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Post-irradiation examination of the Spallation Neutron Source target module

D.A. McClintock [a,*], P.D. Ferguson [b], L.K. Mansur [a]

[a] Materials Science and Technology Division, Oak Ridge National Laboratory, P.O. Box 2008, Bldg 4500S, MS 6151, Oak Ridge, TN 37831-6151, USA
[b] Neutron Facilities Development Division, Oak Ridge National Laboratory, P.O. Box 2008, Bldg 8600, MS 6466, Oak Ridge, TN 37831-6466, USA

ABSTRACT

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is an accelerator-based pulsed neutron source that produces high-energy spallation neutrons by bombarding liquid mercury flowing through a stainless steel target vessel. During operation the proton beam and spallation neutrons produce radiation damage in the AISI 316L austenitic stainless steel target vessel and water-cooled shroud. The beam pulses also cause rapid heating of the liquid mercury, which may produce cavitation erosion damage on the inner surface of the target vessel. The cavitation erosion rate is thought to be highly sensitive to beam power and predicted to be the primary life-limiting factor of the target module. Though cavitation erosion and radiation damage to the target vessel are expected to dictate its lifetime, the effects of radiation damage and cavitation erosion to target vessels in liquid metal spallation systems are not well known. Therefore preparations are being undertaken to perform post-irradiation examination (PIE) of the liquid mercury target vessel and water-cooled shroud after end-of-life occurs. An overview of the planned PIE for the SNS target vessel is presented here, including proposed techniques for specimen acquisition and subsequent material properties characterization.

1. Introduction

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is an accelerator-based neutron source that produces pulsed beams of neutrons by bombarding liquid mercury with 1 GeV protons. The SNS facility consists of three major parts: (1) a medium energy (~1 GeV) and high power (up to 2 MW) proton source, accelerator, and storage system; (2) a liquid mercury target, neutron moderator, and shielding system; and (3) instruments for the study of materials by neutron scattering. Construction of the SNS facility began in December 1999 and beam-on-target operation began on April 28, 2006. A recent review of initial operational experience and testing of the SNS target systems [1] reported that the SNS target system components have demonstrated successful operation and met all initial design goals. The design of the SNS target system prescribes periodic replacement of the water-cooled shroud and mercury target vessels, due to concerns of radiation damage to the vessel material as well as erosion of the inner surface of the target vessel caused by cavitation in the liquid mercury. The next major service to the SNS target system will be replacement of the target assembly and subsequent post-irradiation examination (PIE) of the water-cooled shroud and target vessel material. In this paper a general description of the target design and life-limiting factors are provided along with an outline of the planned PIE activities for the target vessel after removal from the SNS target system.

Early design work for the SNS project began at ORNL in 1994 and one of the most significant initial facility design decisions was the type of target system that would be used to produce spallation neutrons; specifically, would the neutron producing material be a liquid-cooled solid or a flowing liquid metal? A liquid–metal target design was chosen in preference to a solid target with the aid of information produced by a technical study for the European Spallation Source (ESS) [2]. A liquid–metal target has advantages compared to a water-cooled solid target, including: increased heat removal and power handling capacity and the absence of radiation damage to the target material. Mercury has many attractive properties for use as a target material: it remains liquid at room temperature, has good heat transfer properties, and produces a sharper neutron pulse compared to lead–bismuth due to its high thermal neutron absorption cross-section [3]. Therefore, a liquid metal target system utilizing flowing liquid mercury was chosen for the SNS facility.

A brief discussion of the SNS target design is provided here, while a more detailed description of the SNS target system is provided elsewhere [4]. The water-cooled shroud and mercury target vessel that make up the SNS target module are shown in Fig. 1. The target vessel containing the flowing mercury is surrounded by a water-cooled shroud, which is designed to contain the mercury in case the target vessel fails. Failure is defined as any leaking of mercury or water from the target; the region between the two vessels is backfilled with helium and contains leak detectors to indi-

* Corresponding author. Tel.: +1 865 241 2955; fax: +1 865 241 3650.
E-mail address: mcclintockda@ornl.gov (D.A. McClintock).

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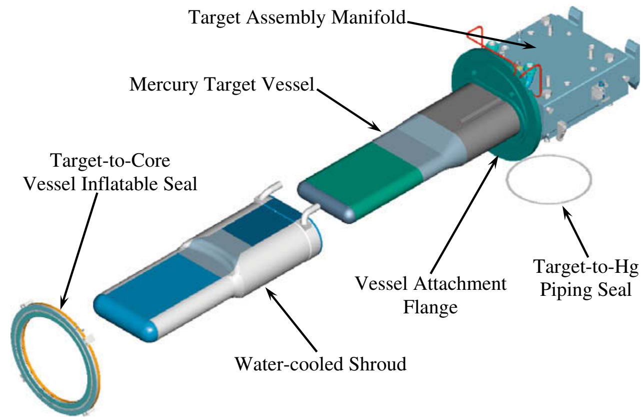

Fig. 1. Exploded view of the water-cooled shroud, target vessel, and manifold assembly.

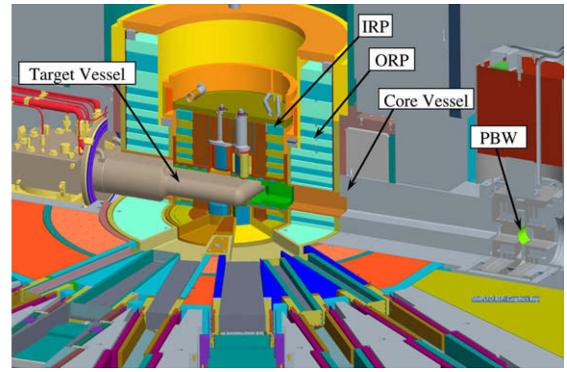

Fig. 3. Schematic of target vessel assembly in operating position, also shown: inner reflector plug (IRP), outer reflector plug (ORP), core vessel, and proton beam window (PBW).

cate target failure. Both the target vessel and shroud are double walled and cooled by liquid flowing in channels between the vessel walls, as shown in Fig. 2; the shroud is cooled by water in the vessel channels, while the mercury target vessel front window is cooled by a dedicated flow of mercury separate from the bulk flow. The bulk flow of mercury enters the target vessel on the side regions and returns through the center section of the vessel. The shroud and target vessel are welded to a manifold containing the water and mercury supply pipes, and the entire target assembly is sealed to the target core vessel using an inflatable seal. The welded attachment of the shroud and target vessel complicates specimen production for PIE and necessitates the use of a large reciprocating saw to separate the vessels, which will be discussed later.

A schematic of the target assembly in the operating position is shown in Fig. 3. The proton beam passes through the proton beam window (PBW), which separates the accelerator vacuum and the core environment, and enters the front section of the target vessel. The front section of the target where the beam enters the target vessel receives the highest level of heat, neutron, and proton fluxes. Though no radiation damage occurs in the liquid mercury target material, the AISI 316L stainless steel shroud and target vessel do experience radiation-induced changes in microstructure and mechanical properties. The effects of radiation on microstructure and mechanical properties of 316 series stainless steels have been well studied and a large volume of experimental data on irradiated 316-type alloys relevant to SNS conditions exist in current literature [5–10]. In addition to radiation damage concerns, erosion of the inner surface of the mercury target vessel is predicted to limit the useful lifetime of the target vessel, but no cavitation erosion data for conditions found in the SNS target vessel currently exist.

Cavitation in the SNS mercury target is induced by the intense, short-pulse proton beam and is not a flow driven phenomena. A single proton beam pulse causes a peak heating in the mercury of only ~10 K but the rate of temperature rise is extremely rapid, about 10^7 K/s, and occurs at a frequency of 60 Hz. The rapid heating rate produces pressure waves in the liquid mercury that reflect from the target vessel surfaces and travel back though the mercury. These reflected pressure waves produce regions of negative pressure that form cavitation bubbles, which subsequently collapse. When the collapse occurs near the target vessel wall the flow field around the bubble forms microscopic jets of liquid mercury that impinge on the vessel inner surface and can remove material causing cavitation erosion damage in the form of macroscopic pits. In addition to the erosion of the vessel wall a degradation of fatigue life of the remaining material is expected due to micro-cracks created during pit formation [11].

Cavitation erosion in short-pulsed liquid metal systems was first observed in ISOLDE molten lead targets [12]. Subsequent experiments with 316SS immersed in mercury and water using an ultrasonic horn have shown the erosion damage rate is much more pronounced in mercury than in water, and the erosion rate in mercury may have a quadratic (P^2) dependence on the input mechanical power [13]. While these early experiments produced useful insight into cavitation erosion, the results were difficult to interpret because the data were for vastly different pressure and frequency regimes compared to the SNS target conditions. In 2000 researchers working for the Japan Atomic Energy Research Institute (JAERI) observed pitting of stainless steel surfaces that

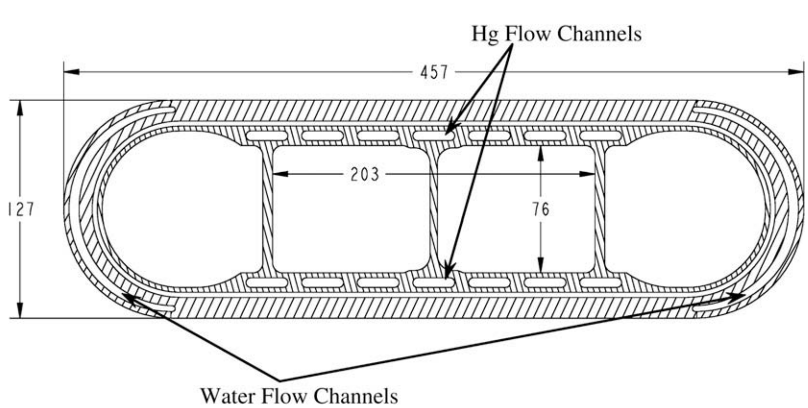

Fig. 2. Cross-sectional view of water-cooled shroud and target vessel (all dimensions in mm).

were in contact with mercury and subjected to mechanically-generated pressure pulses of the same magnitude as those expected for the SNS target, reinforcing the need for further research [14]. Subsequent experiments with an ultrasonic horn suggested the erosion rate may have a P^4 beam power dependence [15], but later results showed the dependence may be closer to P^3 [16]; despite the discrepancies all data to date show the erosion rate is strongly dependent on beam power. Research has also shown that there is an expected threshold of beam power that results in damage [17], but prediction of the power threshold specific to SNS is very uncertain. However, once the threshold is exceeded erosion is expected to follow a power law dependence. Therefore cavitation erosion of the target vessel material is a significant concern for high-power operation of the SNS facility and is predicted to be the life-limiting factor for the mercury target vessel; a more detailed discussion of cavitation erosion experiments is provided elsewhere [14–22]. Main goals of the PIE of the mercury target vessel are to locate regions of cavitation damage inside the vessel and to quantify the amount of erosion to the inner surface of the vessel using both optical microscopy and scanning electron microscopy (SEM). This knowledge will be critical to directing development of effective mitigation technologies which are now being worked on at the SNS.

Since no data exist for 316L irradiated under conditions prototypical to the SNS water-cooled shroud and target vessel, an initial recommendation was made by ORNL researchers to replace the target and measure mechanical properties upon reaching a dose of 5 dpa (displacements per atom) to the shroud [4]. It is well known that 316-type stainless steel alloys progressively lose uniform elongation with increasing dose, and upon reaching 10–15 dpa the remaining ductility can be quite low [8–10,23]. Doses above this level introduce an unacceptable risk of fracture to the target system and necessitate target replacement. Failure of only the target vessel is considered acceptable, since the shroud would contain any leaked mercury, but simultaneous failure of both the target vessel and shroud would permit mercury and water to collect in the target core region, which would necessitate prolonged/costly repairs and should be avoided. The recommended initial dose limit of 5 dpa was a conservative value to ensure the shroud and target vessel retain sufficient ductility until PIE testing could measure the amount of ductility remaining in vessel material of the first target. After successful operation of the first target vessel and consultation with fellow researchers [24] a decision was made to extend the shroud dose limit for removal to ~8 dpa, which is expected to occur in July 2009. When either the target reaches the dose limit or vessel failure occurs the target assembly will be replaced with the second target module and PIE activities will begin on the vessel material of the first target.

2. Examination of the intact target

After the first target module reaches end-of-life the primary objective will be replacement of the target with the second target module to return the SNS to full operational status and begin producing neutrons for facility users. The first target will be placed in a shielded container during target replacement to protect equipment in the target service cell from radiation, and will be allowed to decay for a 60–90 day period before PIE operations begin. Regardless of the target end-of-life mode, failure or not, visual examination of the target vessel interior will be the first PIE procedure performed to provide valuable information about the extent of, or lack of, cavitation erosion to the target interior. A fiber optic camera has been modified for remote operation in the target service cell and will be used to inspect the internal cavity of the target vessel and visually examine the interior surfaces, and if necessary the point of failure. The fiber optic camera is on the end of a cable approximately 1.5 m in length, which will be lowered into the target vessel through the mercury supply passages for examination of the vessel interior. Streaming video from the camera will be monitored during the examination to guide the inspection and saved to disk for further review. Equipment and procedures for an optional leak test of the target vessel are being prepared and may be executed depending upon the condition of the target and the results of the visual inspection.

Characterization of the proton beam intensity profile on the target vessel is another initial PIE task that may be performed on the first target. The intensity profile of the proton beam entering the target vessel has been previously characterized using a phosphor view-screen and was found to have an intensity distribution approximated by rotated double Gaussian distributions, with the beam profile intensity more spread in the horizontal orientation compared to the vertical [1]. Though the beam intensity is distributed across the front of the target, significantly higher proton intensities were found in the center of the beam profile compared to the outer edges of the beam, which is characterized by a peaking factor. The area of increased proton intensity in the center of the target vessel is where the maximum proton and neutron displacement damage occurs. Though the beam profile was characterized by the phosphor view-screen during early stages of SNS operation, currently there exists no capability to monitor the beam intensity profile during operation and approximate the peaking factor. Dose calculations for the target vessel material depend on the amount of beam peaking and conservative estimates of the peaking factor have been used to estimate the displacement dose from both proton and neutron radiation. Since the actual peaking factor cannot be measured during operation an approximation of the accumulated beam intensity distribution will be measured by the remnant radioactivity from the front on the target vessel before PIE specimen production commences. The accumulated intensity profile will be characterized using radiographic film and will provide information on the accumulated beam profile during the first operational period of the SNS. Radiographic film will be exposed to the front of the target using an exposure fixture that is presently under design. Therefore, further description of the radiographic equipment and characterization procedures will be included in future publications.

3. Specimen material production

After visual inspection of the target vessel interior and radiography of the target are completed, material will be taken from the water-cooled shroud and target vessel for microscopy and mechanical properties characterization. The extent of PIE characterization of the first and subsequent target modules will depend on the mode of target end-of-life. If the target fails during operation, before the dose limit is achieved, identification and characterization of the point of failure will be completed before the target is sectioned for specimen material production. The shroud and failed target vessel will then be separated from the target supply manifold and specimen material will be obtained from the area near the failure point and the front area of the shroud and target vessel. Targets that reach the dose limit without failure will not be separated from the manifold and fewer specimens will be taken from the front area of the vessels for testing.

3.1. Specimen production from non-failed target

Two general types of specimen samples, nose and body samples, will be taken from the target vessel for PIE characterization, as shown in Fig. 4. If the target vessel does not fail during operation, only nose samples will be taken from the front of the target

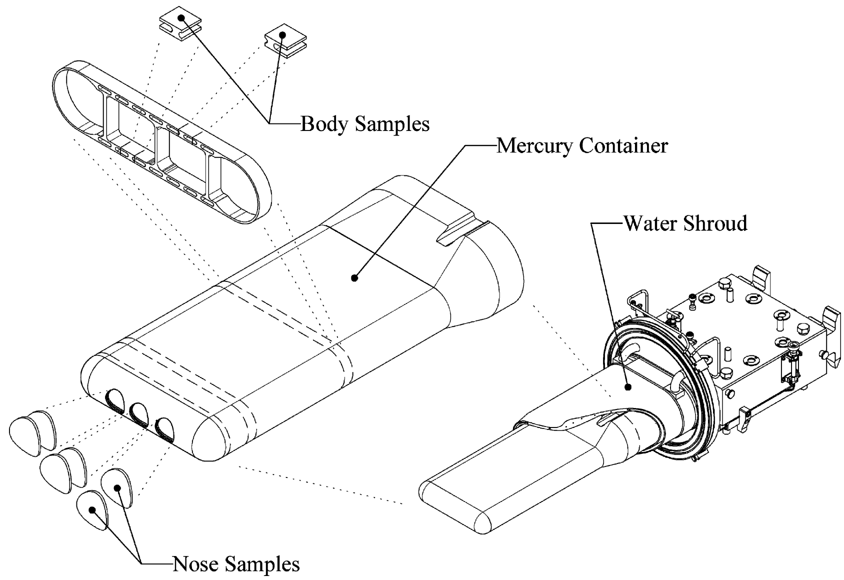

Fig. 4. Schematic of material samples from water-cooled shroud and target vessel (mercury container).

using a dual-cutter drilling unit designed at ORNL for the SNS target. The dual-cutter drilling unit contains two carbide-tipped annular cutters attached to drill motors that are mounted to linear slides, which are actuated by pneumatic pistons, as shown in Fig. 5a and b. The drilling unit is transported into and removed from the target service bay by a crane attached to a swing away attachment, which is swung to the side during cutting. To prevent excessive heating of the sample material during cutting, which could alter mechanical properties and microstructures of samples, the annular cutters will be cooled by water sprayed through nozzles directed at each cutter.

The target is positioned onto the drilling unit with an overhead crane and held on the drilling unit by two clamps that grip the shroud using the weight of the target module (1130 kg), as shown in Fig. 6a. The location of the target relative to the cutters is determined from reference points on the side of the unit base. Specimen samples will be taken from the water-cooled shroud and target vessel in the center of the front nose and to each side, similar to what is shown in Fig. 4. Only one cutter will be operated during cutting; two drill motors and cutters were included in the design for redundancy, in case a motor failure occurs after the unit is contaminated with radioactive chips. The cutters are attached using a custom chuck and can be removed from the unit remotely using through-wall manipulators. After a cut the cutter containing the specimen material will be removed from the machine to extract the samples. Though the cutters are designed to be stack cutters, capable of cutting through multiple layers of material, prior experience has shown that sometimes the specimen material remains

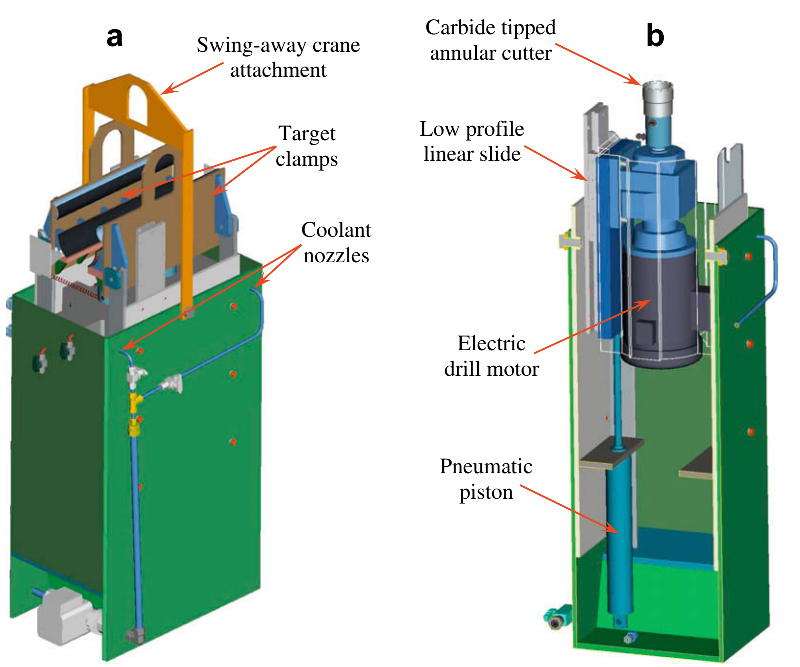

Fig. 5. (a) External and (b) internal view of dual-cutter drilling unit.

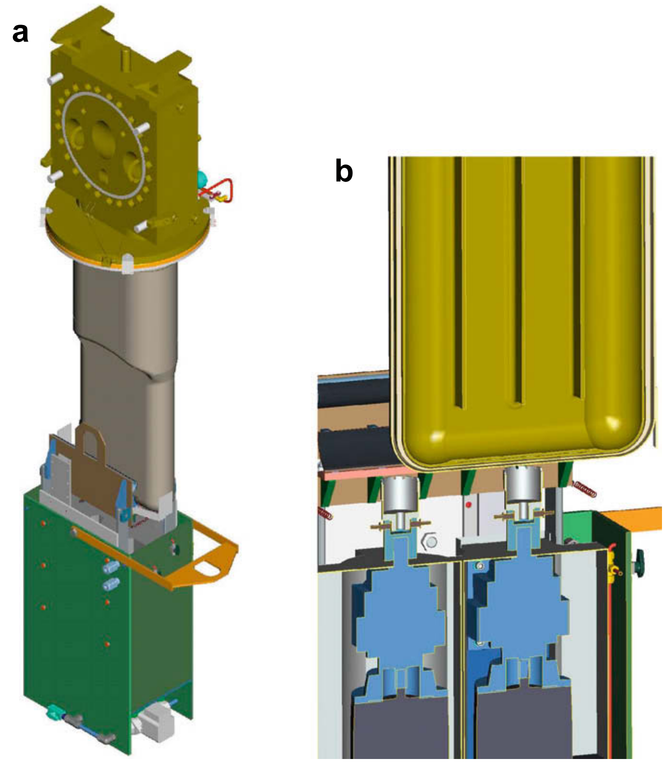

Fig. 6. (a) Target module in cutting position and (b) cross-sectional view of target during cutting.

Fig. 7. Example of specimen material obtained with an annular cutter from the nose of a non-irradiated mockup target vessel.

stuck in the cutter. If this occurs, the brittle cutters will simply be broken using a hammer or vise, and the specimen samples will be extracted. The resulting specimen material is in the form of curved disks, as shown in Fig. 7, from which tensile and microscopy specimens will be produced.

3.2. Specimen production from failed target

In the case of a target failure a more ambitious PIE characterization campaign would be performed, since the point of failure would need to be identified and sampled for testing and failure mode characterization. To obtain the point of failure on the target vessel the water-cooled shroud and target vessel would be separated from the manifold assembly. The shroud and target vessel are welded to the vessel attachment flange, therefore both must be cut from the flange with a large mechanical saw. A vertically oriented reciprocating saw, seen in Fig. 8, was designed and produced in a collaborative effort between ORNL and E.H. Wachs Company to cut the shroud and target vessel from the mounting flange. The target module will be lowered vertically into the saw and the initial cut will be located near the flange, which will allow the shroud and target vessel to separate from the manifold assembly. After the target vessel is separated a hoist adapter will be attached to the vessel to allow positioning of the vessel by an in-cell crane. The separated mercury target vessel will be reinserted into the saw and subsequent cuts will be made to produce specimens for PIE testing.

A failure point may reside in the body of the target vessel and body samples would be required to isolate the point of failure, which would be cut from the vessel using the Wachs saw. The body samples would be taken from the vessel by first cutting narrow slices from the target vessel, then a smaller section containing the point of failure would be taken from the slices using a modified steel "rebar" cutter, seen in Fig. 9. Body samples may also include areas of the target with stress concentrators such as weld joints, cooling channel transition areas, and corners of internal flow baffles. These areas of stress concentration may be prime candidates for examination due to the cyclic loading of the target and concerns of material fatigue.

Since the front section of the target receives the largest radiation dose, material from this section is critical for PIE characterization and will be removed from the target vessel using the vertical saw. Depending on the type of failure and amount of cavitation damage observed on the interior of the nose section, specimens may be produced from the entire nose section or select areas of interest. After the nose section is removed from the target vessel, nose samples from areas of interest may be obtained using a modified annular cutter drilling unit, seen in Fig. 10. A Eurobor® drill system has been modified for remote operation in the target service cell by mounting the unit to a jig assembly designed to secure the target nose section during cutting operations. The travel on the drill unit has been modified such that the handle no longer functions and movement of the cutter is controlled through a pneumatic cylinder attached to a nitrogen tank. Pressure is applied to the cylinder during cutting and reversed to remove the cutter after each cut. To ensure that no significant heating of the target material occurs, the drill system has been equipped with a drip system to apply water to the cutter during operation.

4. Characterization techniques

Cavitation erosion damage to the inner surface of the target vessel will be characterized using images obtained via optical microscopy and SEM examination. Cavitation erosion damage can be estimated from images of the pitted interior surface by measuring the area and morphology of the pits. Special care will be taken during specimen production to document the location of each specimen from the interior surface of the target vessel. The extent of cavitation erosion from each location inside the vessel could be used to gain insight into which areas of the vessel experienced the greatest erosion. This information could then be used to gain

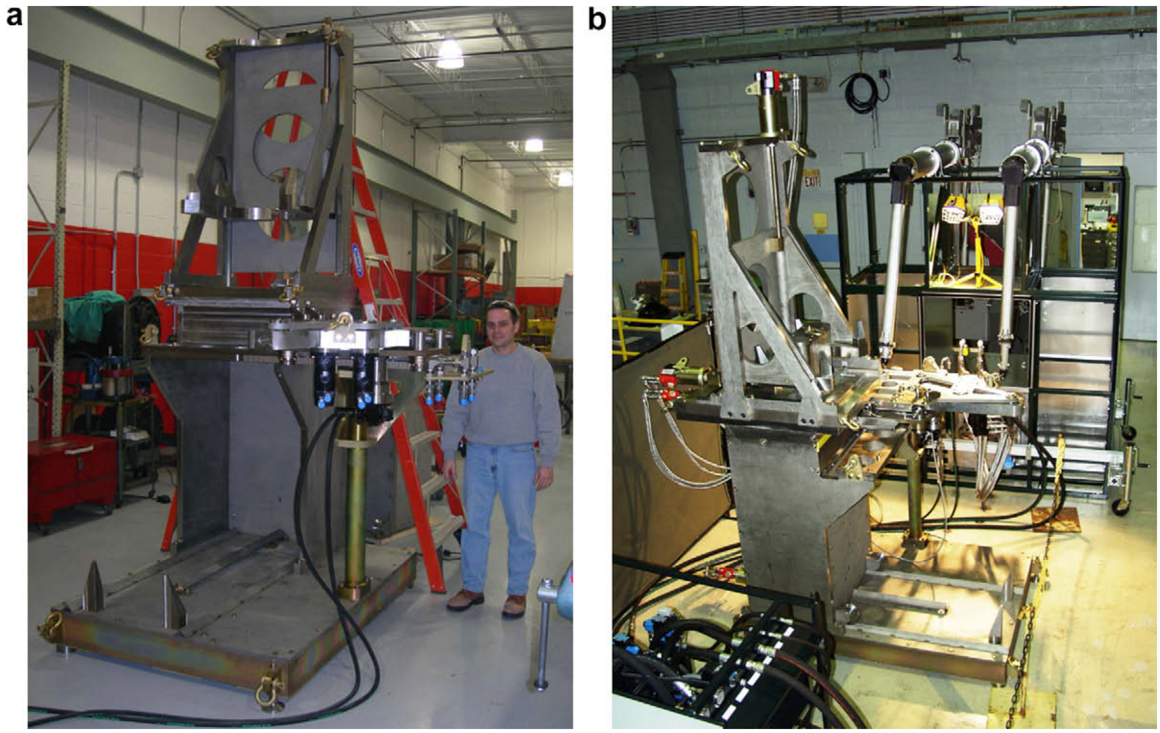

Fig. 8. Vertically oriented Wachs reciprocating saw for target separation and sectioning: (a) front view and (b) side view.

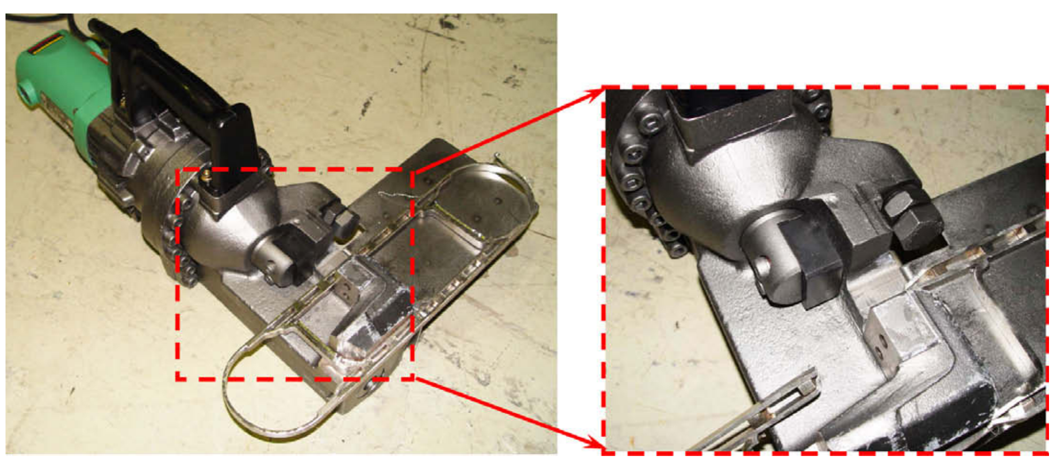

Fig. 9. Concrete steel "rebar" shear-cutter modified to remotely cut sections from target vessel slices (close-up shows the result of a cut).

insight into the cavitation erosion phenomenon and guide cavitation mitigation techniques for future targets.

Several mechanical properties characterization techniques may be applied to specimen material from body and nose samples, including microhardness indention, ball indention testing (BIT), and conventional tensile testing. Microhardness testing using Vickers indentation could be performed to characterize the change in material hardness after irradiation, and a profile of indentions may be obtained to quantify the change in hardness of different areas of the vessel samples. A hardness profile may also help verify the accumulated dose profile across the target nose section initially obtained by the radiographic film. BIT testing provides quantitative mechanical property data of the target vessel through simple indentation of the vessel material by a small tungsten carbide ball. Though BIT does not provide conventional tensile data it does produce good estimates of yield strength, ultimate strength, and plastic strain. The main advantage of BIT and microhardness indentation testing is minimal specimen preparation is required, with only a small relatively flat piece of material required for testing. Though indentation testing is relatively easy to perform and provides good estimates of changes in mechanical properties, conventional tensile testing produces standardized mechanical data that can be compared to other tensile properties data sets and used in stress calculations for target design modifications.

In order to perform conventional tensile testing on the SNS target vessel material, an electrical discharge machining (EDM) unit located in a hot cell must be utilized to machine specimens from the activated 316L vessel material. Installation of an EDM unit into a hot cell facility at ORNL is an additional task of the SNS target PIE activities. But extensive time-consuming modifications, that allow

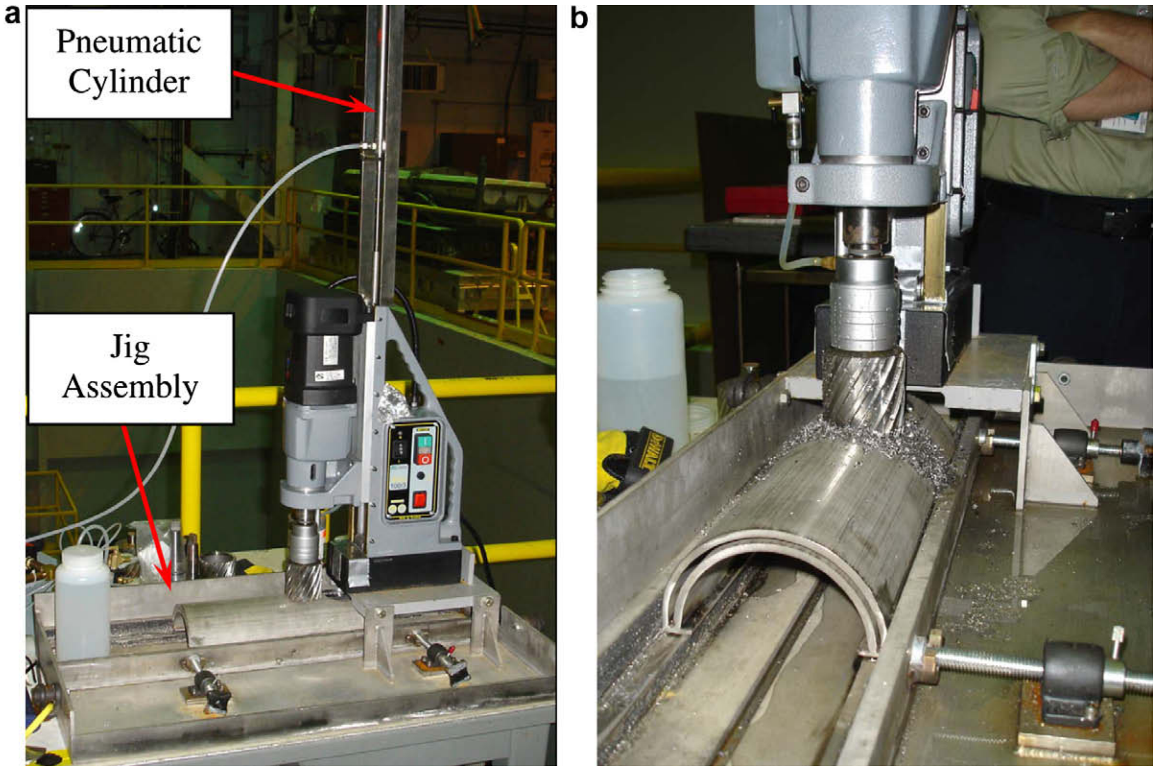

Fig. 10. Modified Eurobor® annular cutter unit: (a) side view and (b) front view [during trial cut].

remote operation of a commercial EDM unit in a hot cell environment, are required prior to installation. These activities are currently underway but will not be completed before replacement of the first target occurs. Since the modifications and installation of the commercial EDM unit chosen for installation will not be completed before the planned examination of the first target vessel, an outside vendor may be used to produce tensile specimens for the initial PIE examinations.

5. Summary

Characterization of the change in mechanical properties and extent of cavitation erosion of the 316L SNS target material will be critical for further development of the SNS target system and life extension of future target modules. PIE of the first target vessel will commence when the target reaches end-of-life, which will occur either when the target fails or reaches the prescribed ~8 dpa dose limit. If failure of the target vessel occurs during operation, the first PIE activity will be identification of the point of failure and characterization of the failure mode. The total proton and neutron fluence through the target vessel nose will be characterized using radiographic film before commencement of machining operations to obtain specimen material from the target. Two types of specimens will then be taken from the target vessel; nose and body samples. Nose samples may be taken from the target vessel using one of two modified annular cutter drilling units, while body samples will be produced from body slices using a modified steel rebar cutter. The extent of cavitation erosion damage to the target vessel inner surface will be characterized utilizing images obtained with optical microscopy and SEM examination. Changes in mechanical properties of specimen material may be estimated using BIT and microhardness indentation testing. Conventional tensile specimens may also be produced from the water-cooled shroud and target vessel material to accurately quantify the changes in tensile properties and provide engineering data for future target design modifications.

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References

[1] T. McManamy, A. Crabtree, D. Lousteau, J. DeVore, L. Jacobs, M. Rennich, J. Nucl. Mater. 377 (2008) 1.
[2] G.S. Bauer et al., The ESS Technical Study, The European Spallation Source Study, vol. III, The ESS Council, ESS-96-53-M, 1996. ISBN: 090 237 659.
[3] G.S. Bauer, in: Proceedings of the 13th Meeting of the International Collaboration on Advanced Neutron Sources, Villigen PIS, Switzerland, October 1995, p. 547.
[4] L.K. Mansur, T.A. Gabriel, J.R. Haines, D.C. Lousteau, J. Nucl. Mater. 296 (2001) 1.
[5] E.H. Lee, J.D. Hunn, N. Hashimoto, L.K. Mansur, J. Nucl. Mater. 278 (2000) 266.
[6] E.H. Lee, J.D. Hunn, T.S. Byun, L.K. Mansur, J. Nucl. Mater. 280 (2000) 18.
[7] J.D. Hunn, E.H. Lee, T.S. Byun, L.K. Mansur, J. Nucl. Mater. 282 (2000) 131.
[8] K. Farrell, T.S. Byun, J. Nucl. Mater. 296 (2001) 129.
[9] T.S. Byun, K. Farrell, E.H. Lee, L.K. Mansur, S.A. Maloy, M.R. James, W.R. Johnson, J. Nucl. Mater. 303 (2002) 34.
[10] L.K. Mansur, J. Nucl. Mater. 318 (2003) 14.
[11] M. Futakawa, T. Naoe, H. Kogawa, M. Teshigawara, Y. Ikeda, J. Nucl. Mater. 356 (2006) 168.
[12] J. Lettry, R. Catherall, P. Drumm, A. Evensen, O. Jonsson, E. Kugler, J. Ober, J.C. Putaux, J. Sauvage, H. Ravn, M. Toulemonde, ISOLDE Collaboration, in: Proceedings of the 13th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-XIII), Villigen, Switzerland, 11–14 October 1995.
[13] M.D. Kass, J.H. Whealton, N.E. Clapp Jr., J.R. DiStefano, J.H. DeVan, J.R. Haines, M.A. Akerman, T.A. Gabriel, Tribol. Lett. 5 (1998) 231.
[14] M. Futakawa, H. Kogawa, R. Hino, J. Phys. IV France 10 (Pt 9) (2000) 237.
[15] J.R. Haines, B.W. Reimer, D.K. Felde, J.D. Hunn, S.J. Pawel, C.C. Tsai, J. Nucl. Mater. 343 (2005) 58.

[16] B. Riemer, J. Haines, M. Wendel, G. Bauer, M. Futakawa, S. Hasegawa, H. Kogawa, J. Nucl. Mater. 377 (2008) 162.
[17] M. Futakawa, T. Naoe, C.C. Tsai, H. Kogawa, S. Ishikura, Y. Ikeda, H. Soyama, H. Date, in: Proceedings of the fifth International Symposium on Cavitation (CAV 2003), November 2003, pp. 1–4.
[18] K. Kikuchi, H. Kogawa, H. Futakawa, S. Ishikura, M. Kaminaga, R. Hino, J. Nucl. Mater. 318 (2003) 84.
[19] B.W. Riemer, J.R. Haines, J.D. Hunn, D.C. Lousteau, T.J. McManamy, C.C. Tsai, J. Nucl. Mater. 318 (2003) 92.
[20] M. Kawai et al., J. Nucl. Mater. 377 (2008) 21.
[21] M. Futakawa et al., J. Nucl. Mater. 377 (2008) 182.
[22] D. Felde, B. Riemer, M. Wendel, J. Nucl. Mater. 377 (2008) 155.
[23] Y. Dai, G.W. Egeland, B. Long, J. Nucl. Mater. 377 (2008) 109.
[24] L.K. Mansur, B.W. Riemer, T. McManamy, D.A. McClintock, Y. Dai, S.A. Maloy, Consultations during The ninth International Workshop on Spallation Materials Technology (IWSMT-9), Sapporo, Japan, 19–24 October 2008.