neutron Science Center/Weapons Neutron Research (LANSCE/WNR) facility and Brookhaven National Laboratory's (BNL)

Alternating Gradient Synchrotron (AGS) facility. The first campaign at the LANSCE/WNR was completed in May 1997. The purpose of these tests, dedicated to thermal shock, was to develop shock wave instrumentation for this severe environment and to start to gather data to benchmark shock physics codes. The energy density in the Hg, contained by a stainless steel vessel, was two times greater than in the SNS but the test module was much smaller (~ 1/5 volume) than the SNS target. No visible damage was observed and data analysis has shown that measured peak strains were in reasonable agreement with predictions. More extensive and improved instrumentation will be used to gather benchmark data in tests scheduled for December 1998.^{9,10}

Additional Hg target tests have been conducted at the AGS Facility to study thermal shock and neutron production (via activation foil analysis) versus proton energy (1 to 24 GeV). This effort is a collaboration between many organizations led by BNL, the Paul Scherrer Institut (PSI), Forschungszentrum Jülich (FzJ), the Japan Atomic Energy Research Institute (JAERI), and ORNL. Initial tests were conducted June 18-26, 1997. The measured and calculated strains were in good agreement. Additional tests are scheduled for September 1998.

B. Materials Science and Technology Issues

High power spallation neutron sources like the SNS will place significant demands on materials performance. The target system will be subjected to an aggressive environment that will degrade the properties of materials. Indeed, the satisfactory performance of materials for sufficiently long time periods will determine the viability of the target station for the facility. Components at the heart of the facility include the liquid target container and water-cooled shroud, beam windows, support structures, moderator containers, and beam tubes, for example. A recent series of workshops summarized the present state of knowledge of materials for spallation sources and began implementing materials R&D programs for the SNS and ESS facilities.¹⁸ The materials R&D program for the SNS is oriented toward materials qualification. This means that materials are selected based on existing experimental data and analysis, testing in actual and partially simulated application environments, lifetime estimates for the SNS environment, and iteration and optimization of properties to improve performance. The program is structured around technical areas expected to be key to the design, fabrication, and performance of the target station. The radiation effects and materials compatibility areas are further discussed below.

1. Radiation Damage. The main problems associated with structural materials center around

embrittlement, hardening and associated loss of ductility, and irradiation creep. Swelling at the modest temperatures currently under consideration for the SNS, < 200°C, is not likely to be a serious problem. Irradiation creep is not expected to be a problem because of the open structure of the components.

By contrast to the few-MeV range of neutrons in fission reactors, materials in the SNS will be exposed (1) to protons in the GeV range and below and (2) to neutrons with energies spanning from the proton energy down to thermal energies. The common unit of measure of displacement damage is the displacement per atom (dpa). One dpa is the dose at which, on average, each atom in the material has been displaced once. Required lifetimes of the most highly irradiated components such as the target vessel and beam windows are expected to be in the range of tens of dpa. Transmutation rates in the spallation environment will be orders of magnitude higher than in fission reactors. The species He and H, as well as heavier transmutation products will be of concern. H production is calculated to be in the range of 1000 appm/dpa. Of more significance, He production is calculated to be in the range of 100 to 200 appm/dpa as compared to 0.2 to 0.5 appm/dpa in fission reactors. Helium is an insoluble rare gas that can increase the severity of radiation effects by triggering or increasing swelling, and by causing or exacerbating grain boundary embrittlement as well as hardening the material to promote overall ductility loss.

The effects of the high He production will be determined in the present R&D program. Irradiations in typical spallation source environments have been completed at LANSCE/LANL and the samples are being processed for test. Additional material irradiations are scheduled at SINQ during 1998. In-beam irradiation tests that examine the combined effects of flowing mercury and radiation damage are discussed below (Section IV.B.3).

2. Compatibility. The compatibility and corrosion behavior of materials in contact with liquid Hg, such as the container and flow baffles, is an important part of the R&D program. Previous experience in liquid metal systems has been evaluated for its applicability to the present system. An R&D program for mercury compatibility with containment materials is presently in progress. The main issues are considered to be temperature gradient mass transfer, liquid metal embrittlement, and wettability of materials by Hg. Experimental evaluation now under way includes constant extension rate tensile tests for liquid metal embrittlement (LME) and thermal convection loop (TCL) tests for temperature gradient mass transfer.⁹ So far, the results are very encouraging; i.e., no LME or mass transfer. Further testing is planned to include notched tensile and fatigue tests in mercury as well as

further small scale recirculating TCL tests. This work interfaces closely with related engineering R&D on thermal hydraulics and mechanical design. In particular, it supports planned work on more prototypical large scale and high flow rate engineering test loops.

3. In-Beam Irradiations for a Hg Loop. Plans are being made to irradiate a small Hg loop in the Oak Ridge Electron Linear Accelerator facility (150 MeV electrons) at ORNL. The purpose of this test will be to determine the mass transfer characteristics of Hg/SS-316, Hg embrittlement, radiation damage, and thermal hydraulics under irradiation conditions. Future plans call for potential irradiations at proton accelerator facilities of medium energy (70-800 MeV).

V. CONCLUSIONS

Preliminary design and analyses indicate that a very attractive short-pulse neutron source operating at 1 MW of proton beam power can be constructed for the SNS using liquid mercury as the target material. Research and development activities have been identified to validate design concepts and to allow future upgrades to higher power levels. Reasonable design configurations have been proposed for major component assemblies.

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