Need for Improved Numerical Tools and Instrumentation for Mercury Targets at the Spallation Neutron Source

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The Spallation Neutron Source (SNS) First Target Station (FTS) at Oak Ridge National Laboratory (ORNL) uses elemental mercury as a target material for pulsed high energy protons to create intense pulses of neutrons for scientific experiments. The use of a liquid metal for a target material allows for a dense target, as the metal is used as both as a target material and a coolant. This type of target is used at the two highest power accelerator neutron sources in the world, the SNS and the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC). While the SNS and J-PARC have accumulated significant experience operating these systems, they remain a new technology with significant development challenges.

The SNS is increasing demands on the mercury target system with two major planned upgrade projects over the next decade: 1) the Proton Power Upgrade (PPU) project and 2) the Second Target Station (STS) project. The PPU project will increase the power available for neutron production from 1.4 MW to 2.0 MW at the FTS [1], and the STS project will establish a second source of cold neutrons that are optimized for brightness [2]. As these projects complete, the progression of total energy per pulse injected into the target will increase 43% from 23.3 kJ (1.0 GeV pulse at 60 Hz) during 1.4 MW operation for current targets to a 33.3 kJ (1.3 GeV pulse at 60 Hz) during 2.0 MW operation for PPU targets, and then a (potential) 33% increase to 44.4 kJ (1.3 GeV pulse at 45 Hz) to maintain 2.0 MW operation at the FTS while STS operates at 0.8 MW. This is a challenging progression of energy on the target at the FTS—additional research and development (R&D) is necessary to ensure the target operates reliably throughout the process to fully mature the FTS and STS.

Significant progress has been made in the last two decades in simulating the target response using conventional FEA and CFD techniques, however, the target lifetime prediction remains an empirical exercise, and unexpected results do occur. Approximately one-third of SNS targets have prematurely failed. Since 2017, small Helium bubbles have been injected into the mercury to mitigate the pressure and increase target reliability [3], and improvements were observed [4, 5]. However, the presence of these small bubbles in the mercury makes our current numerical approach inadequate, since it does not consider the effects of the small bubbles. A new numerical model needs to be developed and validated for this complex multi-physics problem.

Although much progress has been made in simulation, post-irradiation examination (PIE) and measurements, more is needed to advance the state of the art in predicting target reliability. Structural simulation models need to incorporate the effects of the injected helium gas and cavitation and may require more and higher-quality target response data for validation. Development of a highly-instrumented "test target" for use at LANSCE[i] or at SNS could enhance and expedite model validation—there is a potential to utilize the beam extraction dump inside the ring tunnel at SNS to receive full power proton pulses in a test target (at less than 60 Hz). Alternatively, an electro-mechanical loading device similar to that developed by J-PARC [6] could be used to artificially induce similar loading in a test target, although the time scale would be quite different than an accelerator pulse.

Measurement instrumentation continues to be a major area of research and development focus for SNS. All instrumentation sensors must survive without intervention in an extreme radiation environment during the several months of target operation—the effects of this environment on sensor signals are not yet fully understood. Today, limited thermal and strain measurements are available on the exterior surface of the target mercury vessel. Advanced sensor and measurement technology is needed to embed sensors on and in the vessel and mercury flow (with minimal interference) that may be used for validation or direct failure prediction. Arrays of thermal, pressure, and strain sensors [7] are needed to validate CFD and FEA models. Acoustic or electrical impedance sensors may be able to assess the evolution of cavitation damage. Advanced inspection techniques that leverage new sensors could assess a target's probable remaining useful life and help to extend the operational lifetime.

A higher accuracy target imaging system [8] could reduce the uncertainties related to the proton beam position. The current technique uses a luminescent coating on the target and an optical transport system that uses a multifiber bundle [9]. Improvements to the coating to improve its luminescence over time and improvements to the optical transport are needed to accurately measure the smaller beam sizes over the lifetime of a target. Alternatively, a grid of wires, like the upstream harp but mounted on the target, can be used to measure beam size and position on the target. The effect on the grid measurements due to the wires being mounted on, or closely to, the conducting metallic surface will have to be determined before this technique can be applied.

In summary, mercury targets have demonstrated their ability to operate as a high-power accelerator-based neutron source. Injecting small helium bubbles has shown to be an efficient way to improve reliability and allows for operation of a mercury target at higher power. However, better numerical tools, instrumentation, and additional PIE are still required to be capable to more accurately predict the lifespan of the target and decrease the operational cost associated with the target.

References

[1] "Conceptual Design Report - Proton Power Upgrade Project," Oak Ridge National Laboratory, ORNL/TM-2016/672, PPU-P01-PD0001, August 2017.

[2] "Spallation Neutron Source Second Target Station Conceptual Design Report Volume 1: Overview, Technical and Experimental Systems," Oak Ridge National Laboratory, S01010000-TR0001, 2020.

[3] P. Rosenblad *et al.*, "Initial implementation of helium Gas into the SNS mercury target for mitigation of fatigue and cavitation damage," in *IOP Conf. Series: Journal of Physics: Conf. Series*, 2018, vol. 1021, p. 012073.

[4] D. A. McClintock, D. Bruce, R. Schwartz, T. Carroll, M. J. Dayton, and D. Winder, "Laser Line Scan Characterization of Cavitation-Induced Erosion to SNS Mercury Target Vessels," Oak Ridge National Laboratory, January 2019 2019.

[5] Y. Liu *et al.*, "Strain measurement in the recent SNS mercury target with gas injection," in *Journal of Physics: Conference Series*, 2018, vol. 1067, no. 5.

[6] M. Futakawa, T. Naoe, H. Kogawa, C.-C. Tsai, and Y. Ikeda, "Pitting Damage Formation up to over 10 Million Cycles: Off-line Test by MIMTM," *Journal of Nuclear Science and Technology*, vol. 40, no. 11, pp. 895-904, 2003, doi: 10.1080/18811248.2003.9715433.

[7] M. Wang *et al.*, "Multiplexable high-temperature stable and low-loss intrinsic Fabry-Perot in-fiber sensors through nanograting engineering," *Optics Express*, vol. 28, no. 14, 2020, doi: 10.1364/oe.395382.

[8] T. Shea *et al.*, "Installation and initial operation of an on-line target imaging system for SNS," in *Proceedings of 19th meeting on International Collaboration of Advanced Neutron Sources (ICANS XIX), Grindelwald, Switzerland, PSI-Proceedings*, 2010, pp. 10-01.

[9] L. C. Maxey *et al.*, "A hybrid reflective/refractive/diffractive achromatic fiber-coupled radiation resistant imaging system for use in the Spallation Neutron Source (SNS)," in *Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XIII*, 2011, vol. 8142: International Society for Optics and Photonics, p. 81420N.

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[i] Los Alamos Neutron Science Center (https://lansce.lanl.gov/)