EVOLUTION OF THE HIGH-POWER SPALLATION NEUTRON MERCURY TARGET AT THE SNS*

D. E. Winder†, on behalf of the SNS staff
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Spallation Neutron Source (SNS) began operation in 2006 and first operated at its full 1.4 MW power in 2013. Targets, which receive the pulsed proton beam, were a limiting factor for reliable full power operation for several years. Reaching reliable target operation at 1.4 MW required not only changes to the target design but also support and coordination across the entire SNS enterprise. The history and some key lessons learned are presented.

BACKGROUND

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) is the most powerful pulsed spallation neutron source in the world. The SNS is a user facility operated by ORNL for the U.S. Department of Energy. The SNS's status as a user facility is a key driver for its operation, as its final output is not neutron production but rather scientific productivity. For maximum productivity, the SNS needs to work with users to provide operating neutron instruments reliably and predictably.

The SNS is a very complex machine, with many components vital to the operation of the facility. Any of these components can be viewed in isolation, or as part of the broader story of the SNS. In this paper, we review the evolution of targets over time and how changes to them related to the overall operation of the SNS. In so doing, we hope to demonstrate how the success of those components required not just a small set of engineers but also relied on the skills and support of the entire enterprise.

This paper provides the author's views of more than twenty years of history leading to the current state. It is necessarily limited in depth, and for context, the author provides historical information on activities that occurred before they joined the SNS. References are provided where available for additional information, and the author is indebted to all those that came before and continue to support target development.

TARGET SYSTEM

The SNS target system operates at high power (>1 MW) and uses short (0.7 μs) pulses of high energy (>1 GeV) protons. The protons are used to generate neutrons through spallation reactions in a target material. The SNS was a significant jump in power over previous spallation facilities, and so a novel approach to the target system was used. The SNS uses liquid elemental mercury as the target material. The use of a liquid metal allows the target material to be used throughout the multi-decade life of the facility and provides for a compact target, as the liquid metal can be pumped and cooled, eliminating the need for a secondary fluid for cooling [1].

This novel approach also brought potential challenges, including removing the energy deposited by the beam through heat transfer with the liquid metal, material compatibility with the liquid metal, and beam-induced thermal shock. The thermal shock is induced by the short duration of the beam, which deposits energy into the target material, causing near-instantaneous heating that generates pressure in the fluid. This pressure field then travels through the fluid and surrounding structure. Early on, it was found that damage to structures from cavitation of the mercury was a potential challenge to reliability [2, 3].

Another facility, the Materials and Life Science Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC), also produces neutrons through megawatt pulsed proton beams and also uses mercury as their target material [4].

The target systems at both facilities are complex engineered systems with many components. This paper will focus on the SNS target module, a consumable component constructed of stainless steel where the beam strikes the mercury and deposits energy. For convenience, this component will be referred to as the target throughout this text. The exterior and an interior cross-section view of the target are shown in Fig. 1.

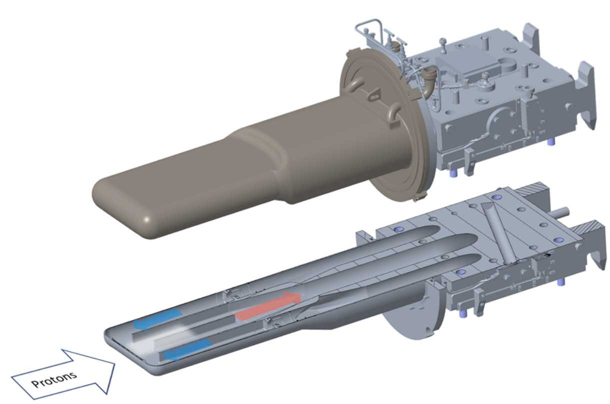

Figure 1: Exterior (top) and cross-section (bottom) view of the SNS target module.

The target exterior shows the outer shroud, which serves as a secondary barrier to contain mercury leaks from the

* This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).
† winderde@ornl.gov

inner mercury vessel. The space between the outer shroud and inner mercury vessel is instrumented to detect mercury leaks. Such leaks require the replacement of the target. The target module structure, mercury target material, and surrounding components are highly activated, and so operations such as replacements take place in a shielded area using remote handling. The need for remote handling limits the speed of target replacement, which generally requires ten days or more during which no neutrons can be produced. As each unplanned replacement is a major impact on the user program, it is desired to replace the target before it leaks during scheduled maintenance periods.

OPERATIONAL HISTORY

Before operations began, both ORNL and J-PARC invested heavily in understanding the potential limitations of their target system. Initial studies indicated that cavitation damage might be life-limiting for targets and the rate of damage might scale with the fourth power of beam power [5, 6]. Early in the design evolution of SNS, injecting small bubbles of gas into the mercury was identified as a potential method of improving target lifetime and performance [7], but gas injection was not included in the initial design for the SNS targets.

The initial SNS target design was finalized in 2004. The structural performance of the target was analyzed using simulation techniques developed at ORNL [8]. This initial design set key interfaces with permanent equipment, such as the piping layout of three mercury inlet pipes and one combined outlet pipe. Two inlets provide cool mercury down the sides of the target, where it is combined at the center and returns down the middle of the target. The third inlet provides a smaller amount of flow which passes as a thin layer of mercury between two layers of stainless steel to provide cooling at the proton beam entrance region. The SNS first delivered beam to target in 2006. The first target, referred to as T1 using a sequential operating number, operated for three years with a maximum beam power of 850 kW, an average power of only 380 kW, and total energy received of 3,055 MW*hr. The number of hours during which the target received beam and the average power are provided in Fig. 2. Targets like T1, which were removed preemptively before a leak, are shown in green. Targets of the original design are shown as circles. This design has been updated multiple times to include improvements and address lessons learned from operation.

Post-irradiation examination of the first targets operated confirmed cavitation damage on the inside surfaces of the target modules [9]. The layered structure of the targets at the beam entrance area allowed them to weather this erosion. These observations led to tightened design requirements for surface finish and materials to resist cavitation damage.

T3, the third target operated, was the first target to develop a leak during operation. Targets that developed a leak in service are shown in Fig. 2 in red. Before leaking, T3 had operated at an average power of 845 kW for a total energy of 2,791 MW*hr. The location and cause of the leak in the mercury vessel could not be determined due to the surrounding outer shroud. The initial observations led to the SNS developing a new target design with two main improvements. These were an added sweeping flow on the inside surface near the beam area to resist cavitation damage [10] and a removable outer shroud. Fabrication of this design began in 2012. Targets of this design are shown in Fig. 2 as diamonds. This design has also been updated multiple times.

In 2012, two targets, T6 and T7, developed leaks in operation shortly after being installed [11]. At this point, the SNS accelerator could operate reliably at ≥1 MW. The short life of two target modules left the SNS without an adequate supply of spare target modules. The beam power

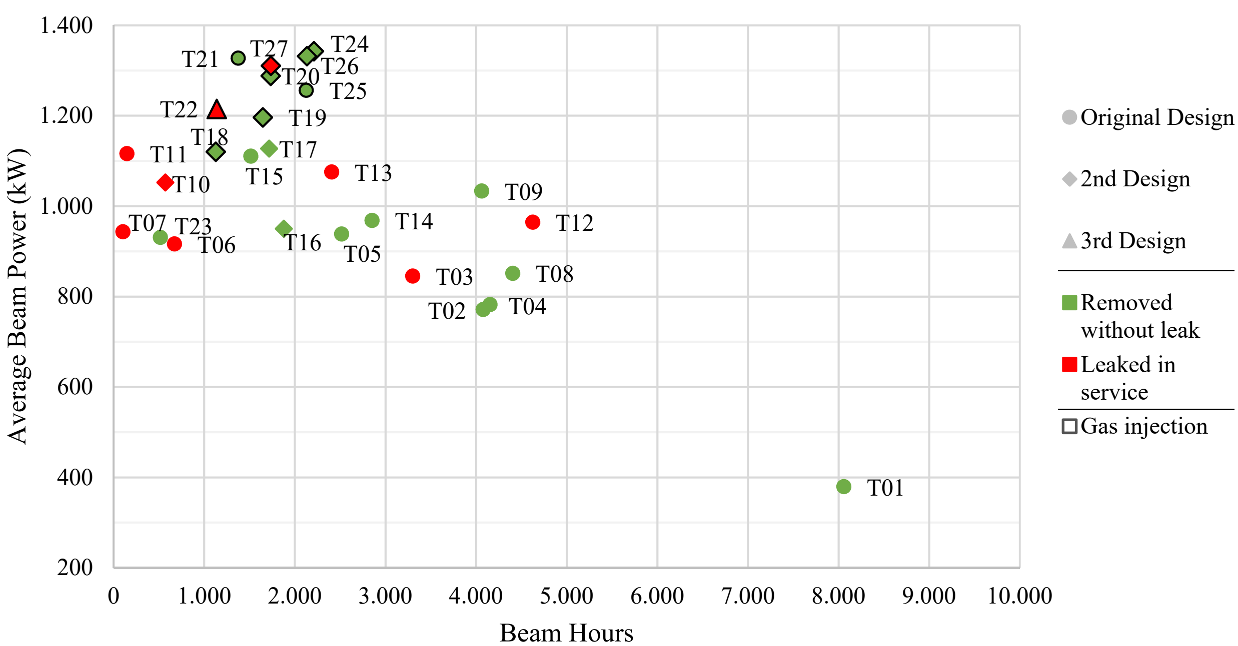

Figure 2: Beam hours and average power for SNS targets operated to date.

was reduced as a precautionary measure to maximize target life until more spares were delivered. This was done to ensure that neutron production would not be interrupted by the lack of a replacement target in the event of leak. The cause of the T6 and T7 leaks was traced to fabrication issues related to the weld-fit up of a trapezoidal plate on the bottom of the target. Changes were made to the design of targets to remove this feature. The failures led the SNS to improve their fabrication oversight. At ORNL, the High Flux Isotope Reactor has operated since the mid-1960s and had a mature manufacturing oversight program. The SNS was able to import expertise from that program and stand up a significantly increased manufacturing oversight and quality assurance effort.

In 2014, T10, the first target of the new design that began fabrication in 2012, was operated. This target developed a leak in service. A manufacturing hold was put in place while the cause of the issue was investigated. The removable shroud allowed the leak location to be found at a partial penetration portion of a weld far from the beam area. Unfortunately, T11 developed a leak in service shortly after installation. The SNS was again low on spares, and again the beam power was reduced until additional spares were available. Replacing stores of spares was complicated by the hold placed on the new design.

The targets had now for a second time limited SNS power and reliability. The SNS and ORNL provided resources for target reliability improvement, including reviews of target manufacturing, design, and simulation by ORNL experts. Concepts which has not been pursued due to risk, including instrumenting targets and adding gas injection, were revisited. In this effort, previous investments such as a full-scale mercury test loop and support from ORNL and other SNS groups were critical to deploying these systems with acceptable levels of risk. The target designs were updated based on the lessons learned, and modifications to targets under fabrication were made to add strain sensors and gas injectors.

The strain sensors initially used were commercial units [12]. The target is exposed to high radiation fields even before it is struck by the proton beam from the surrounding activated components. Obtaining useful information from the commercial sensors before they were destroyed by radiation required coordination and support from SNS remote handling and operations groups to install the target and take beam pulses quickly. The measurements showed a good match with the simulations, though with some surprises. This provided assurance that the simulation methods used were adequate to help steer design decisions.

T12 and T13 also developed leaks in service, though they operated for 4,600 and 2,400 hours, respectively, before leaking. Both leaked from cavitation damage at the same location, outside of the beam entrance area where the target design was only one layer thick. A new design that added flow to this area to reduce cavitation damage was developed. Targets of this design are shown in Fig. 2 as triangles.

In 2016, SNS made a serious change to its operational paradigm in response to the target leaks. The operational tempo of target changes was increased to three target changes per year. This tempo change required support from the entire SNS enterprise, as it affected the duration of each maintenance outage. Instead of operating at the maximum power, the beam power was set at a constant level for a target operating cycle, starting at 1 MW. The power was then increased in 200 kW increments for the next target while maintaining the same operating duration. This set of controlled target exposures provided data to validate models of cavitation erosion progression in the targets [13, 14] and provide reliable operation for our users.

The SNS began operating with helium gas injection into the mercury in 2017, several years after J-PARC started operating such a system in 2012 [15]. Due to differences in the SNS and J-PARC target systems carrying the mercury, the SNS had safety concerns that had to be addressed before such a system could be used. The SNS system does not have a good location to remove the gas from the mercury. There was a concern that gas accumulation and transients could allow mercury to escape the shielded area via the gas inlet or outlet of the system. Several SNS and ORNL groups supported the needed evaluations to verify safety. The gas routing to the target made use of spare penetrations and pipes that had been installed at facility construction. Targets that have operated with gas injection are shown in Fig. 2 with a black outline.

The use of gas injection was instrumental in reaching steady operation at 1.4 MW. Strain measurements confirmed that the load on the target structure was reduced, and examination after operation showed reduced cavitation damage. The SNS targets use inlet orifice bubblers, which use multiple small (10 to 25 micron) orifices to provide a choked flow of gas. These orifices have clogged in operation, providing unsteady and generally diminishing gas injection flow rates for SNS targets, as shown in Fig. 3. T25 was an exception as it had an internal gas tube break allowing the orifices to be bypassed.

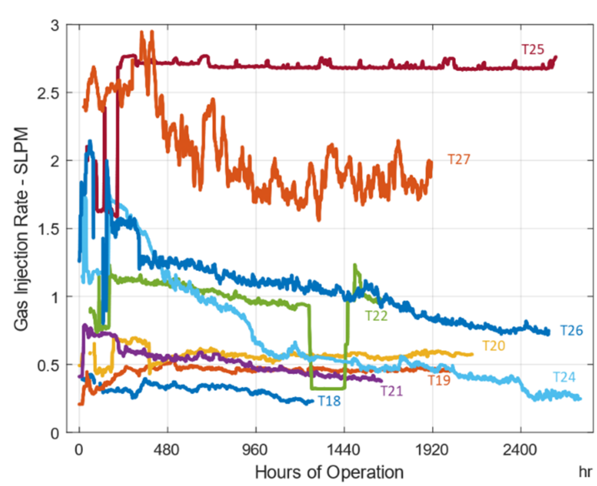

Figure 3: Gas injection flow rates for SNS targets.

The Proton Power Upgrade (PPU) project is working to increase the SNS accelerator capability to 2.8 MW [16]. As part of this effort, the PPU project provided the resources for a thorough redesign of the target module, including changes to the mercury loop to allow higher gas injection rates and replacement of the inlet orifice bubblers with swirl bubble generators. J-PARC provided support that allowed ORNL to develop swirl bubble generators like those used successfully at J-PARC but compatible with the SNS target [17]. The new 2 MW target design began fabrication in 2020.

In 2019, T22, the first target of the design with features to resist cavitation damage outside of the beam area, was operated. T22 developed a leak in operation after 1,140 hours at an average of 1.2 MW. The design did not fail from cavitation damage but rather from a fatigue crack that grew from a corner of an internal layer through connecting ribs to the target mercury vessel exterior. An older original design target was installed as T23. T23 was the same vintage design as T6, T7, and T11, and so it was only operated for a short period at 1 MW before being preemptively replaced. The cause of the leak in T22 was located thanks to skilled remote handling and post-irradiation examination experts. Lessons learned from the T22 leak allowed the designs, including the 2 MW design, to be updated to resist this failure mode.

Due to the success at 1.4 MW, operating schedules were adjusted to allow longer target lifetimes. The limiting factor of run time between outages began to shift away from targets to other systems, requiring more coordination across the SNS. Targets were no longer the limiting factor for beam power. From targets T14 to T26, the SNS delivered 23 GW*hr of proton beam energy to the target over 4½ years with only one unplanned target leak.

Recently, T27 developed a leak in operation after 1,700 hours of operation. At the time of writing, the SNS is working to determine the cause of this leak, which occurred after operation at a power level and duration that two targets of the same design had successfully exceeded. The SNS's excellent remote handling technicians and investments in spare targets allowed a quick return to high-power beam operation. Design features such as the removable shroud create confidence that the cause of this unexpected leak will be quickly found.

KEY LESSONS LEARNED

The SNS benefited heavily from some decisions made early in the project. The safety basis for the SNS does not rely on the target module containing the mercury target material for facility safety. While targets still impact reliability and therefore our users, any issues with this novel technology do not cause a safety issue. The SNS also provided shielded space for post-irradiation examination, which has been vital in understanding and improving target performance. Spare penetrations and pipes into and through the shielded area were also provided, which could be repurposed for new systems such as gas injection. The equipment and shielding surrounding the target were built to be capable of 2 MW, providing space for growth as the facility and targets matured. The facility also invested in experimental facilities and development early in the process, which pays dividends even now.

STATUS AND FUTURE WORK

The SNS target has evolved to the point where it can support reliable operation at 1.4 MW. The current target and its supporting systems have much greater capacity and reliability than available at the start of SNS operation in 2006. New targets are being fabricated now for use at even higher powers. Systems are now in place to learn and respond to unexpected events, such as the recent leak of T27 in service. These systems include an adequate supply of spare targets, strain measurements using radiation-resistant sensors [18], post-irradiation examination of used targets, and excellent support from the SNS, ORNL, and other collaborators, including J-PARC.

Challenges will continue as we work to extend the target capacity to higher power levels and longer lifetimes. The SNS is working to improve the ability to predict and enhance target performance and reduce future impacts on the user program [19, 20]. Through continuous improvement, work will continue toward the ultimate goal of fading into the background until targets become just one more of the thousands of components at the SNS that quietly work to provide users with the tools they need for impactful science.

ACKNOWLEDGEMENTS

This research used resources of the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory under contract DE-AC05-00OR22725. The author acknowledges the staff of the SNS, ORNL, and J-PARC for their work in the success of targets.

REFERENCES

[1] T. A. Gabriel, J. R. Haines, and T. J. McManamy, “Overview of the target systems for the Spallation Neutron Source”, Oak Ridge National Lab., Oak Ridge, TN, USA, Rep. ORNL/CP-100114, 1998.

[2] M. D. Kass *et al.*, “Nonlinear cavitation erosion of stainless steel in mercury versus applied power”, *Tribology Letters,* vol. 5, pp. 231-234, 1998. doi:10.1023/A:1019102026886

[3] C. D. West, “Radiation induced cavitation: A possible phenomenon in liquid targets?”, Oak Ridge National Lab., Oak Ridge, TN, USA, Rep. ORNL/CP-98775, 1998.

[4] M. Arai, “J- PARC and the prospective neutron sciences”, *Pramana – Journal of Physics,* vol. 71, no. 4, pp. 629-638, 2008. doi:10.1007/s12043-008-0251-5

[5] M. Futakawa, H. Kogawa, R. Hino, H. Date, and H. Takeishi, “Erosion damage on solid boundaries in contact with liquid metals by impulsive pressure injection”, *International Journal of Impact Engineering,* vol. 28, no. 2, pp. 123-135, 2003. doi:10.1016/S0734-743X(02)00054-4

[6] J. R. Haines *et al.*, “Summary of cavitation erosion investigations for the SNS mercury target”, *Journal of Nuclear Materials,* vol. 343, no. 1, pp. 58-69, 2005.

doi:10.1016/j.jnucmat.2004.08.033

[7] K. Okita, Y. Matsumoto, and S. Takagi, "Propagation of pressure waves, caused by a thermal shock, in liquid metals containing gas bubbles", in *Proc. of the Fluids Engineering Division Summer Meeting*, Houston, TX, USA, Jun. 2005, pp. 575-580. doi:10.1115/FEDSM2005-77397

[8] B. W. Riemer, "Benchmarking dynamic strain predictions of pulsed mercury spallation target vessels", *Journal of Nuclear Materials,* vol. 343, no. 1, pp. 81-91, 2005. doi:10.1016/j.jnucmat.2005.01.026

[9] D. A. McClintock, B. W. Riemer, P. D. Ferguson, A. J. Carroll, and M. J. Dayton, "Initial observations of cavitation-induced erosion of liquid metal spallation target vessels at the Spallation Neutron Source", *Journal of Nuclear Materials,* vol. 431, no. 1-3, pp. 147-159, 2012. doi:10.1016/j.jnucmat.2011.11.021

[10] M. W. Wendel, P. J. Geoghegan, and D. K. Felde, "Simulation and mockup of SNS jet-flow target with wall jet for cavitation damage mitigation", in *Proc. of the 4th Joint US-European Fluids Engineering Summer Meeting*, Chicago, IL, USA, Aug. 2014. doi:10.1115/FEDSM2014-21119

[11] B. Riemer, J. G. Janney, S. Kaminskas, D. A. McClintock, and P. M. Rosenblad, "Target operational experience at the Spallation Neutron Source", in *Proc. of the 11th International Topical Meeting on Nuclear Applications of Accelerators (AccApp 2013),* Bruges, Belgium, Aug. 2013, paper THZTA02.

[12] W. Blokland *et al.*, "Measurements of Beam Pulse Induced Mechanical Strain Inside the SNS* Target Module", in *Proc. of the 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, pp. 532-537. doi:10.18429/JACoW-HB2016-THAM2Y01

[13] T. Naoe *et al.*, "Cavitation damage prediction for the JSNS mercury target vessel", *Journal of Nuclear Materials,* vol. 468, pp. 313-320, 2016. doi:10.1016/j.jnucmat.2015.08.035

[14] D. Winder, D. McClintock, and D. Bruce, "Cavitation-induced erosion in liquid metal spallation targets – A comparison between a predictive method and measured erosion damage to stainless steel target modules at the Spallation Neutron Source", *Wear,* vol. 450-451, p. 203257, 2020. doi:10.1016/j.wear.2020.203257

[15] P. Rosenblad *et al.*, "Initial implementation of helium Gas into the SNS mercury target for mitigation of fatigue and cavitation damage", *Journal of Physics: Conference Series*, vol. 1021, p. 012073, 2018. doi:10.1088/1742-6596/1021/1/012073

[16] "Final Design Report Proton Power Upgrade Project", Oak Ridge National Laboratory, Oak Ridge, TN, USA, Rep. ORNL/TM-2020/1570-R0, Jun. 2020.

[17] C. Barbier, E. Dominguez-Ontiveros, and R. L. Sangrey, "Small Bubbles Generation With Swirl Bubblers for SNS Target", in *Proc. of the 5th Joint US-European Fluids Engineering Summer Conf. (FEDSM2018)*, Montreal, Canada, Jul. 2018. doi:10.1115/FEDSM2018-83077

[18] Y. Liu, W. Blokland, C. D. Long, B. W. Riemer, M. W. Wendel, and D. E. Winder, "Strain measurement in the spallation target using high-radiation-tolerant fiber sensors", *IEEE Sensors Journal*, vol. 18, no. 9, pp. 3645-3653, 2018. doi:10.1109/JSEN.2018.2816261

[19] K. Okita, K. Ono, T. Shu, and Y. Matsumoto, "Multi-scale analysis on cavitation damage and its mitigation for the spallation neutron source", in *Proc. of the 4th International Conference on Computational Methods for Coupled Problems in Science and Engineering (COUPLED PROBLEMS 2011)*, Kos, Greece, Jun. 2011, pp. 600-610.

[20] D. Winder, L. Lin, and J. Mach, "Incorporating bubble growth volume feedback to improve simulation of the response of a structure containing liquid and gas to sudden energy input", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 1005, p. 165371, 2021. doi:10.1016/j.nima.2021.165371