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Overview of the SNS target system testing and initial beam operation experience

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Abstract

The Spallation Neutron Source (SNS) construction project has been completed including initial beam operation with the mercury target, moderators and associated systems. The project was initiated in 1999, with groundbreaking in December of 1999. Final integrated system testing for the mercury target, cryogenic moderators, shutter systems, water and other utility systems and all control and safety systems were completed in April 2006 and first beam on target was delivered April 28, 2006. This paper will give an overview of the system testing conducted in preparation for beam operation and initial operating experience with low power beams. One area of testing was extensive remote handling testing in the target service bay to demonstrate all key operations associated with the target and mercury loop. Many improvements were implemented as a result of this experience. Another set of tests involved bringing the supercritical cryogenic moderator systems on line. Again, lessons learned here resulted in system changes. Testing of the four water loops was very time consuming because of the complexity of the systems and many instrumentation issues had to be resolved. A temporary phosphor viewscreen was installed on the front of the target which has been extremely useful in evaluating the beam profile on the target. Initial profile results will be presented. Target system performance for initial beam operation will be discussed. In general, all systems performed well with excellent availability. There were some unexpected findings. For example, xenon spallation gas products are believed to have deposited on a downstream gold amalgamation bed designed to remove mercury vapor and this disposition increased the local dose rate. A summary of findings and plans for ramping up in power will be given.

1. Introduction

The Spallation Neutron Source Project was started in 1999 and was declared complete by the Department of Energy in May 2006 [1]. This paper will give an overview of the testing conducted for the target systems prior to beam and the initial operating experience with beam through September 2006. Target systems consisted of the major systems needed to convert the short pulse proton beam into useful neutrons for the scattering instruments. The major elements were the mercury target and associated process loop, supercritical hydrogen moderator and refrigeration systems, reflector assemblies surrounding the target and containing the moderators, vessel systems, bulk shielding systems including the neutron beam line shutters, water and gaseous utility systems, remote handling systems and instrumentation and control for all systems. Test plans and schedules were developed for testing each of these systems essentially independently and then together. Fig. 1 shows a view of the core region with a horizontal section centered on the lower moderators which illustrates most of these systems. The sections below will describe the testing and current overall status for each of the major systems.

2. Current status as of October, 2006

All of the individual system testing and integrated system testing was completed by April, 2006. In the final test series prior to beam, all systems were operated together in the same manner as needed for beam operation at 1 MW or

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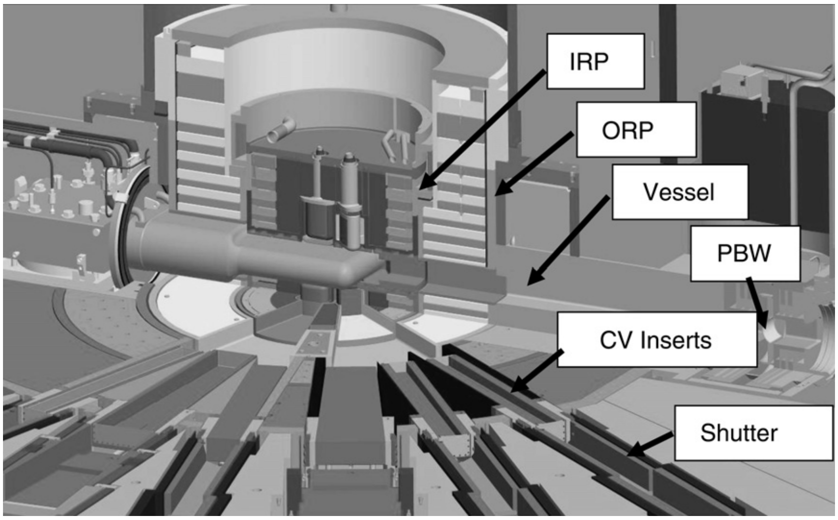

Fig. 1. Target systems core region showing target, inner and outer reflector plugs (IRP and ORP), core vessel, proton beam window (PBW), core vessel (CV) inserts, and shutter systems.

greater. On April 28th, beam on target operation began. Within hours, the two performance goals set for project completion were attained and [2] exceeded. The first goal was to demonstrate short pulse intensity of at least 10^{13} protons in a pulse and the second goal was to demonstrate at least 5×10^{-3} neutrons/proton/steradian from a moderator. With a few exceptions, all target systems are capable of operation at 2 MW of beam power. The principal exceptions are the first target module which is designed for 1 MW operation, the inner reflector plug with is capable of 1.4 MW and the cryogenic system helium refrigeration system which would support up to 1.4 MW of beam operation. After initial beam operation in April, the accelerator was run through the month of May, shutdown in June, and run for July and August with a shutdown in September for maintenance. Beam to target reached a maximum power of 10 kW at 5 Hz and 860 MeV. Single pulse intensities of up to 5.3×10^{13} were demonstrated.

3. Target assemblies

The first double-walled mercury target module was fabricated from 316 L. One material problem that was encountered was porosity on the mid-plane of the thick plates (>100 mm) which were used for both the mercury vessel and water shroud as shown in Fig. 2. These flaws were first discovered after machining the side walls. They were all repaired by TIG welding. The curved nose section which formed the target proton beam window did not have this problem. Another issue was that in order to hold dimensional control the vendor had to perform a stress relief heat treatment on the material prior to machining. After initial installation, survey and alignment measurements showed that the upper and lower horizontal surfaces were within approximately 1 mm of the nominal location within the core vessel. Close control of these dimensions was needed since the target must be inserted into the inner

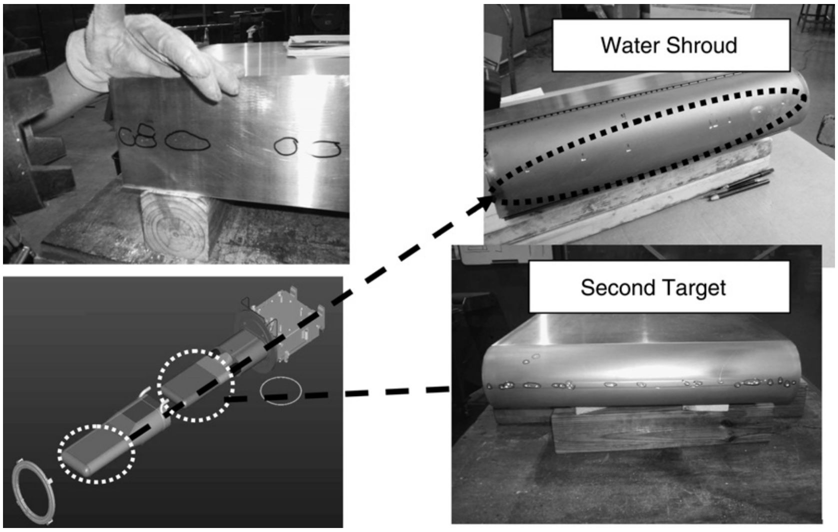

Fig. 2. Porosity observed on mid-plane in 316L Plate used for the target module mercury vessel and water shroud.

reflector plug with a nominal clearance of 7 mm (see Fig. 3).

A summary of the major target assembles system and integrated system tests are given in Table 1.

The water testing demonstrated the leak tightness of the system, initial check-out of instrumentation and controls, pump operation, and flow and pressure head measurements. The target seal testing included planned shimming of the target carriage stop to have the inflatable seal surface 3 mm from the core vessel flange surface and leak testing of the seal in the inflated condition. The major test was running the loop with mercury. This was done a number of times and for up to 3 continuous days. The flow data agreed well with analytical [3] predictions as shown in Table 2.

The 380 gallons/min flow is the design flow for 1 MW and 2 MW operation. The loop was also tested at up to 60 °C by using the heat input from the pump and not running the secondary side of the heat exchanger. This is the nominal target inlet temperature for 2 MW operation. The mercury loop was run again during the full integrated system testing in April demonstrating all normal operating procedures. After the start of beam operation, the loop was run at nominal conditions for the month of May. After shutdown, a grease leak was discovered on the pump shaft below the lip seals for the upper and lower bearings. Investigation determined that the radiation hard grease made from an alkylated aromatic base oil is not chemically compatible with the radiation hard lip seal material (EPDM). Backup sealing methods are being tested and installation is planned for December, 2006. Operation after May has been at 150 rpm instead of 400 rpm to reduce bearing temperatures and wear. This speed allows for beam operation at greater than 100 kW. As part of the investigation of this problem, vibration monitoring systems have been added to the pump to monitor the bearings. Fig. 4 shows the model of the process loop equipment with its shielding removed and Fig. 4 shows the installed shielding. In general the system has been very reliable and has supported neutron production when scheduled (see Fig. 5).

Table 1
Major target assembly testing

Name	Comments
Water test of mercury loop	Demonstrated loop operation with water
Target seal testing	Demonstrated inflatable seal operation
Mercury loop operation with mercury	Full operation with mercury for up to 3 days at nominal flow rates for 2 MW beam
Mercury loop run with all other systems	Integrated testing of all systems to simulate beam operation

Table 2
Mercury loop flow data and predictions

Nominal mercury flow condition	SNS data (410 rpm) taken 4/17/2006	FATHOM model
Total supply flow (gpm)	380	382
Return flow (gpm)	391	382
Window flow (gpm)	30	27
Pump discharge pressure (psig)	43	43
Pump head (psid)	40	41

4. Hydrogen moderator and refrigeration system

The hydrogen system is comprised of a number of subsystems that are located throughout the target and compressor buildings. As shown in Fig. 1, there are three supercritical hydrogen moderators installed in the inner reflector plug, two above the target and one below in the

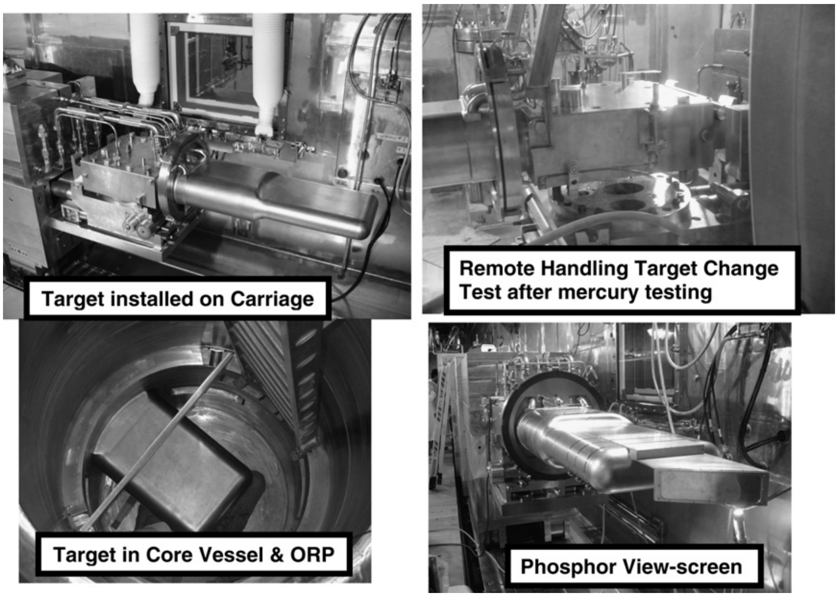

Fig. 3. Views of the target module on the carriage, in the operating position, during a target change and with the view-screen installed.

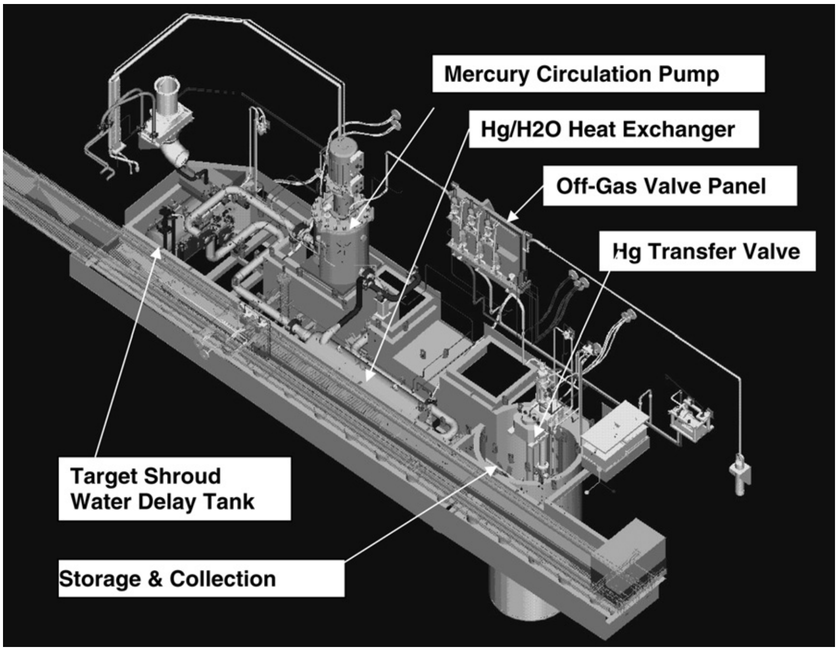

Fig. 4. Mercury process loop components.

Fig. 5. Top floor shielding around mercury pump and carriage.

downstream position. The bottom upstream moderator uses ambient water. All moderators are fabricated from 6061 Al. The top upstream moderator includes a 1.5 mm gadolinium poison plate enclosed in aluminum and the vacuum vessel surrounding this moderator has a flame-sprayed cadmium coating approximately 1.5 mm thick for neutronic decoupling. The moderators are ASME code stamped vessels. The transfer lines use invar for the hydrogen supply, intermediate vacuum and return to minimize thermal contraction. The entire lines are all welded including invar to aluminum friction welds to the moderator vessels. In normal operation the vacuum region of the line is isolated and maintains static vacuum.

Each moderator has a separate loop and can be run independently. The principal hydrogen subsystems are a pump module, containing three circulators and three accumulators, a warm gas management system, a heat exchanger module with three heat exchangers, and a hydrogen safe vent system. The accumulators have stainless steel bellows to accommodate expansion associated with normal and anticipated off-normal operational swings in temperature without the need to add or subtract hydrogen to or from the system. The purpose of the accumulator is to minimize pressure swings that would otherwise accompany temperature changes. For example, the circulator outlet pressure is nominally about 15 bar (for an approximately 14-bar inlet pressure) with the system at temperature with the proton beam off, but increases only to 16 bar when the beam reaches full power (2 MW) owing to the action of the accumulator.

Fig. 6 shows the layout in the hydrogen utility room. Also shown in this figure is the design validation and training module. This vessel contains a mockup of one loop with a heat exchanger, accumulator, circulator, heater and representative length of piping. This was used for early system and circulator [4] testing and can be used for operator training.

The other major subsystem is a 7.5 kW helium refrigeration system. The compressor and oil removal systems are located outside the target building in a separate structure and the cold box is located on the shielding above where the beam enters the target building as shown in Fig. 7. Initial acceptance testing of the refrigeration system showed that the capacity was approximately 4 kW. While below specification, this was adequate for beam operation up to 1.4 MW and the decision was made not to attempt repairs prior to project completion. An initial test of all three loops was performed in March, 2006. For this test the 3 transfer lines were not connected to the inner reflector plug, but had the supply and return lines connected together near the monolith. The system cooled down smoothly in approximately 6 h with the circulators running at 15 000 rpm. Stable operation at 20 K with design flow rates for all three loops was demonstrated (40 gm/s for the two decoupled moderators and 117 gm/s for the top upstream moderator). A second full integrated operational test was performed after installing the inner reflector plug. Again all 3 loops were operated at design flows and temperatures for more than 48 h with all other target systems operating. This test also included the design flows for the ambient moderator. The test summary is given below (see Table 3).

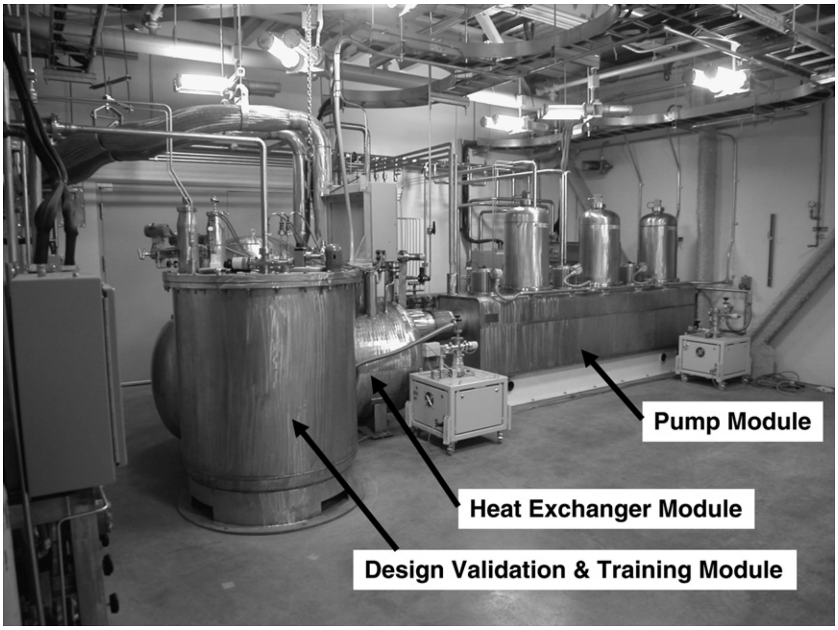

Fig. 6. Hydrogen utility room.

Fig. 7. 7.5 kW helium refrigeration system compressor (left) and cold box (right).

Table 3
Major moderator system testing

Test number	Name	Completion date	Comments
SST1.6.2-6	DVTM testing	11/16/05	Accumulator control system demonstration and refrigeration system test
SST1.6.2-7	Full hydrogen system test	3/13/06	First run with all 3 loops
Full integrated operational testing	Hydrogen system run with all other systems	4/23/06	Integrated testing of all systems to simulate beam operation

A number of system improvements were implemented after operation for extended periods. These included the following:

- Bolted burst disk assemblies were replaced with all welded burst disk assemblies to reduce leakage.
- Accumulator helium overpressure protection was changed from burst disks to relief valves to prevent damage to accumulators if helium relief occurs before hydrogen pressure relief in an off-normal event.
- Relief valves on hydrogen system were found to be too restrictive and were replaced with a larger size and increased blow-down capacity.
- Accumulator position measurement by laser required development.
  - Protection from window condensation.
  - Improved lasers.

A serious problem with the refrigeration system was discovered during the long running periods. The capacity was found to decrease as a function of time such that after about three weeks the system needs to be warmed to room temperature to restore capacity. Resistive temperature devices (RTD's) were attached to the helium heat exchanger and they indicated a flow maldistribution. Corrective measures are being developed in cooperation with the vendor.

5. Reflector plugs

The installation of the outer reflector plug (ORP) was started in November 2004 and completed in April 2005. Jumpers were installed on the connections for the inner reflector plug (IRP) to allow flushing, pressure and flow testing of the water loop. The inner reflector plug final assembly was completed on site. Despite helium leak testing of the transfer line welds, after installation in the core vessels helium leak testing of the completed assembly showed leaks between the hydrogen zones and the vacuum space of the transfer line. The IRP was removed, disassembled, leaks found and repaired and reinstalled within 6 weeks on March 23rd, 2006 (see Fig. 8). This was just in time to support the integrated system testing of the water and cryogenic loops. The IRP in the as-built configuration will support beam operation up to 1.4 MW and has a design life of 6 MW-years. It also requires the core vessel to be operated in the helium mode during beam operation for heat removal from the vacuum shell around the top upstream moderator.

6. Vessel systems

The vessel systems include the core vessel which holds the reflector plugs and target, the proton beam window and shielding near the core vessel (see Fig. 9). Functional testing included operation under rough vacuum and in the helium mode (approximately 680 Torr helium pressure in the vessel). A base pressure of 9 mTorr was achieved with the target and proton beam window inflatable seals operating and all 18 core vessel inserts installed. After installation of the IRP, the base pressure was approximately 90 mTorr. No component leaks during water pressure and flow testing were detected. The proton beam window inflatable seals demonstrated low leak rates to the high vacuum accelerator side ($\sim 2 \times 10^{-6}$ Torr-l/s) and to the core vessel vacuum region with the core vessel under rough vacuum. With the vessel in the helium mode (approximate 1 bar) the leak rates were approximately 2×10^{-5} Torr-l/s.

7. Bulk shielding

The bulk shielding includes the shielding and shutter equipment external to the core vessel assembly (($\sim$4.3 m) diameter) extending out to the interface with the instrument halls at the chopper archways at $\sim$408 in. diameter and includes the removable 'shine shield' beam at the interface with the high bay. Fig. 9 shows a view of the monolith region along the center line and Fig. 10 shows a typical shutter in the open and closed position. The monolith has 18 shutter positions. Twelve are single channel and six are designed for 2 neutron beams 4.8° apart, giving a total of 24 potential beam lines. Initial installation included 11 active shutters and 7 concrete and steel plugs in positions where instrument will be installed later. The shutters are driven by a 2100 psi water hydraulic system which has the power unit in the basement. All shutters have been tested and shown to operate properly. The time to open or close is one minute for single channel shutters and slightly longer for the multi-channel shutters. The shutter gates for the first three instruments on beam lines 2 and 4 (a multi-channel shutter) are now in regular use.

Fig. 8. IRP lift for installation after repairs.

8. Utility systems

Utility Systems include four water loops, vacuum systems and gaseous systems. Water loop 1 cools the mercury heat exchanger and is not activated. Loop 2 cools the proton beam window and the water cooled shroud surrounding the mercury target vessel. Loop 3 is used for the ambient moderator and the core vessel inserts. Loop 4 is used for the reflector plugs and core vessel. This loop currently uses light water but eventually will be filled with heavy water for improved neutronic performance. All loops were designed for the heat loads associated with 2 MW beam operation with a 25% contingency. Each loop included a gas liquid separator tank under shielding in the high bay, two pumps, heat exchanger factor, a by-pass clean up loop with dual ion exchange columns and filters, and a drain tank in the basement. The activated loops also included a delay tank in the high bay under shielding. The segment of loop 2 for the target water cooled shroud also had a delay tank in the target service bay. A major element of the testing program was the process for getting each of these loops operational with their associated instrumentation and experimental physics and industrial control system (EPICS) systems and validation of the operating procedures. Initial system testing included pressure tests for leak tightness and loops were first run with temporary strainers in place near the pumps with the technical component by-passed by jumpers. The strainers did collect a significant amount of foreign material. Getting all the instrumentation and the control screens to operate properly was a large effort. Fig. 11 shows a typical EPICs screen from loop 3 during integrated system testing.

The utility systems also included vacuum systems for the core vessel, mercury loop and the inflatable seals for the target and proton beam window. Normal operation for all these systems was demonstrated. An overheating problem was found with the vacuum turbo pumps for the inflatable seals. These pumps were replaced with a different type which also used a compact self contained chiller.

Gaseous nitrogen is used to purge the system, as cover gas for the water loops and for leak detection on the target mercury seals. Helium is used for core vessel operation as the purge and cover gas for the mercury and for pressure transfer of the mercury from a storage tank up to the loop. All these systems completed initial subsystem testing and later integrated system testing.

Approximately 30 separate tests were identified and accomplished. Some tests were performed multiple times in order to bring all the utility systems to the point were

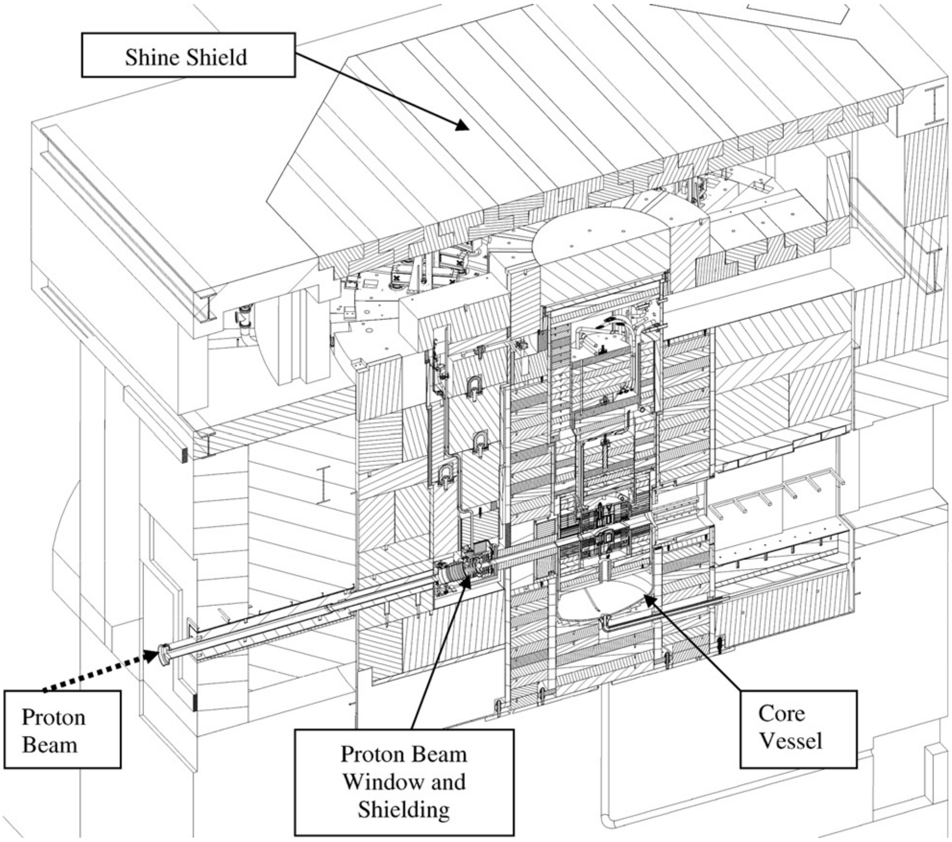

Fig. 9. Monolith and bulk shielding on beam center line.

they were fully functional and the operating procedures had been demonstrated.

9. Remote handling systems

The principal remote handling systems were installed by the general contractor by 2005. These included bridge systems for a 7.5 ton crane and pedestal mounted dual arm manipulator, 4 window work stations with 2 Central Research Laboratory (CRL) through-the-wall manipulators at each station, video and audio systems, and a remote handling [5] control room. The major testing performed prior to beam operation was the use of these systems to demonstrate all key remote handling tasks in the target service bay and to validate the procedures. Target replacement was demonstrated both before and after loading mercury in the loop. Fig. 12 shows the remote handling control room and the target service bay with the carriage retracted and the manipulator in position for working on the target in combination with the CRL manipulators. Testing was conducted starting in July 2005 and resulted in many system changes. Some of the changes are listed below:

- Added pump motor alignment features.
- Added water jumper supports to hold flexible sections in place.
- Added lifting slings to many components.
- Developed new greasing method for pump to allow greasing from the adjacent service bay.
- Modified the carriage drive system to fix tendency to stall and reduce torque required to set the restraint system.
- Added a system using vacuum transfer to the storage tank for putting recovered spilled mercury back into the loop.
- Replaced nitronic bolts on 316SS four bolt flanges which experienced galling by carbon steel.
- Replaced electrical and instrument line connectors with those of a more robust design.
- Repositioned electrical and utility tubing connector to more accessible positions.

The major tests performed are listed in Table 4.

During the beam shutdown for maintenance in September the target was retracted, the view-screen removed remotely and the target placed back in operation. This remote operation was similar to what will be done for the first target change.

Planning has started for post irradiation examination (PIE) of targets. A contract has been placed for developing a saw to be used in the target service bay to section a target. This will be done with the target in a vertical position and the first cut will separate the water cooled shroud from the

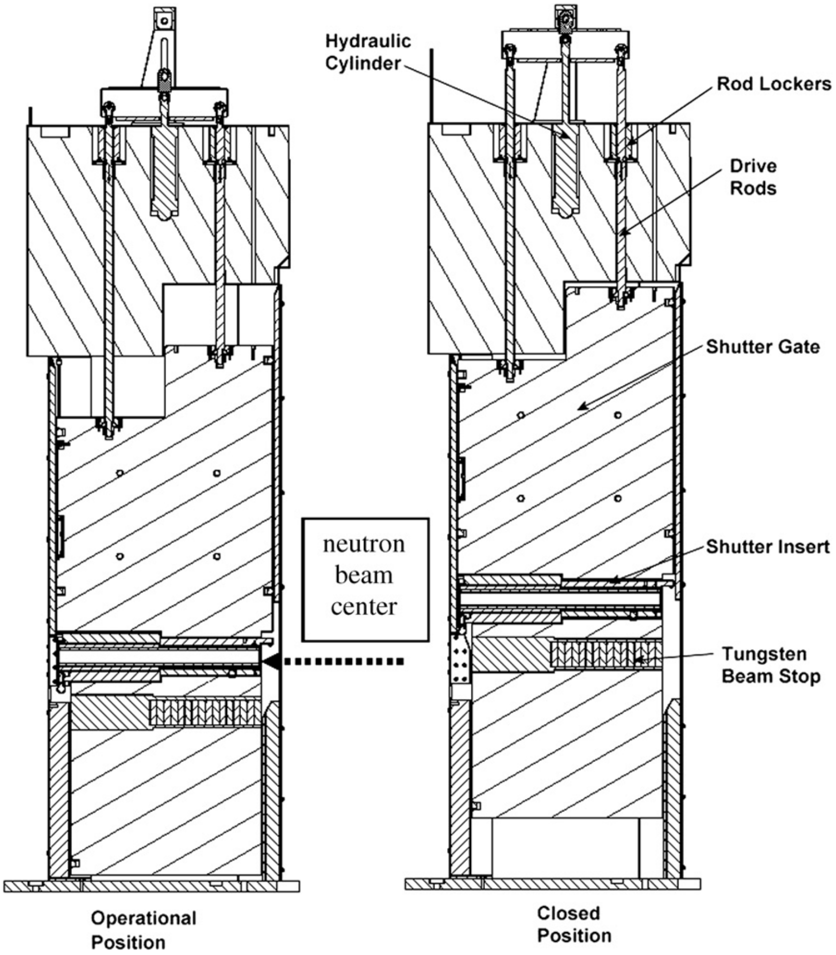

Fig. 10. Typical shutter positions showing down to open and up to close.

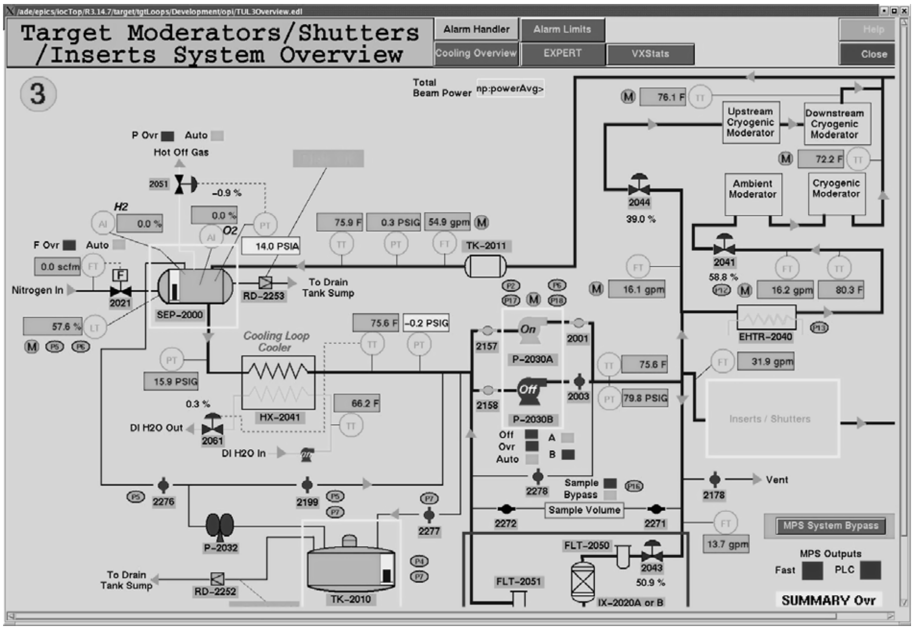

Fig. 11. Typical water loop EPICs screen (loop 3 shown).

Fig. 12. Remote handing control room and target service bay.

Table 4
Remote handling testing

Remove and install pump motor
Demonstrate handling of wall mounted video camera
Demonstrate ziplift operation inside HC
Demonstrate removal & installation of shield blocks
Demonstrate hot cell filter change-out (in-cell)
Demonstrate target module replacement
Demonstrate pump greasing with tooling
Demonstrate handling of wall mounted light/bulb
Demonstrate access to vacuum pump
Demonstrate hot cell cooler maintenance
Demonstrate change-out of a penetration service
Demonstrate target cart retract mechanism
Check access, view & handling of valve panels
Demonstrate and check access & view of all Hg joints
Disengage-& re-engage pump discharge pipe fitting.
Demonstrate/check access & viewing of mercury heat exchanger
Demonstrate remote handling of Hg dump valve
Demonstrate change-out of safety related instruments

mercury vessel to allow leak detection. The systems in the cell will be designed to produce a sample that can be shipped to hot cell with examination capability.

10. Beam operation with view-screen

Fig. 13 shows the image from the phosphor view-screen for a 5.3×10^{13} proton pulse. The view-screen was found to be very useful for setting the beam size (70 mm × 200 mm) and seeing the shape. Non-uniform effects and tilts were easy to observe. Very good numerical fits to the digitized counts from the images were found using double rotated Gaussians. These were used to evaluate the peak current density on the target for varying accelerator parameters. The view-screen was only intended for low power operation and was removed after reaching 10 kW. Initial concepts are now being developed to allow a future similar diagnostic to be used. The second proton beam window assembly will be modified to install a small mirror downstream of the window in the corner of the flight path where it would not be in the direct beam and could see the target which is 2.3 m away. The mirror would be viewed through a 25 mm ID tube run vertically through the shield plug above the window. Fiber optics could be used starting approximately 1 m above the window and would have expected lifetimes at least as long as the window. The mirror could be used with another temporary phosphor view-screen. Other options under consideration are a tungsten mesh, similar to what has been used at Swiss spallation neutron source (SINQ) or viewing transition radiation from the target nose.

11. Mercury off-gas system

Helium purge cover gas that is in contact with mercury is routed through a mercury off-gas treatment system (MOTS), which is located in the target service bay and in

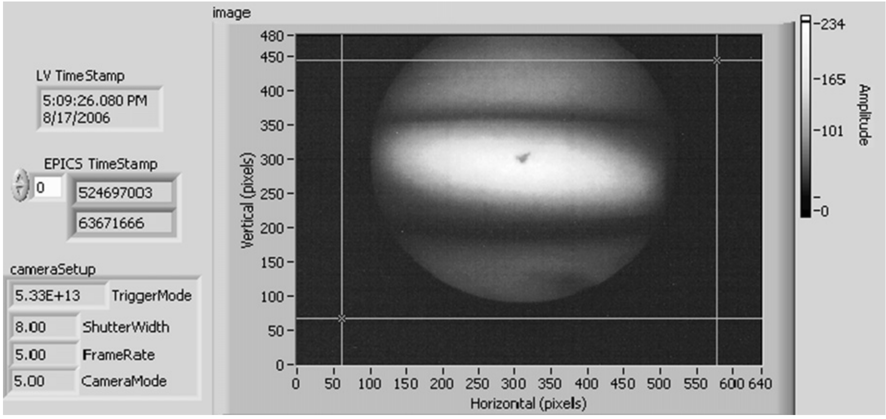

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Fig. 13. View-screen image for 5.3×10^{13} proton pulse.

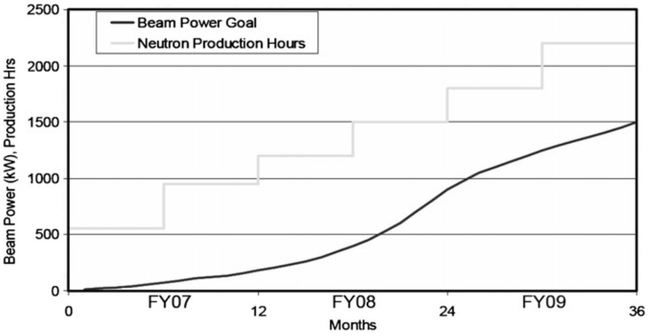

Fig. 14. SNS beam power goals.

the tritium removal room areas in the basement. This system removes mercury, noble gases, and tritium from the target off-gas. The MOTS consists of the following elements:

1. Two gold adsorbers in series (one in the target service bay and one in the basement) for removal of mercury from the off-gas stream.
2. A CuO/dessicant oxidation/adsorption system for removal of tritium from the off-gas stream.
3. A cryogenically cooled charcoal adsorber for removal of noble gases from the off-gas stream.

During the first month of low power operation, higher than expected dose rates (∼15 mrem/h at 0.3 m) were observed on the gold amalgamation bed located in the basement. Investigations using gamma spectroscopy revealed that the gold adsorber was adsorbing krypton and xenon isotopes (produced from mercury by spallation), something which was unanticipated since the adsorption coefficient for these species at room temperature is very low. This adsorber is unshielded and not designed for the retention of noble gases. Treatment of the adsorber with stable xenon to saturate adsorption sites appears to have reduced the content of noble gases in this component to that which would be expected to exist in the normal bulk gas stream. Because xenon is more strongly adsorbed than krypton (i.e., krypton does not displace xenon), stable xenon treatment only was required.

Additional problems with excessive amounts of system moisture were encountered, and coupled with undersized desiccant beds, required regeneration of the carbon bed. The excess moisture is thought to have originated from higher than anticipated moisture content of the gold sorbent and from residual moisture from mercury system testing. Moisture removal capacity has been increased by enlarging the desiccant beds and adding a regeneration feature.

12. Future plans

Fig. 14 shows the current internal beam power goals and targets for neutron production hours per 6 month periods. It is hoped to reach 1 MW early in FY09 and up to 1.4 MW a year later.

13. Summary

The SNS has successfully completed installation, construction and testing for project completion. All target systems are designed for at least 1 MW and where possible have demonstrated operation at nominal design values. Initial beam operation has been at up 10 kW and target systems have operated with good reliability. A gradual ramp-up in power is planned which should reach 1 MW in early FY09.

Acknowledgments

The completion of installation, testing and commissioning for target systems was the result of a team effort by many people. It should also be noted that the view-screen development was led by Tom Shea. This research is sponsored by the Office of Science under contract with Oak Ridge National Laboratory managed by UT-Battelle, LLC, for the Department of Energy.

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