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Status of R&D on mitigating the effects of pressure waves for the Spallation Neutron Source mercury target

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ABSTRACT

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory has been conducting R&D on mitigating the effects of pressure waves in mercury spallation targets since 2001. More precisely, cavitation damage of the target vessel caused by the short beam pulse threatens to limit its lifetime more severely than radiation damage as well as limit its ultimate power capacity – and hence its neutron intensity performance. The R&D program has moved from verification of the beam-induced damage phenomena to study of material and surface treatments for damage resistance to the current emphasis on gas injection techniques for damage mitigation. Two techniques are being worked on: injection of small dispersed gas bubbles that mitigate the pressure waves volumetrically; and protective gas walls that isolate the vessel from the damaging effects of collapsing cavitation bubbles. The latter has demonstrated good damage mitigation during in-beam testing with limited pulses, and adequate gas wall coverage at the beam entrance window has been demonstrated with the SNS mercury target flow configuration using a full scale mercury test loop. A question on the required area coverage remains which depends on results from SNS target post irradiation examination. The small gas bubble technique has been less effective during past in-beam tests but those results were with un-optimized and un-verified bubble populations. Another round of in-beam tests with small gas bubbles is planned for 2011.

The first SNS target was removed from service in mid 2009 and samples were cut from two locations at the target's beam entrance window. Through-wall damage was observed at the innermost mercury vessel wall (not a containment wall). The damage pattern suggested correlation with the local mercury flow condition which is nearly stagnant at the peak damage location. Detailed post irradiation examination of the samples is under way that will assess the erosion and measure irradiation-induced changes in mechanical properties. Similar samples were cut from the second SNS target after it was removed from service in mid 2010. More extensive damage was observed on the target inner wall but damage to the containment wall was minimal.

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1. Introduction

The question of beam-pulse induced cavitation in a mercury target option for SNS was considered and studied in the early conceptual phase of the project. Theoretical investigations [1] suggested that cavitation activity was likely but the potential for pitting damage was only speculated upon. Experimental studies on mercury's tensile strength [2,3] obtained values considerably lower than reported values and supported the probability of cavitation in a MW class mercury target. R&D at that time went so far as to employ ultrasonic horn testing which led to the observation that the damage erosion rate had a quadratic dependence on horn power in mercury compared to a linear dependence in water [4]. Despite potential for cavitation to occur the likelihood of significant damage was not taken seriously until late 2000 – after SNS construction had started and target engineering was well under way – when Japan Proton Accelerator Research Complex (JPARC) target researchers investigating pressure wave propagation in mercury observed pitting damage after only a few pressure waves of magnitude and dynamic characteristics comparable to a MW class mercury target [5,6]. Observation of cavitation damage in molten lead-filled tantalum targets at CERN's Isotope Separator On Line (ISOLDE) facility was as yet unknown at SNS [7].

An intense R&D effort began in 2001 to study beam induced cavitation damage in mercury targets. The critical decision was made to stay with the mercury target option based on results from in-beam and off-line experiments along with other investigations that supported the likelihood of a tolerable target vessel lifetime at 1 MW. Along with the decision was the commitment to continue

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R&D with the goal to develop damage mitigation technologies sufficiently effective to keep cavitation damage from being the target's life limiting mechanism – for any future SNS power level [8].

Early advice from two expert review panels suggested that while gains could be made from considering alternative target vessel materials and surface treatments with higher damage resistance, prolonging target life and power capacity may very well require mitigation within the mercury itself. Two approaches were suggested: introducing a dispersed population of small, non-condensable gas bubbles that could absorb and/or attenuate beam-induced pressure waves that drive cavitation; and establishing protective gas walls or bubble curtains at the mercury – vessel interface where damage was likely to occur. The former concept had been under consideration by the European Spallation Source as a means to reduced target vessel stress [9,10]. The latter approach had been developed for naval applications to mask ship noise and also for hydropower to protect turbines from cavitation damage.

The early effort leading to the decision to keep mercury strengthened collaboration between SNS and JPARC target teams. A broad strategy agreement was made in early 2005 that JPARC researchers would emphasize small gas bubble mitigation while SNS would work on protective gas walls. No doubt there would be some overlap but the strategy would help economize with limited R&D budgets.

Progress has largely been published elsewhere; recent developments will be described herein. Importantly, operating experience at the SNS has provided direct observation of cavitation damage in both of the first two target modules. A range of post irradiation examination (PIE) techniques are being applied to assess and quantify actual pitting damage as well as mechanical property evaluation of target vessel material [11,12]. Both targets were taken out of service because radiation damage was approaching the SNS adopted limit of 10 displacements per atom; there were no indications of a target leak. Nevertheless, through-wall cavitation damage was observed on both targets' inner mercury vessel walls at the beam entrance location.

The disk specimens shown in Fig. 1 were located on beam axis and the viewed surfaces faced the bulk mercury volume; the back sides (not shown) facing the mercury cooling channel had relatively little damage. The directly photographed Target #1 specimen (A) had been cleaned and reveals a damage pattern suggesting correlation with the incident beam profile and local mercury flow field. The Target #2 specimen (B) had yet to be cleaned and was photographed through a shield window. Its fracture is believed to have occurred during specimen cutting. However, near through-wall erosion traverses its entire width.

It is important to recognize the increasing beam power on target as SNS accelerator operations mature. Fig. 2 shows two measures of this: accumulated energy and instantaneous beam power on target plotted from October 2006 through the present. Targets #1 and #2 had about the same accumulated beam energy over their lifetimes but their power histories are quite different. Target #2's lifetime was largely consumed in the near mega-watt power regime while the opposite was true for Target #1 (Fig. 3). Predictions for cavitation erosion rate dependence on beam power have been by a power law dependence with exponent perhaps as large as four [8]. While the experience with these two targets has demonstrated that projections for severely limited target lifetimes have not been realized, concerns remain as power approaches 1.4 MW and higher as accelerator upgrades are installed.

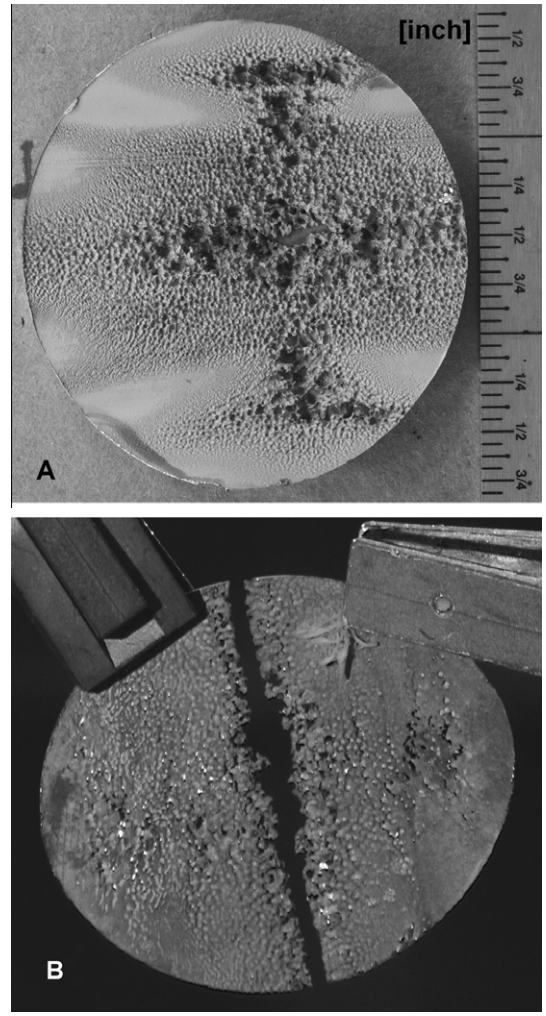

Fig. 1. Mercury vessel specimens cut from SNS Targets #1 (A) and #2 (B) from their inner (non-containment) beam windows. Horizontal orientation during operation in (A) was close to the photograph orientation and along the fracture line in (B). Specimen (A) diameter is 60 mm; specimen (B) diameter is 57 mm; original thicknesses were 3 mm.

2. R&D program attributes

The SNS R&D program for the development of cavitation damage mitigation technologies includes theoretical, experimental and simulation work employing resources at Oak Ridge National Laboratory (ORNL), universities and research industries. It has utilized and drawn upon

- The Target Test Facility (TTF) at ORNL, a full scale mercury test loop hydraulically prototypic to SNS [13].
- In-proton-beam mercury target experiments at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) and proton radiography facilities [14–20].
- ORNL staff with expertise in erosion, corrosion, and irradiated material science [21–29], single- and multi-phase Computational Fluid Dynamics (CFD) [30–38], and design/fabrication/operation of water and mercury test hardware [39].
- Resources from university and industry R&D subcontracts (for small gas bubble diagnostic and generation development, gas wall physics, cavitation detection, helium in mercury solubility) [40–44], and

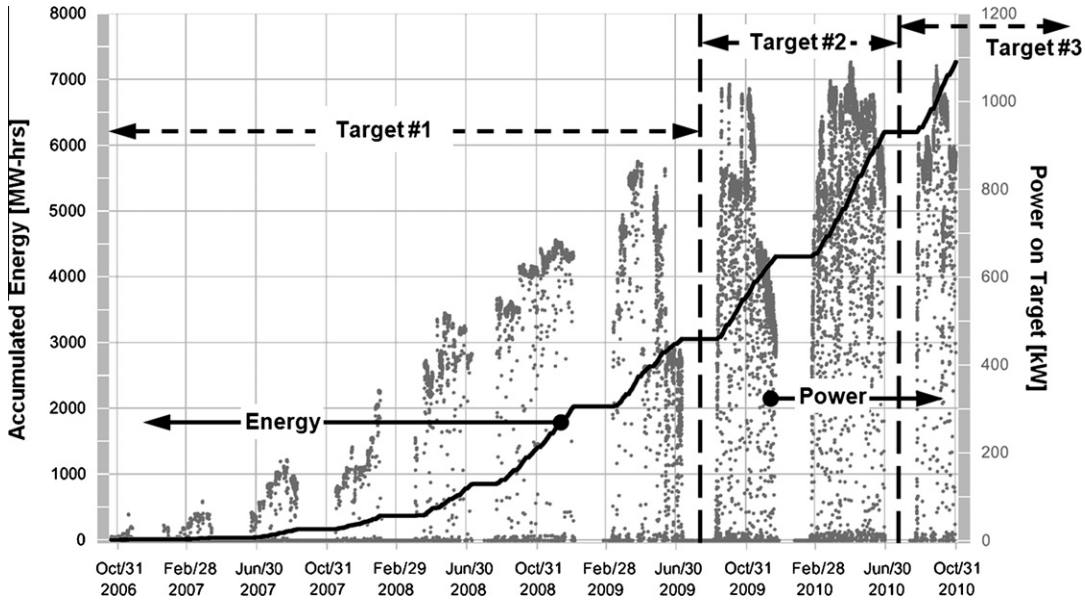

Fig. 2. SNS accumulated beam energy to the target station (solid line) and power on target (scattered data).

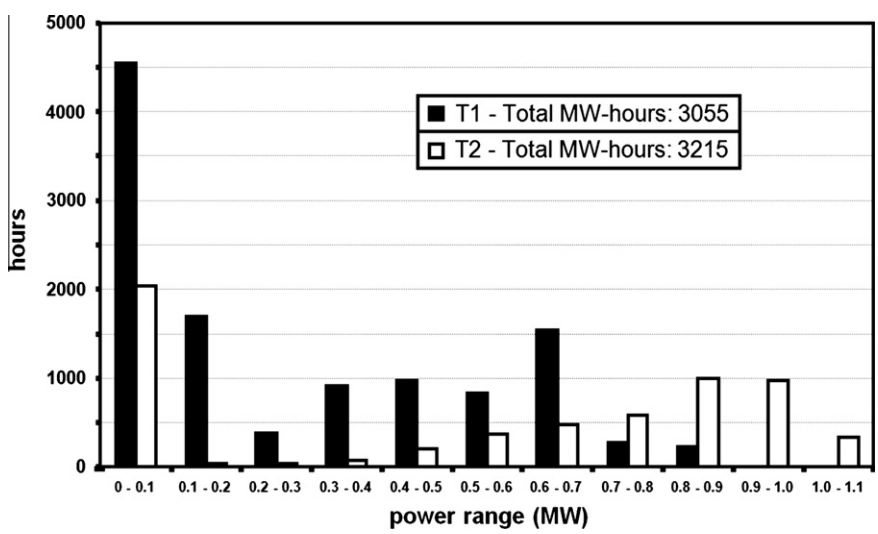

Fig. 3. Power histograms for Targets #1 and #2.

- Collaboration with the Japan Atomic Energy Agency (JAEA) and JPARC, including access to their Magnetic IMpact Testing Machine (MIMTM) [45–47].

3. Recent developments

Major activities of the R&D program in the period from 2007 through present have included:

- Gas wall development and testing including two-phase CFD, gas injection testing in the TTF and damage testing in MIMTM.
- Delivery and testing of acoustic diagnostics for assessment of small gas bubble populations in mercury.
- SNS development of optical methods for assessment of small gas bubbles in mercury.
- In-beam experiments investigating
  - o damage dependence on mercury flow velocity in a channel prototypically shaped like that in the SNS target design,
  - o damage dependence on beam intensity,
  - o damage mitigation efficacy of gas walls.
- Small gas bubble generator development testing on the TTF, and
- Design, fabrication and testing of a new mercury test loop for in-beam experiments to evaluate small gas bubble mitigation.

3.1. Protective gas wall development

Injected gas at the mercury – wall interface is strongly acted upon by local fluid, buoyancy, surface tension and interface contact forces. Efforts have led to categorizing protective gas walls in three general approaches: free gas layers, where gas is simply injected via ports on a smooth vessel wall; porous wall gas layers, where gas is injected through a porous media to create a bubbly layer at the interface; and surface texture enhanced gas walls, where small grooves and/or cone features in the vessel surface aid the movement along and adhesion to the vessel wall. Helium is the gas of choice for gas walls (and small gas injection) because it is the cover gas for the mercury process system. It is inert and is a good choice for leak testing.

Two key assumptions were made regarding the requirements for gas walls: in the bulk flow region, only the mercury vessel inner surface at the beam entrance window will need protection; window cooling channel surfaces can be protected by either switching from mercury to water cooling or by virtue of high speed flow that inhibits damage. Examinations of SNS targets 1 and 2 – to the limited extent that has been possible – have supported these assumptions.

Damage mitigation efficacy for the first two categories seems well enough established. A primitive in-beam experiment for free gas layers conducted with a mercury target demonstrated substantial damage reduction [8]. Water-based experiments employing a ceramic porous media to create a protective bubble layer succeeded in stopping damage from a shock-wave lithotripter [42]. Efficacy for surface texture enhanced gas walls also looks good based on results from a 2008 in-beam experiment [20]. However, there are issues with each approach which will be explained.

The SNS bulk mercury flow is illustrated in Fig. 4A. Two supply flows (nominally 12 L/s each) move along the sides of the target towards the beam entrance window where they turn inward and join into a common return. Beam window cooling is assured by the dedicated narrow mercury channel between the dual windows which are not shown in the figure. The bulk flow has a central, quasi-stagnation zone at the center of the inner wall surface where the two bulk supply flows collide. Here the local pressure is high which adds to the difficulty of keeping gas at this wall location. The TTF was equipped with a gas wall test section (Fig. 4B) to test a number of free, porous media and surface texture gas wall configurations. Gas wall coverage was usually assessed by high speed video through acrylic test sections except for the porous media when ultrasonic techniques had to be employed.

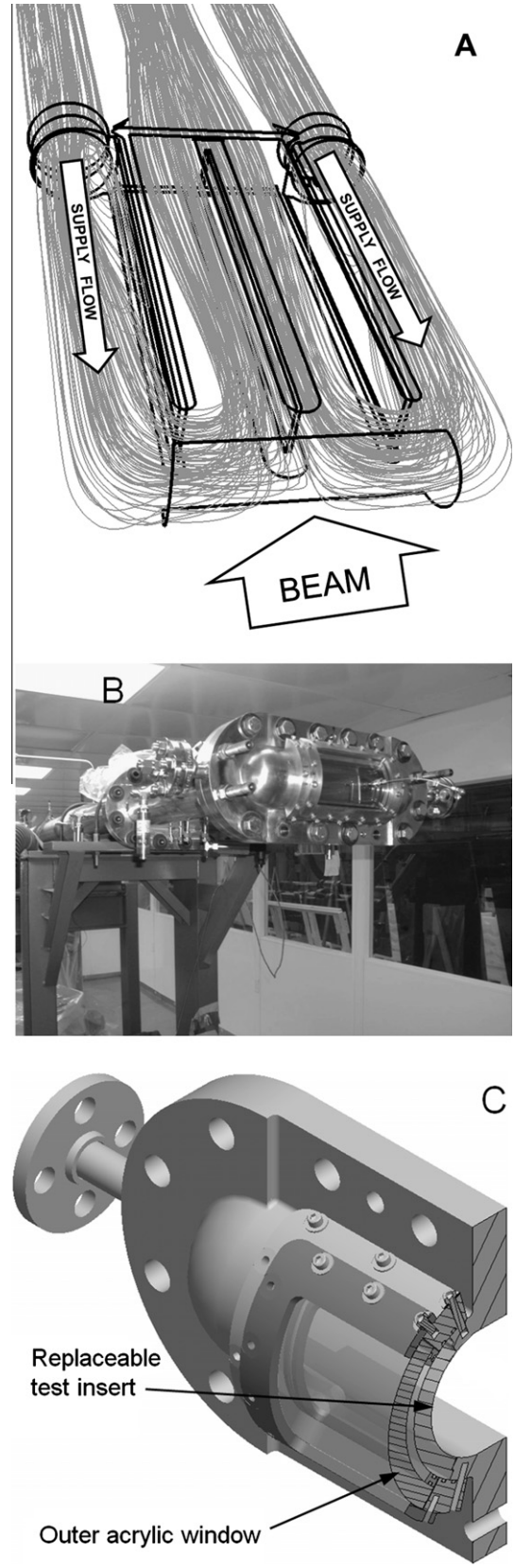

Fig. 4. SNS bulk mercury flow streamlines illustrate the quasi-stagnation point at the center (A). The Target Test Facility (B) is hydraulically prototypic to the SNS; here it is configured with a gas wall test section (C).

3.1.1. Free gas layer

A 2002 in-beam experiment successfully demonstrated damage mitigation with a free gas layer but employed a stagnant mercury target [30]. It is more difficult to keep gas on the wall over the beam spot area in a flowing mercury target.

Fig. 5A–C shows example frames (ca. 50 ms apart) of one free gas layer configuration tested in the TTF. Here, the mercury flow rate was about half that of SNS nominal. At some brief moments there are regions of gas at the wall – even at the stagnation point/beam axis. Maps of time-averaged gas wall coverage were obtained using image processing techniques. At this mercury flow the coverage was modestly encouraging. However at nominal mercury flow, the coverage was insignificant due to much greater turbulence that drastically increases mixing and pulls the gas off the wall close to injection points. Sufficient gas coverage using the free gas layer approach will require a substantial reconfiguration of the bulk flow. One example would be a sweeping mercury flow arrangement (one side to the other or bottom to top), but re-routing flow paths in the target module and/or piping carriage could be costly and difficult.

3.1.2. Porous media

Experiments with porous media to create gas walls in mercury revealed some difficulties and one unresolved issue. It became apparent that pressure drop through the media had to be sufficiently higher than mercury pressure variations over the media surface (ca. 0.5 bar). Without this condition, injected gas would be emitted preferentially at local low pressure regions. Pressure drop can be designed into porous media by adjusting thickness, average pore size and density. Next, the media itself must be cooled since any material in the proton beam path is heated. Satisfying the cooling and pressure drop requirements along with the need to limit total gas injection rate to about 1% of mercury volumetric flow appears challenging. Stainless steel and carbon foams were considered as porous materials because of their proven radiation damage resistance. Some experimental observations raised

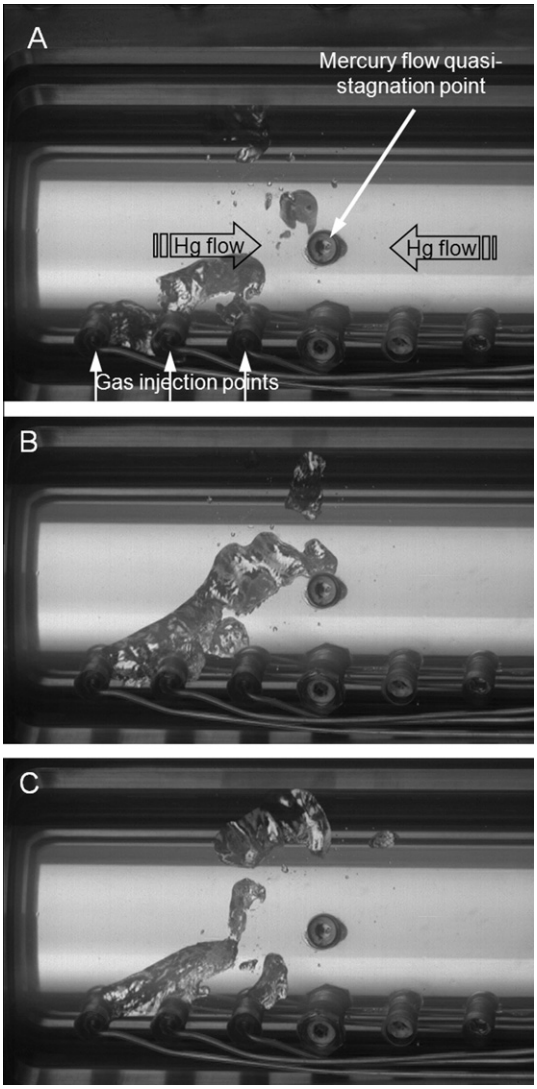

Fig. 5. Example frames from a free gas layer video looking through a smooth acrylic test wall. Mercury was flowing at half the SNS nominal rate. Helium gas injection through each of the indicated points was 500 standard cubic centimeters per minute (sccm). The time interval between frames is ca. 50 ms.

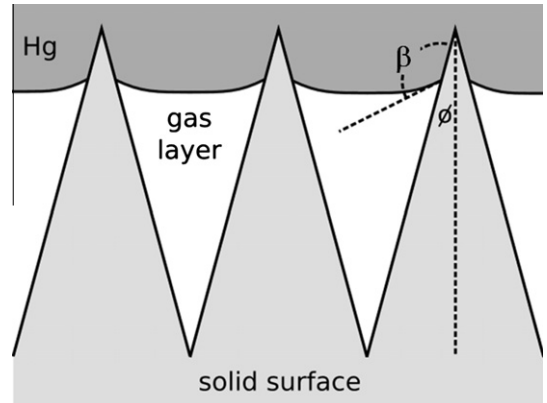

Fig. 6. Illustration of surface texturing where partial gas layer coverage is achieved. Angle β is the mercury – surface contact angle (ca. 133° when not wetted); ϕ is the characteristic surface feature half-angle (ca. 15°). Typical feature pitch is 0.5–1.0 mm. Full gas layer coverage is when the gas layer traverses several adjacent feature peaks.

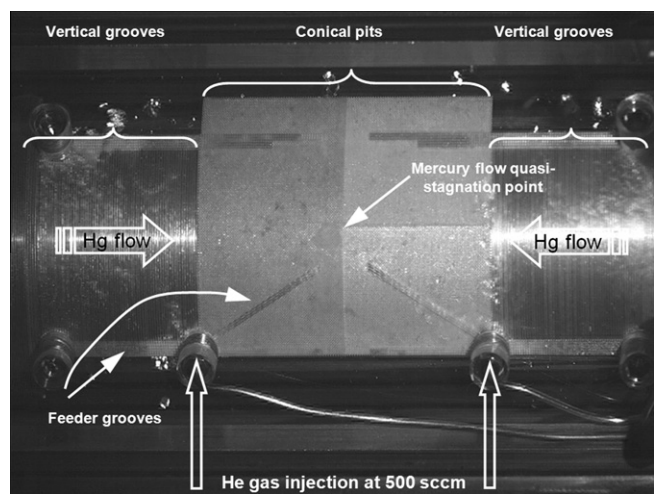

Fig. 7. Gas injected at a textured acrylic test wall in the TTF with a combination of cone and groove features. Here the light intensity is indicating at least partial gas coverage everywhere and full coverage in transient locations. Mercury flow is at nominal SNS (24 L/s).

the concern of mercury intrusion into the media pores. If this occurs, gas will flow around blocked pores leaving some of the media surface unprotected. The SNS mercury piping system is loaded under vacuum to avoid trapping gas in the pipes; this will exacerbate the problem. A means to recover from intrusion could not be found so development on this approach ceased.

3.1.3. Textured surface enhanced gas walls

Also called surface-modified gas walls, this concept exploits the generally non-wetting behavior of mercury at many solid interfaces. Appropriately sized and shaped features such as cones or grooves in a vessel wall (Fig. 6) can act to hold up gas at the wall despite strong mercury flow dynamic forces [33,36]. Experiments with a combination of such features on the TTF showed that at least partial gas coverage could steadily be established over the beam spot area even under nominal SNS mercury flow. Here the coverage quality "partial" means the surface feature is largely filled with gas as opposed to "full" coverage where gas is observed to form a continuous layer that totally separates mercury from the wall. These conditions can be visually distinguished when employing acrylic gas wall test sections in TTF (Fig. 7). Full coverage was only achieved intermittently and only over part of the desired coverage area. However, partial coverage may provide sufficient damage mitigation.

The mitigation efficacy of partial gas coverage was investigated in two experiments. An in-beam test was performed at LANSCE-WNR in 2008 where a test target with cone type texturing was hit with 100 pulses [17,20]. The simple test target contained stagnant mercury, but the gas wall condition on the target window was designed for partial coverage to mimic the predominant condition that was observed in TTF testing. The textured steel beam entrance window configuration was developed using acrylic pieces that were tested at ORNL prior to irradiation. One hundred beam pulses with peak intensity equivalent to SNS at 2 MW operating power were applied. Despite using only partial gas coverage, no damage was observed.

High-cycle damage testing in flowing mercury was desired following the encouraging WNR test result. Such testing was done in 2009 using JAEA's MIMTM device [45] in a flowing mercury loop configuration with various textured gas wall test surfaces (Fig. 8). These tests were developed with two-phase CFD simulations and evaluated for gas coverage using TTF [35]. Some 15 textured

surface, gas and mercury flow test combinations were tested with MIMTM, each exposed to up to 1 million impacts. Preliminary results were encouraging based on surface inspection and weight loss measurements. However, inspection of control surfaces located in the damage chamber across from the test surfaces revealed less than expected damage. It is now believed that the introduced gas inhibited the driving tensile pressure cavitation mechanism of the MIMTM impacter. This off-line device creates surface driven pressure impulses as opposed to volumetric impulses characteristic of a pulsed spallation target; furthermore MIMTM's pressure rise time is about 1000 times slower than the micro-second rise time in a short pulse target such as SNS. Regretfully, no conclusions regarding high-cycle damage mitigation efficacy could be drawn from these tests.

Despite the lack of demonstrated high-cycle damage mitigation, existing data is sufficient to proceed in developing surface textured enhanced gas walls for a future SNS target design. Uncertainty remains about a potential change of the mercury non-wetting property to wetting of the stainless steel wall surface, and how that might affect gas wall coverage. Such change has been observed in unrelated high-cycle mercury cavitation testing in MIMTM, mercury cavitation testing with ultrasonic horns, and possibly in post-irradiation observations of the two used SNS targets. Fig. 9 is a view looking inside the second SNS target through a hole cut in the beam entrance window. Residual mercury droplets appear to wet the surface. This contrasts with typical testing experience where mercury usually beads up on stainless steel surfaces. Continuous gas injection might maintain the non-wetting property but a definitively prototypic experiment is not possible.

An in-beam test of surface texture enhanced gas walls where the surface is deliberately made to wet by adding a thin coating of a material such as gold is being planned as part of the next WNR experiment. By comparison to an uncoated surface the effect of wetting on damage efficacy can be estimated, albeit at a low number of pulses.

3.2. Small gas bubble mitigation

While the SNS program has emphasized gas wall development over small gas bubble (SBG) mitigation it has not been to the point of exclusivity. Indeed two in-beam experiments investigating SGB were conducted in 2002 and 2005 [8,16]. In both cases damage was reduced only by a factor of 2–4 compared to control conditions. In the later experiment the benefit of flowing mercury alone became apparent. In neither case the generated bubble populations could be adequately assessed. However the test loop used for the 2005

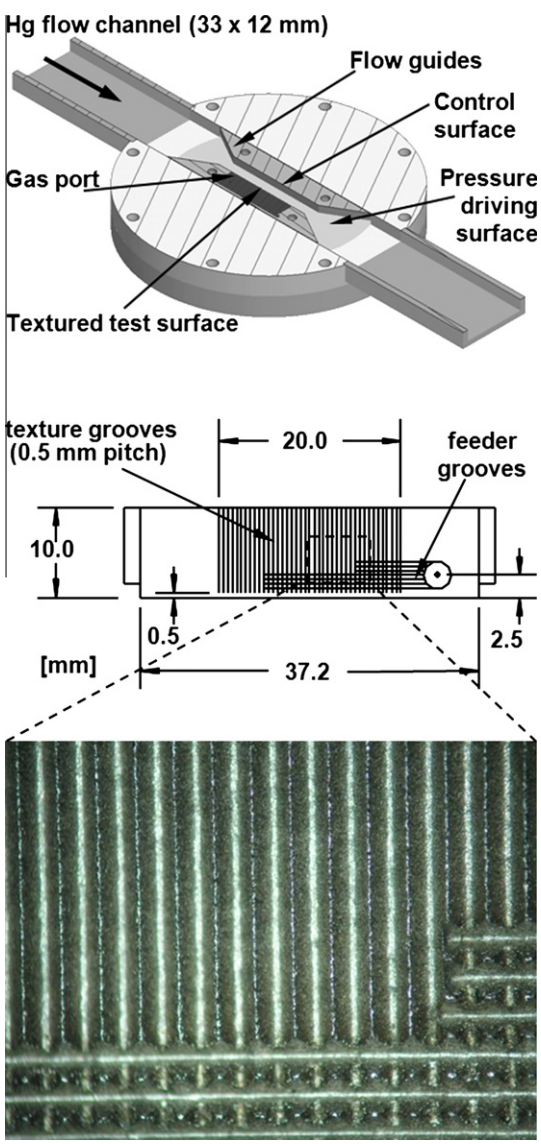

Fig. 8. Top: cut view of JAEA's MIMTM configured for textured gas wall experiments. Mercury velocity at the test surface was ca. 1 m/s. Middle: Example textured test surface insert. Bottom: image detail of textured surface.

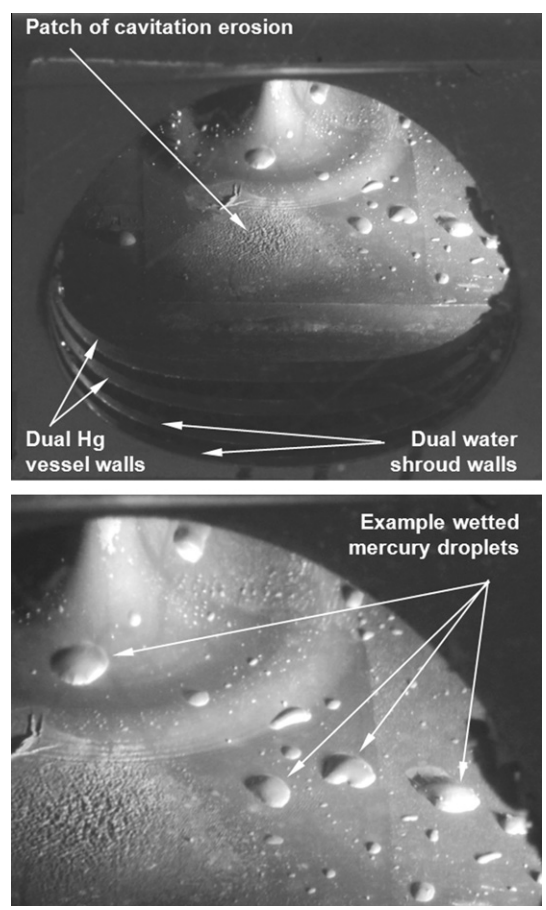

Fig. 9. Top: view looking inside Target #2 through a hole cut at the center of the beam entrance window. Two mercury vessel and two water shroud walls can be seen at the cut location. Also seen are several apparently wetted droplets of mercury on the interior surface and a patch of cavitation erosion in front of the central flow baffle; this patch is above the incident beam profile. Bottom: magnified view.

experiment was subsequently taken to the LANSCE proton radiography facility where it was revealed that its bubble generator did poorly in creating the small bubble sizes believed necessary for effective mitigation [18,19].

Measuring small gas bubble populations in dense, opaque mercury is challenging. A variety of bubble generators have been tested in parallel with development of improved methods for assessing bubble populations in mercury over the past few years. Testing has utilized the TTF and the new MultiBubbler Test Loop (MBTL). Considerable investment by the SNS R&D program was made in acoustic techniques to determine bubble sizes and void fraction but with little success. Two of the diagnostics appear credible and self consistent under specific deployment configurations but have yet to be benchmarked in mercury.

Very recently two optical approaches have produced credible measurements. One requires that a flowing test loop be stopped quickly whereupon any entrained bubbles rise to a horizontal viewport surface and are recorded by high speed video. Image analysis and data processing provide the required bubble size distribution data. It cannot be generally applied to any flow configuration but the technique is doing well with the MBTL under many test conditions. Adaptation of this technique to the TTF is underway. The other optical technique involves tracking incident bubbles at viewports (horizontal or vertical) during steady flow conditions. The correlation between the latter and former techniques is lacking. Nevertheless they have significantly improved our ability to assess bubble generator performance.

3.2.1. Small gas bubble testing in TTF

Small gas bubble generators tested in the TTF over the past few years have included a needle bubbler array, a jet bubbler, the so-called ShockWave Power Reactor™ or SPR [48] and SNS developed inlet orifice bubblers [38]. During this period bubble population assessment has been qualitative given the aforementioned measurement difficulties. An experimental version of the TTF target features a trio of optical viewports at the top surface as well as the gas wall test section (Figs. 10 and 4B). Bubbles incident upon and passing by these viewports were captured by high speed video for making comparisons between bubblers.

The needle bubbler array (Fig. 11) was based on the design used in the In Beam Bubble Test Loop (IBBTL) experiments utilizing LANSCE proton radiography [18,19]. In the IBBTL the mercury flow field around the needle produced predictable bubble sizes and generation rates as a function of mercury and gas flows. It was hoped such behavior could be duplicated in TTF in an attempt to benchmark acoustic diagnostics. The benchmark failed because the turbulent flow in the TTF target inlet line around the needle array prohibited predictable and consistent bubble generation. Needle bubblers have low potential for deployment at SNS because they are too delicate and their generated bubbles sizes too large.

The SPR (Fig. 12) is also unappealing for deployment in the SNS mercury process loop because of the bulk of its equipment, anticipated difficulties with installation into the service bay and relative operational complexity. Nevertheless, the SPR produced some of the more abundant small bubble populations observed at the time.

Inlet orifice bubbler performance in TTF appeared comparable to the SPR based on qualitative assessment at the viewports. This bubbler design is relatively robust and easy to implement; simply modifying existing SNS target inlet flow orifices just upstream of the spallation zone looks feasible. The tested orifice plate is shown in Fig. 13.

3.2.2. Small gas bubble testing in MBTL

Substantial use has been made of the MBTL in the past year (Fig. 14). This mercury test loop was designed and built for in-beam experiments at WNR to investigate small gas bubble damage mitigation with substantially improved populations from those used in earlier experiments. It holds 26 L of mercury which can be circulated at up to 1 L/s for a pump head of 3 bar. At the beam spot/damage test section this results in an average flow speed of 1 m/s.

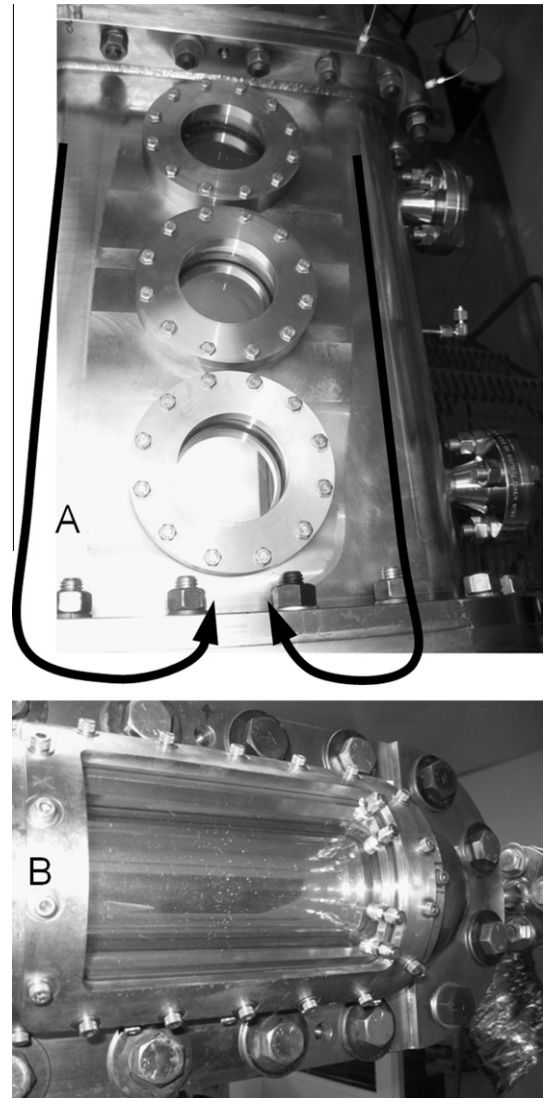

Fig. 10. Optical viewports at the top (A) and beam window (B) regions of the TTF experimental target. The bulk mercury flow arrangement is indicated in (A).

Several goals must be achieved with MBTL during the pre-irradiation testing and development phase. First, credible quantified assessment of bubble populations is essential; at this point in the R&D program there is no value in further irradiation testing without knowing bubble size distribution and void fraction. Second, populations with good prospects for substantial damage mitigation must be achieved.

Heretofore the population goal was loosely based on so-called absorption mitigation. This is simply a gas void fraction sufficient to absorb the beam-pulse induced thermal expansion of the mercury thus preventing the buildup of pressure that later leads to cavitation. At the maximum point of energy deposition in the SNS target this void fraction is about 0.13% for 2 MW of beam power on target; the goal of 0.5% was adopted for development purposes. Furthermore, bubble sizes must be quite small to have sufficiently fast response time in order to react within the time of the beam pulse. For a 1 μs beam pulse this infers bubble radii

Fig. 11. Needle bubbler array for use in one of the TTF target inlet lines. Each needle has outside diameter of 0.2 mm. When installed the needles align with the mercury flow direction.

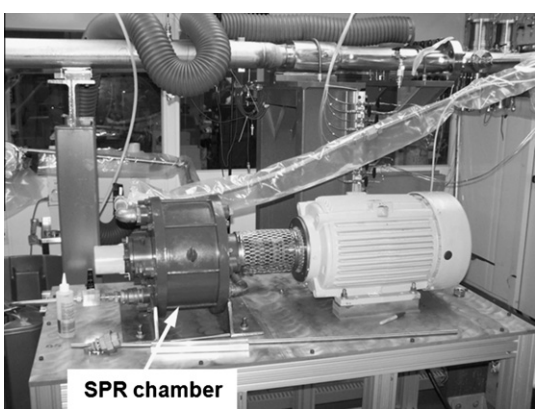

Fig. 12. ShockWave Power Reactor™ connected to one of the TTF target inlet lines. A bypass flow sent a fraction of total system flow through the SPR where helium gas was introduced and small bubbles generated. The bubbly mixture then rejoined the inlet flow upstream of the target.

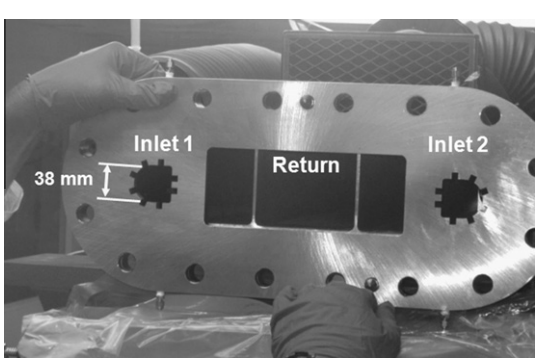

Fig. 13. Inlet orifice plate used in TTF small gas bubble generation experiments. The inlet orifices are approximately 0.6 m upstream from the front of the target.

of about 1 μm. Over time however, developments – in particular from the JAEA/JPARC spallation target team – have suggested that

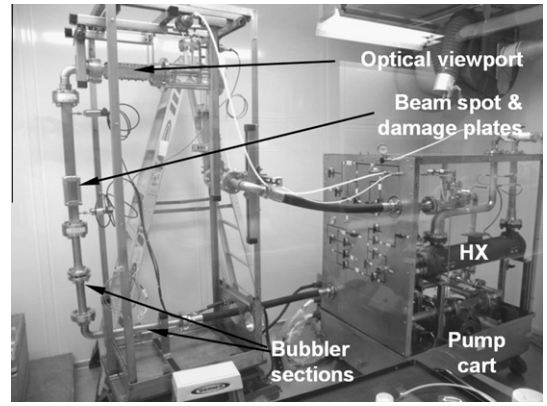

Fig. 14. The MBTL during early testing in a mercury vapor controlled laboratory. Damage plate exterior dimensions are 80 × 145 mm.

substantially larger bubbles and lower void fractions may be sufficiently effective in mitigating damage. The physics of shock propagation in multi-phase fluids with flow and fluid–structure interaction is very complex and – at the moment – lacking comprehensive and credible simulation tools to predict either small gas bubble or gas wall mitigation. Funding the development of such tools has been beyond the resources of the SNS program.

Nevertheless, the JAEA team's work suggests that bubbles up to about 150 μm radius are potentially effective [49–51]. Larger bubbles can respond to the significantly slower dynamic *tensile* pressure changes that occur well after the beam energy is deposited. Indeed, it is the tensile pressure that leads to cavitation bubble growth, and larger gas bubbles can reduce tensile pressure magnitude and duration thus suppressing cavity growth. Reduced cavity growth in turn reduces cavity collapse intensity – the driving mechanism for pitting damage.

While bubble size and void fraction requirements now seem less challenging than once believed, clear criteria for judging a population's prospects for significant damage mitigation are lacking. The MBTL experiment scope will include several void fraction and bubble size distribution combinations. One candidate example is shown in Fig. 15 from an inlet orifice bubbler using the latest optical technique. While biased to larger radii within the range of interest, the achieved void fraction of more than 10^{-4} is among the larger results measured during tests. Furthermore, its simplicity is appealing for incorporation into a possible future SNS target design. JAEA's swirl bubbler is better at producing smaller bubbles and high void fraction but its pressure loss is currently too high for adaptation to SNS. Note that the void fractions reported in Fig. 15 should be reduced by about a factor of 2 to account for the change in local pressure between the viewport and beam spot locations.

Additional bubblers tested in the MBTL have included a jet bubbler, an adaptation of Komax Systems' static ozone mixer [52], and a purpose built variation of Dynaflow Inc.'s Dynaswirl® bubbler [53]. The jet bubbler is the same design used in the 2005 WNR SGB mitigation experiment. Evaluation in MBTL established a basis for judging new bubbler relative performance. The Komax bubbler makes a relative uniform population of large bubbles which may be of interest for irradiation testing. The Dynaswirl bubbler testing is incomplete.

WNR irradiation testing with MBTL and selected bubblers is expected to be performed in the summer of 2011.

3.3. In-beam mercury target experiments

The SNS program last completed an in-beam mercury target experiment in 2008. Two issues were investigated, the first being

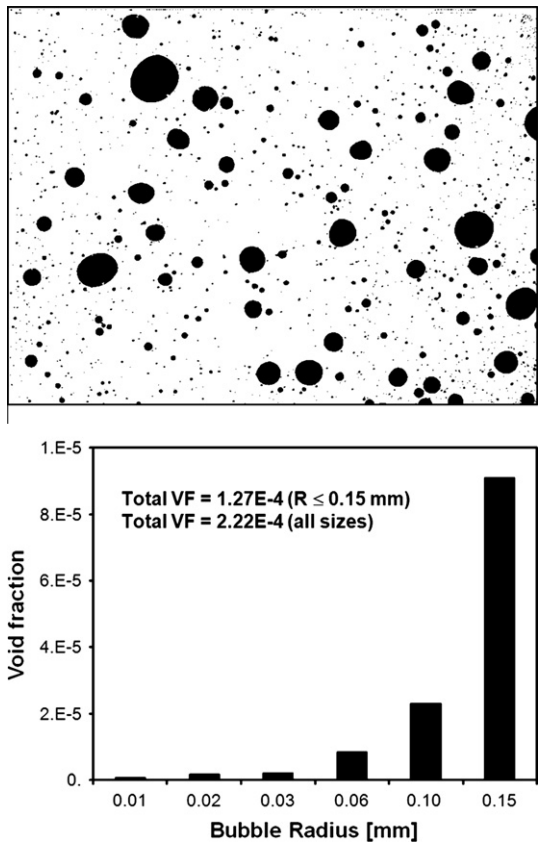

Fig. 15. Top: example binarized image from video taken of bubbles rising to the MBTL viewport surface during testing of an inlet orifice bubbler. The field of view is 10×7.5 mm; mercury depth is 22.4 mm. Bottom: bubble size distribution from associated video.

damage vulnerability of the SNS target's narrow mercury channel which conducts flow to cool the beam entrance windows. Prior in-beam experiments that used simple mock-ups of the flow channel indicated this region to be very susceptible to cavitation damage [8,16]. Such mock-up tests did not include mercury flow. Conversely, other in-beam results showed that flow reduced damage but those tests were not in configurations representative of the SNS target design [16]. The latest so-called Window Flow Vulnerability Test Loop (WFVTL) experiment employed target channel geometry based on the SNS design and investigated damage as a function of flow velocity. These test results were expected to guide a needed decision as to whether the target should be re-designed either by switching to water cooling in this channel or by finding a design solution that did not require the channel at all.

Details of the experimental scope and preparations are described in [17]; comprehensive results are available in [20]. Briefly, WFVTL results supported the recommendation that the SNS target channel design change was unnecessary. Damage in the channel was less severe than at inner vessel wall surfaces with prototypic flow conditions. Zero channel flow was clearly the worst damage condition but the benefit of increasing flow beyond 1.5 m/s was vague. These results were obtained prior to, and were consistent with, the SNS target PIE observations [12].

The second major part of the 2008 in-beam experiment investigated once again damage dependence on beam intensity (protons per unit area per pulse). Three intensities were achieved by changing beam spot size while maintaining a constant number of protons per pulse on the test targets. In this way only intensity was varied while deposited beam energy was constant. The results suggested damage rate dependence on intensity is weaker than previously believed, which was a power law dependence with exponent as large as four. These data indicate that the exponent is closer to two. The results do not elucidate anything on correlation of beam power to damage rate.

4. Post irradiation examination

Examination of real SNS targets after removal from service has provided opportunities to learn about mercury spallation target cavitation and radiation damage in unprecedented ways. While in-beam and off-line experiments provide valuable insight and data they fall short of including all meaningful conditions simultaneously. However, difficulties with examinations of real targets are substantial: targets are highly radioactive and contaminated with mercury and a range of spallation products. There is no suitable facility for performing the full range of PIE activities on target modules at ORNL; the initial large-scale activities must take place within the SNS target service bay whose operational functionality cannot be compromised.

A remotely operated saw was designed and built for large sectioning of the target module inside the service bay [11]. It would enable a thorough survey of target interior surfaces and could be used in locating leaks. However, its deployment has been indefinitely deferred because of a number of issues that put service bay operations at risk and complicate the waste disposal path for the target.

What has been permitted was cutting two circular holes through each of the beam windows of Targets #1 and #2. Each cut produced four curved specimens (two from the mercury vessel and two from the water-cooled shroud). Both the mercury vessel and shroud were made from type 316L stainless steel, but the mercury vessel was twice treated with Bodycote Kolsterising®, a low temperature carburizing case-hardening process. Photographs of the specimens while in the service bay were taken through shield windows using telephoto lenses. The holes enabled limited visual access to the target interior. Some direct examinations inside the front of the target using remote handling adapted CCD surveillance cameras were successful. Viewing perspective was restricted and it was not possible to examine elsewhere on the insides of the target inner surface. The acquired images were useful but the cameras suffered from radiation interference noise; they cameras completely failed after roughly an hour in the targets.

Four of the eight specimens cut from Target #1 were selected for an extensive range of examination and analysis activities. These include: cleaning; direct photography; ultrasonic surface profiling; surface morphology replication and examination; hardness testing (macro and micro); machining and preparation of tensile and microscopy specimens; SEM examination; metallographic examination; tensile testing; and radiochemical analysis. These efforts will provide detailed assessment of the cavitation damage as well as measures of the irradiation-induced changes in mechanical properties. The latter may lead to higher radiation damage limits for future SNS target modules. The PIE characterization and testing of the Target #1 specimens should be completed in the first quarter of 2011.

Examination of Target #2 has so far been limited to photography through shield windows. Equipment for direct photography in the SNS transfer bay has been prepared and awaits installation. A long video borescope probe with radiation damage resistant light fibers and tip articulation capability has been procured for the purpose of providing better examinations of target interiors. Both direct photography of the disk specimens and examination of the target interior surfaces with the video borescope are planned for Target #2 in the spring of 2011.

The damaged surfaces shown in Fig. 1 are from the innermost disks removed from the centers of Targets #1 and #2. The severe

damage erosion pattern seen in 1A shows a profile that seems to correlate with beam profile, i.e., the horizontal ellipse. Superposed on this is a long vertical line of damage terminated in horizontal features. The vertical line might correlate with the local mercury flow field. At target center the two bulk supply flows meet and something of a vertical stagnation region exists. This does not explain the horizontal patches at both ends of the vertical line. Both the horizontal and vertical damage features might be the result of pressure wave focusing, or, some added vulnerability due to stresses. In any case, since the nominal beam profile for SNS has a width of 200 mm (height is 70 mm), it would uniformly extend across both the center cut and most of the offset cut in the horizontal direction. It is recognized that the beam profile varied considerably from nominal during the life of Target #1. Precise beam profile data from the target imaging system [54] was not available until Target #2 after accelerator operations had considerably matured.

Specimens were also cut offset from center. In the case of Target #1 the erosion damage on the offset location was minimal. This dramatic difference in damage between the center and offset locations seemed to correlate with local flow velocity, with flow mitigating damage. However, damage observed on the offset specimen in Target #2 was severe. There is evidence of multiple through holes in that offset piece, although damage diminishes somewhat moving further from target center. The damage pattern in Target #2 correlates more closely with the nominal SNS beam profile and the correlation of damage to local flow velocity seen in Target #1 was not seen on Target #2 specimens. The different power histories and incident beam profiles must be considered in judging this.

Both of the Target #2 inner wall specimens were found broken when removed from the annular cutters. It is believed that fracture occurred during cutting operations but this cannot be confirmed. There are indications in Target #2 of the same unusual vertical and horizontal damage lines seen in the center specimen of Target #1. Target #2 specimens have not been cleaned at the time of publication, so mercury and other contaminants may be concealing damage. Such was the case with Target #1 specimens prior to cleaning.

Finally, the channel facing surfaces from both targets at both locations show remarkably little damage. There are a small number of elongated pits on Target #1 specimen surfaces oriented in the direction of flow. But these pits are isolated and did not progress into erosion on those surfaces. PIE and damage observations are covered in more detail by McClintock [these proceedings, 12].

5. Next generation target conceptual design

Conceptual engineering work has started at the SNS to develop target designs incorporating cavitation damage mitigation technologies. Several options are currently in contention. Choices that require the least change to current target and process equipment design are preferred. Installation of any needed equipment into the service bay is best avoided or at least minimized. Fortunately some piping was added to the target carriage prior to commissioning in anticipation of needing gas supplies for mitigation technologies.

Keeping the same bulk mercury flow configuration is most appealing and appears feasible for both gas wall and small gas bubble mitigation. Clearly some kind of surface texturing on the inner surface at the beam window is necessary for partial gas wall coverage across the beam spot. A texture pattern similar to that in Fig. 7 is envisioned but further development and testing is planned. Gas can be routed by way of jumpers from gas supply lines in the carriage through new passages running from the target mounting block and forward to the to the base of the inner window. Connection to small ducts machined in the inner window make the final path to the injection ports. The viability of this approach depends on these assumptions: the beam spot is truly the worst damage location (future PIE could reveal otherwise), that surface texturing/partial gas coverage will be effective long term, and that the beam windows can continue to be cooled by the mercury channel flow.

Small gas bubble generators are simultaneously envisioned in this concept. The so-called transition section of the mercury vessel is well suited to the addition of bubblers in each mercury inlet line. Currently there exist flow orifices in the transition; changing these to toothed inlet orifice bubblers is feasible. Swirl bubblers based on the JAEA design now being tested in MBTL are problematic because of their high pressure loss at required flows. Improved designs are being developed. Results from the next WNR test will help decide what the best option would be for SNS deployment.

Another concept being examined does not use either gas injection technique. Based on the assumption that flow across the inner surface of the inner wall could be sufficiently mitigating, this concept adds a wide jet of mercury flow along the inner wall from bottom to top. This flow would be diverted from the existing window channel flow supply in the transition section; rebalancing of supplies will be needed. An added channel would conduct high speed flow from the transition to near the base of the inner window where it would jet along the surface and mix with bulk flow. CFD studies have begun. A goal is to establish about 2 m/s flow across the surface since this is comparable to channel flow velocity. The feasibility of successfully rebalancing target supply flows is also being studied.

Reconfiguration of the flow to establish bulk sweeping flow across the beam window is a third approach being studied. Sweeping flow could serve for flow mitigation without gas injection. It can also be designed to improve flow conditions for gas walls. Side to side sweeping flow – like the JPARC mercury target – would require some very difficult re-routing of mercury passages within the target module or even more difficult changes to the major supply pipes in the target carriage. Bottom to top sweeping flow is less difficult with respect to re-routing of flow and preliminary thermal analyses are encouraging. Regardless, sweeping flow concept development remains a lower priority for the time being. Hopefully future PIE results from the JPARC target will help determine whether or not a sweeping flow mitigates cavitation-induced damage to the target inner surface.

Either gas mitigation approach will require a helium supply system. Engineering work on a gas recirculation system began recently to identify the needed equipment and an appropriate installation location outside the service bay in the hot off-gas gold amalgamation room. There are unused wall penetrations between this room and the service bay and routing of required gas lines is being laid out. Gas would be drawn from the pump sump to the equipment in the gold amalgamation room; pressurized and metered gas lines return to the service bay and then connect to lines in the target carriage.

Further experimentation is expected using the TTF to refine next generation design target features, validate gas wall coverage and SGB populations under full-scale prototypic conditions, and demonstrate a functional gas supply and recirculation system. Specific plans await the results from the WNR experiment and progress in the engineering design studies.

6. Discussion

The extensive cavitation damage observed on both targets' inner mercury vessel windows was confirmation the phenomenon was real and significant. The fact that the targets functioned

without leaking mercury was a relief that worst case scenarios of very short target life were not realized. Indeed, Target #2 operated at some 2300 h at or above 700 kW. What can be seen of the mercury vessel containment wall has revealed little pitting damage.

The R&D program for cavitation damage mitigation is at somewhat of a crossroad. Understanding of the phenomena in the mercury target has greatly improved and credible options for damage mitigation are close to being ready for deployment. Uncertainties remain; there are a number of remaining studies and experiments to complete. However, limitations in what can be simulated or tested experimentally are such that the only way to test some concepts is to try them in SNS when – or if – they are needed. R&D is set to continue but at a reduced funding level. Emphasis is shifting to PIE and conceptual engineering for the next generation targets.

As accelerator beam power is increased cavitation damage is expected to become more aggressive. As currently configured the SNS accelerator is capable of 1.4 MW. A project to increase proton energy from 1.0 to 1.3 GeV has been approved; related improvements can bring beam power capability to more than 2 MW. Whether cavitation becomes the life limiting mechanism for the target remains to be seen.

7. Summary

Recent progress in R&D for cavitation damage mitigation for the SNS target has been reviewed, covering developments in protective gas walls, small gas bubbles, in-beam and off-line experimentation, and PIE. PIE observations from Targets #1 and #2 showed significant cavitation damage but target lives were not shortened because of it. Experiments and PIE have provided evidence that the narrow channel feature of the SNS design is not the most damage vulnerable region making a channel design change unnecessary. The gas wall approach has shown good mitigation performance under low cycle in-beam tests with surface texturing, which makes keeping the existing bulk mercury flow arrangement feasible. Small gas bubble generation and diagnostics have improved significantly and a new in-beam test campaign to demonstrate damage mitigation is being readied for irradiation in 2011. Conceptual engineering has begun for next generation SNS targets incorporating both gas wall and small gas bubble mitigation technologies.

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