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SNS target tests at the LANSCE-WNR in 2001 – Part I ☆

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Abstract

Testing of mercury filled targets in an 800 MeV proton beam was conducted at the Los Alamos Neutron Science Center-Weapons Neutron Research (LANSCE-WNR) facility on two occasions in 2001. The objective for the first test campaign was to investigate if target vessel cavitation damage could occur under transient pressure conditions much like the Spallation Neutron Source (SNS) target. Such an investigation was inspired after mechanical tests conducted by a Japan Atomic Energy Research Institute (JAERI/KEK) team revealed cavitation pitting in a mercury container having comparable pressure wave intensity. The first WNR test confirmed cavitation damage with 200 proton pulses on each of two test targets. As a result, concerns arose that the lifetime of the SNS target could be seriously limited. A second test campaign was then prepared and conducted to investigate if alternate target materials or geometries could reduce or eliminate the damage. Tested materials included Stellite, Nitronic-60 as well as 316LN stainless steel (the baseline SNS target material) that was cold worked and surface hardened. Theories that the original test target geometry caused the damage were checked with tests using thick beam windows and a target with a non-axisymmetric shape. This paper describes the test program and covers target preparation, irradiation conditions, post-test decontamination and an overview of the examinations performed. J.D. Hunn covers the detailed description of the metallurgical examinations in another paper here at IWSMT-5.

1. Introduction

In November 2000, Japan Atomic Energy Research Institute (JAERI) researchers presented observations from Split Hopkinson Pressure Bar (SHPB) tests [1] where they had modified the apparatus to measure the wave speed through a volume of mercury. Their test conditions sent impact pressure waves of either 40 or 80 MPa in magnitude. Upon examining the ends of the impact bars and the inside of the test cylinder, considerable evidence of pitting damage to these surfaces was apparent; an example is shown in Fig. 1. In fact, pitting damage was seen with test conditions of only a single impact at 40 MPa impact pressure.

This pressure magnitude (compression in the mercury) is what is expected in the Spallation Neutron Source (SNS) mercury target at the instant of each proton pulse under full-power operating conditions (1.4 MW in the target; time averaged for the 60 Hz pulse rate). Although there are certainly differences how a mercury spallation target is loaded and responds to initial pressure compared to an SHPB, the similarities in magnitude and rise time for the JAERI findings were of sufficient concern for SNS to investigate the possibility for target vessel damage.

The SNS mercury target design features a two-layer beam window that provides for a well-defined high-speed flow region that assures cooling (Fig. 2). Even so, each layer is only 1.25 mm thick to keep maximum window temperatures low. Another design consideration is radiation hardening of the target vessel over its operating lifetime. The preferred material is 316LN stainless steel, which has an extensive irradiated material properties database. The design and operating concept is

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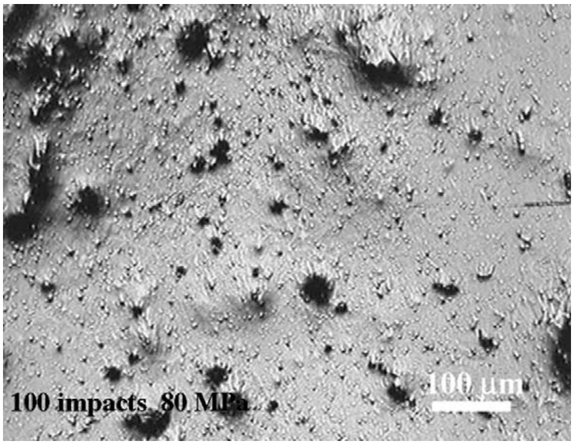

Fig. 1. Pitting damage on impact bar of SHPB with mercury test volume, by Futakawa et al. [1].

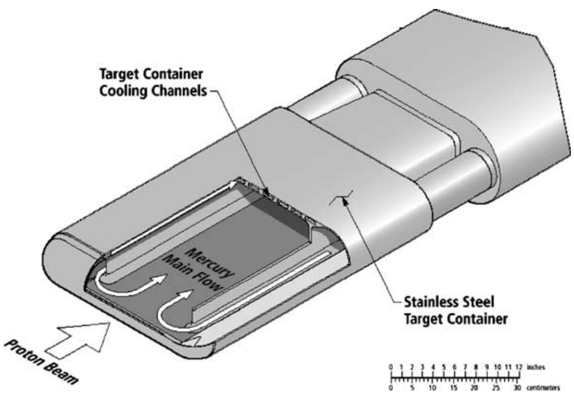

Fig. 2. SNS target configuration.

to limit radiation damage to 5 dpa, where this material still has a considerable elongation to failure. This amount of damage corresponds to about 270 million beam pulses. Consequently, the target module is a replaceable component and the facility will handle target change outs appropriately in about 1 week's time.

The pits seen in the JAERI SHPB tests varied in diameter from a few to tens of microns in diameter; some of the depths measured were ~10 μm, as well. In the hypothetical case where depth damage accumulated linearly with each successive pulse, such damage would quickly break through the SNS target window for pulsing at 60 Hz.

Considering the above, an experiment was planned for pulsed proton beam irradiation of mercury targets in order to confirm or refute cavitation damage under more realistic conditions. This paper describes the experiments conducted by the SNS target group in 2001. The first experiment demonstrated that cavitation damage can occur under conditions relevant to the SNS. A second experiment was conducted later in 2001 to explore what target vessel materials and or features might lead to prevention of damage.

Only high-level damage observations will be presented herein. Part II of this paper describes the extent of damage in more detail with emphasis from a metallurgical perspective.

2. July 2001 test – Verification of damage

After the announcement of the JAERI results, verification of cavitation damage in a mercury target under proton irradiation comparable to the SNS was required in short order. The SNS target group had previously conducted mercury target tests at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) facility to investigate dynamic strain on target vessels. It was decided to employ one type of the strain test targets for the cavitation damage testing at the WNR. These were simple cylinders with flat end flanges that were machined to have thin windows resulting in large strains. Large strains had made interpretation of experiments easier, and this type target was appropriately dubbed Large Effects (LE). While the machined window thickness was comparable to the SNS target, SNS window strains are lower due to its curvature.

As shown in Table 1, WNR beam conditions compare favorably to the SNS in terms of proton energy, deposited energy density, initial pressure rise and pulse length. A proposal made to the LANSCE user office was accepted and tests were scheduled for two days in July.

One design change incorporated into the LE target for the cavitation tests was to have the mercury wetted side of the flange completely flat. Because cavitation damage would likely be small and difficult to identify, careful polishing of the flange surface was required

Table 1
WNR beam parameters for cavitation damage tests

	SNS (@ 2 MW)	WNR
Proton energy [GeV]	1	0.8
Protons per pulse	2×10^{14}	2.8×10^{13}
Beam size [mm]	Elliptic ~70 × 200	Circular $\sigma \sim 10$
Pulse time [μs]	0.7	0.3
Energy deposited in mercury target [kJ]	20	2.2
Maximum energy deposition density [MJ/m^3]	13	19

along with pre-test inspection. The flat surface was required for polishing.

A sketch of a cavitation LE target is shown in Fig. 3. The front beam window thickness and diameter were 1.2 and 89 mm, while for the rear these were 0.9 and 64 mm. Fig. 4 shows one of the targets in preparation. The view shows the rear flange of the target with one of the drain/fill valves in place. Just visible are fiber optic strain sensor on the flange and thermocouples on the target body. The target rests on a wood and Styrofoam stand that was also used during irradiation. Prior to irradiation the target was placed inside a thin steel secondary container that would contain the mercury in the event of a leak. Filled volume was more than 2 l. Not shown in the photograph is the length of Teflon tubing that was connected during irradiation to the valve labeled 'VT2'. This tubing was capped but not filled; it provided expansion space as the mercury gradually heated up over a significant number of pulses.

The target bodies were standard vacuum system components made of type 304 stainless steel. However, flanges were made from the SNS target material: type 316LN stainless steel. After machining and polishing, these test flanges were fully annealed. This softest condition would approximate damage vulnerable locations near target weld zones. Given the limited number of pulses possible for testing it was also felt that annealing the flanges would be more revealing, as far as determining if cavitation damage was possible at all.

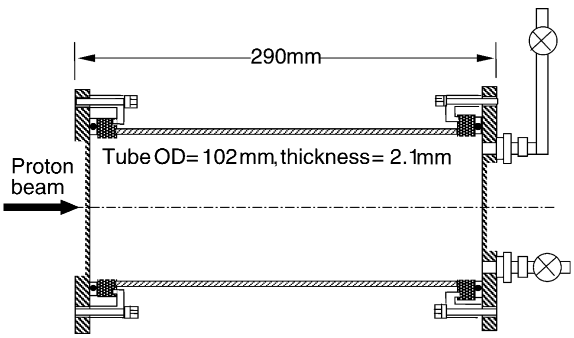

Fig. 3. Large effects target design used in July 2001 WNR tests.

Two targets were prepared for the July test. Designated LE3 and LE4, they were identical with one exception. After annealing, the rear flange of LE4 was later treated with a surface hardening process called 'Kolsterising', a proprietary low temperature carbon diffusion process [2]. The process increases surface hardness up to 1100 Hv over a depth of roughly 30 μm. Note that annealed surface hardness was approximately 140 Hv.

Targets were vacuum checked before filling with mercury. In addition, an attempt was made to saturate mercury with helium in order to be closer to SNS conditions where a nominal 3×10^5 Pa helium cover gas will be maintained. At the WNR the supply mercury was held under vacuum for about an hour, followed by application of approximately 0.3×10^5 Pa helium. The saturated mercury was then gravity fed into the target until mercury just appears in the expansion tube. The target was repeatedly shaken and tapped to assure complete filling. This work was done using a purpose built mercury reservoir system that greatly reduced the mercury vapor hazard and incorporated an activated carbon vapor filter. The reservoir system is shown in Fig. 5.

Irradiation was done in the 'Blue Room' at the WNR. Fig. 6 shows a view inside the Blue Room with a target inside its secondary container, positioned for test. Connections for the fiber optic strain gauges and thermocouples were made and the target was aligned with beam line. A laser was used to simulate the beam axis as

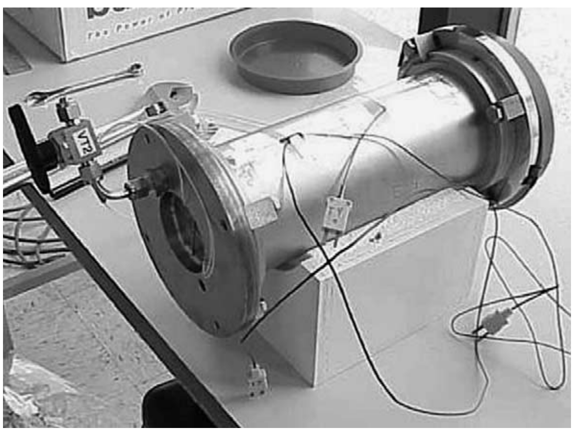

Fig. 4. LE target being prepared for test. Beam will enter from right.

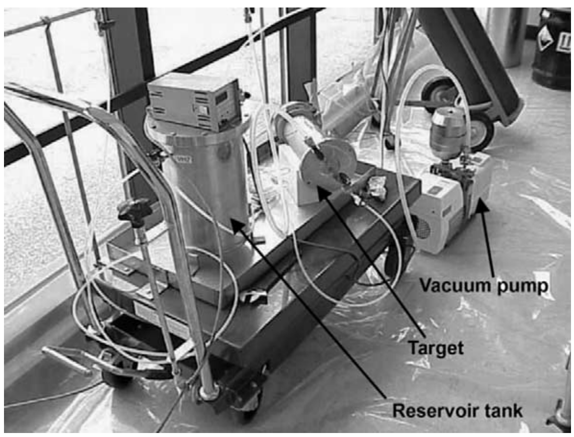

Fig. 5. Mercury reservoir and target ready for filling.

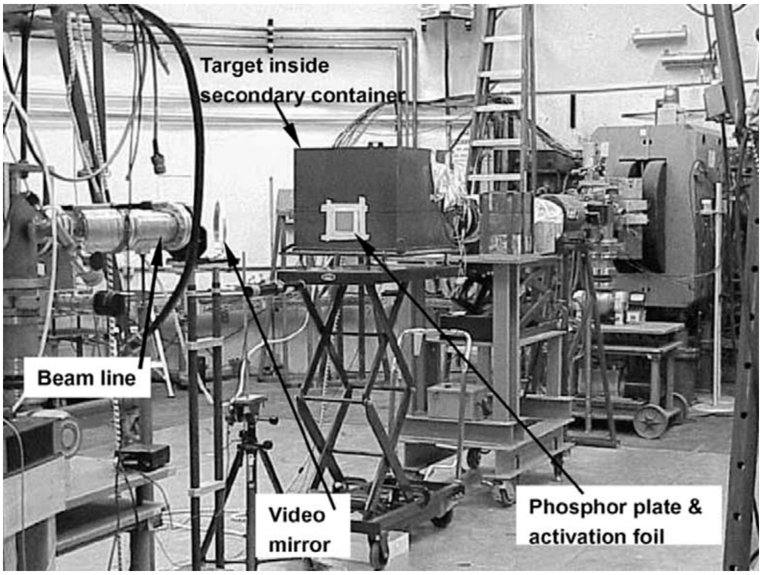

Fig. 6. Test setup inside WNR Blue Room.

target placement was adjusted. Notice in Fig. 6 a phosphor plate on the outside of the container; this phosphor was marked and located on the target axis. During beam pulses the location and shape of the beam on the phosphor plate was monitored by video camera and fine beam adjustments were made by accelerator control. Proton current was measured using a current transformer located between the beam line and the video mirror. In addition to the phosphor plate a thin copper activation foil was placed in alignment with the target and was used as a post-test tool to assess average beam location and total fluence on target.

The Blue Room of the WNR is more typically used for experiments requiring frequent personnel access and not usually for high fluence experiments. Our experiment would be limited to 200 pulses on each target. Once a few initial pulses were applied and satisfactory beam location and shape achieved, pulses were applied at a rate of 1 per min. Strain data was captured for a limited number of pulses while target temperatures were continuously monitored. Maximum target temperature during test was below 50 °C, having started at slightly over 30 °C.

Target LE3 was irradiated on the first day of testing. Two hundred pulses were applied to the target in approximately 9 h time. For the most part pulses were applied a rate of one per minute. There were several interruptions, mostly to monitor activation in the Blue Room.

Prior to the tests a tool was developed to estimate target activation considering the number and timing of beam pulses [3]. A log of each pulse was kept and used to update the estimate in near real time. Fig. 7 shows curves of activation dose at several distances from the target using this tool. During some interruptions during the course of irradiations, LANSCE radiological technicians measured activation near the target. The estimated curve for dose at the secondary container was made using the measurements and scaling the on target contact estimate. The scale factor is consistent with the actual distance from container wall to the target, which is somewhat less than 0.3 m. The decay over more than 40 h was predicted well.

When dose rates off of LE3 had diminished after a few hours, strain and temperature instruments were disconnected and the target moved off to the side in the Blue Room. The LE4 target was then placed in position and irradiation began five hours after LE3. Pulses were again taken at a rate of one per minute; 200 pulses were reached in three periods. The elapsed time to irradiate LE4 was approximately 12 h. Afterwards both targets were moved to a basement storage area. Although checks were made for mercury vapor (none was found), no visual inspection of the targets was made at this time.

The targets remained in storage at the WNR for about one month, at which time the mercury was carefully drained and the targets packaged for shipment back to Oak Ridge National Laboratory (ORNL).

All cavitation damage inspection work was done at ORNL. Before any detailed inspection could begin, a thorough decontamination of the components was performed. The requirements were that removable contamination levels, assessed by standard radiological control swipes, be below 1000 disintegrations per minute (dpm) per 100 cm^2. Further, each component must not have any residual mercury. Each piece was bagged for

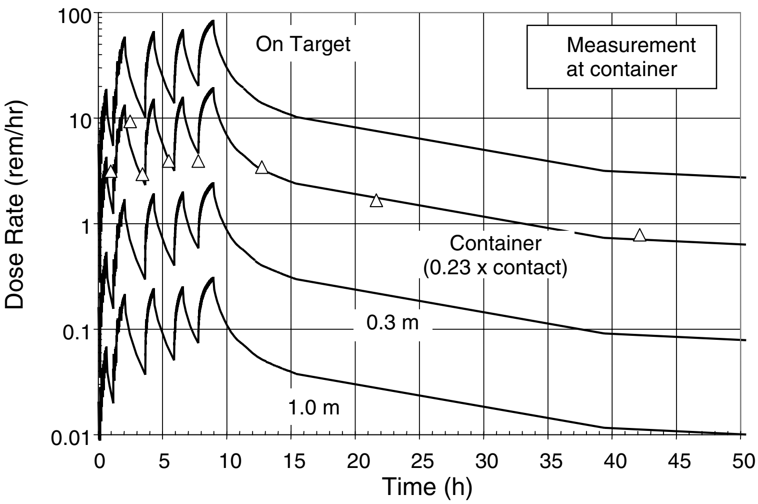

Fig. 7. Activation dose vs. time at several distances from target. Curves indicate prediction; Δ shows measure values.

some time and the air sampled with a mercury vapor detector. Qualified safety personnel perform all checks. The decontamination work required working in a vented laboratory area under appropriate radiological and hazard control procedures.

The flanges were first removed from LE3, and immediately evidence of damage could be seen by eye. Fig. 8 is a photograph of the rear flange with a damaged area circled near the center of the flange (the center is marked by a scribed 'X'). The damage area is a cluster of pits and dents about 4 mm in diameter located about 4 mm below (as oriented during irradiation) the center. Fig. 9 shows the front flange of LE3 after some initial cleaning. Here there is a cluster of pits roughly 5×3 mm in size located about 9 mm below the center. Closer to the center is another cluster more oblong in shape. The uniform circle seen at a larger radius in Fig. 9 is an artifact of flange machining.

Successful decontamination took a considerable amount of time. The optimum procedures were not known and passing the mercury check was more difficult than expected. A combination of ultrasonic washes in acetone and isopropanol, along with manual wiping and mild baking in a vacuum oven were used. Some residue in flange grooves was particularly hard to remove and highly activated. For some components, it was easier to simply epoxy this residue in place to keep it fixed. Lessons learned in the decontamination process were applied in the next test.

Eventually all test pieces were cleaned and detailed examinations began. These included microscopy with optical and scanning electron microscopes, pit

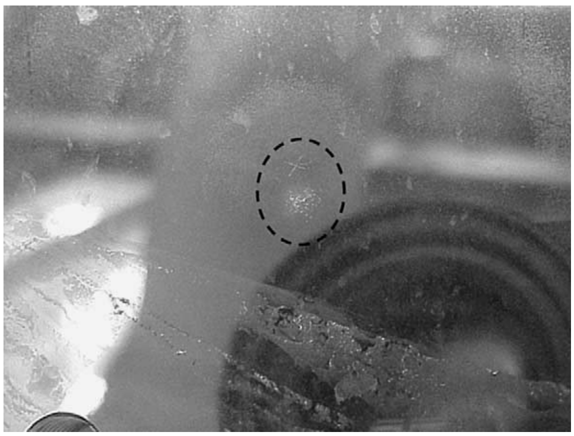

Fig. 8. Visible damage on the rear flange of the LE3 target, before cleaning.

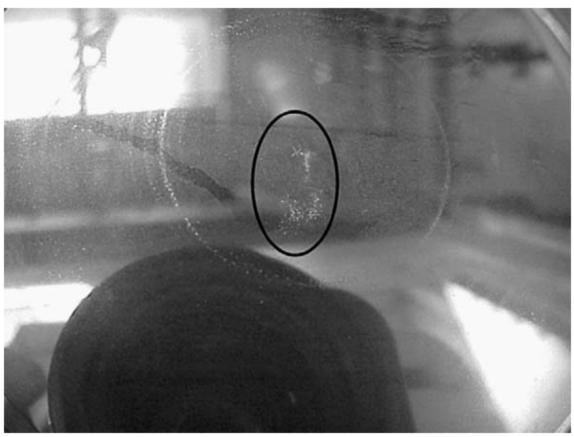

Fig. 9. Damage near the center of the front flange of LE3.

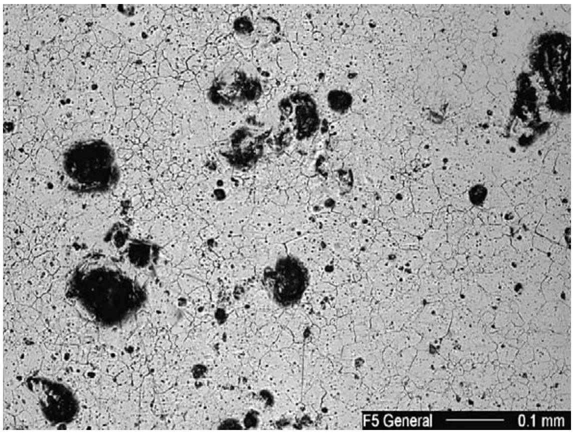

Fig. 10. Optical microscope image of damage on front flange of LE3.

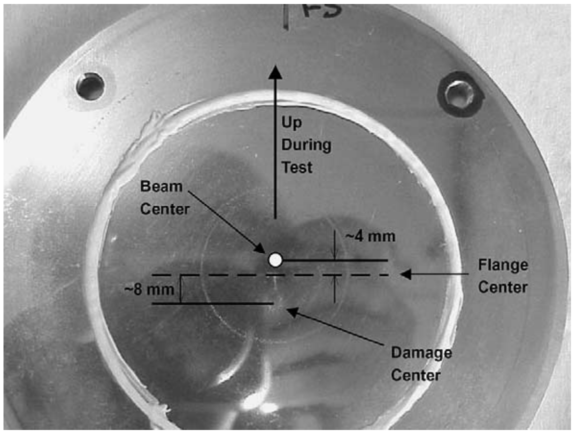

Fig. 11. Location of average beam center on front flange of LE3, as determined by activation survey.

characterization with a laser profilometer and activation surveys. Part II presents the microscopy in detail. An early optical micrograph of the front flange from LE3 is shown in Fig. 10. This region is within the large cluster shown in Fig. 9, and the largest pits are more than 100 μm across. Smaller pits are evident as well. Further, damage was not limited to the visible clusters. Examinations away from the center of the flanges showed numerous small pits; at 40 mm away many pits a few μm across could be found on this and the other annealed flanges.

When compared to pits seen in the JAERI SHPB test (Fig. 1), the size and shape of these pits were found to be generally similar. This would seem to confirm, at least roughly, similar mercury pressure conditions and interaction with target walls.

Some of the pit sizes and depths were measured using a laser profilometer. The largest pits found were 200 μm across and 70 μm deep. The depth is alarming as it is a substantial fraction of the SNS target window minimum thickness, and occurred with only 200 pulses. Survival of the SNS target window to 200 million pulses seems unlikely under full-power conditions if this damage is truly prototypic.

Activation surveys of the front flanges were done to determine the location of the average beam center. The alignment procedure used at the WNR has limitations and could have been off by several millimeters. The surveys indicated an offset of the beam for both LE3 and LE4, an example of which is shown in Fig. 11. For both targets the beam was 4 or 5 mm directly above the geometric center. Further, the large damage clusters on both front flanges were located below the centers by roughly twice that distance. Although activation surveys were not done on the rear flanges (beam intensity was less than 10% than at the front), damage clusters on both rear flanges were below center.

The rear flange on LE4 generally looked better than the annealed pieces. This was the flange that was Kolsterised after annealing. There was a damage cluster 2 or 3 mm across and a few mm below the center. However, outside this area there were no large pits and very few small ones. The harder surface showed a significant resistance to damage for 200 pulses, but it was not immune.

A summary of the major findings of the July tests can be made:

- All flange surfaces had large, visible pit clusters. These clusters were located near, but a few mm below the geometric centers.
- It was determined that the beam entered above center on both targets at roughly half this distance.
- The sizes of the damage clusters on the rear flanges were less than on the front, but the smaller sizes were not in proportion to the proton beam intensity. In fact, beam intensity at the rear flange surface was less than 10% of its value at the front.
- Evidence of damage could be found generally over all of the annealed surfaces using optical microscopes and SEM. Although the size and density of pits varied over these surfaces, they could be found far from the center.
- The hardened surface did notably better as very little damage could be found aside from the 2 mm pit cluster. Damage within the cluster was more comparable to the annealed surface damage clusters.

Much like previous experiments with LE targets, measured strains on the thin flanges were quite large. An example of strain data is shown in Fig. 12 from the LE4 target front flange; rear strains were similar. These are in the plastic regime for annealed stainless steel. Such large strains would not be prototypic of the SNS target.

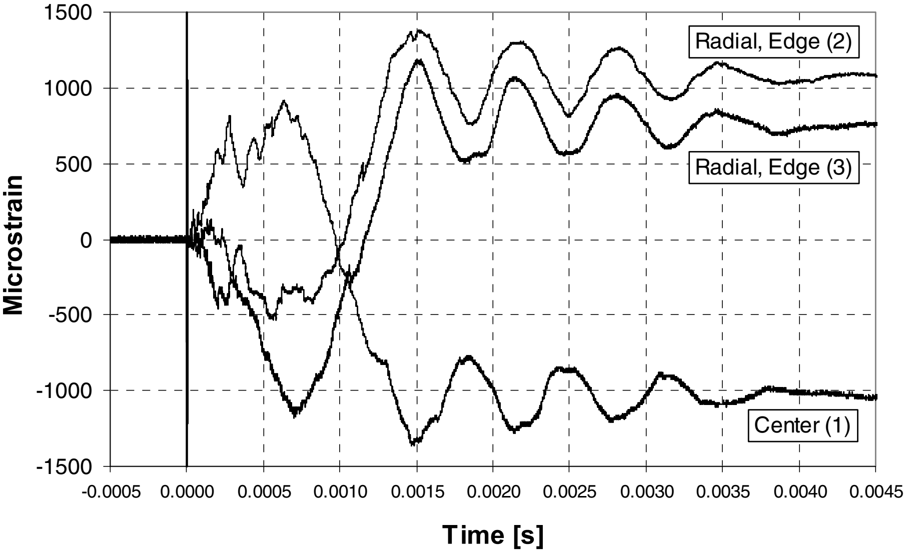

Fig. 12. Strain from front flange of target LE4, Pulse #58.

3. December 2001 test – Geometry and material effects

The results from the July test raised several questions:

- Was the cylindrical geometry somehow focusing rarefaction waves off the walls leading to a region of intense cavitation near the target axis?
- Could harder or 'cavitation damage resistant' materials perform better than annealed 316 stainless steel?
- Did the large strains make the surface more vulnerable to damage?
- Did the large motion or velocity of the center of the flange contribute to the damage?

There was an opportunity to perform another test in 2001 at the WNR before LANSCE would be put on an extended maintenance program at the end of calendar year. This left little time to prepare. There was considerable interest in answering some of the questions from July, on top of showing a new result that might indicate a direction to pursue for mitigating the damage. A test plan was made that adopted an aggressive approach to finding a direction, perhaps at the expense of being completely methodical. There are few opportunities to conduct these tests.

The test matrix for the December test is given in Table 2. Most of the targets used thick flanges to have reduced strains and flange motion. LE5 used Kolsterising on thick 316SS on the front that was cold worked by 50%, thus providing a harder base material under the treated surface. The rear was thick 316SS but annealed; by comparison to July test results this condition addressed the large strain question. Target LE6 used wrought Stellite (front) and Nitronic 60 (rear, cold worked 20%), alloys both known to be more cavitation damage resistant in conventional water applications. In fact, Stellite is top ranked for damage resistance and represented an extreme for changing the bulk material [4]. The front end of the LE7 target was a compromise for what was desired to be a hemisphere. The concept was to move the window surface away from the region where waves coming off the cylinder wall would converge. A frustum of a cone presents a surface that is easier to polish and inspect than a hemisphere.

The target called RECT1 avoided cylindrical geometry entirely, and it also incorporated a double-walled beam window to include a narrow space of mercury in similar fashion to the SNS target design. This target used thick, cold worked Nitronic 60 for all test surfaces.

Targets LE8 and CROSS1 attempted to find out if useful beam test results could be obtained from fewer pulses. Both of these targets used thin test flange pieces. Further, CROSS1 looked at increasing the usable surfaces for a test. In the end, neither of these was successful.

LANSCE researchers working on lead bismuth targets for accelerator applications requested to collaborate on this experiment. The PB1 target was an LE type target with thin flange ends and was prepared with heating tape, insulation, and a heat tolerant expansion/fill reservoir.

Testing proceeded in much the same manner as for the July test. LANSCE operations gave special approval to provide pulses at a rate of 2 per minute, which helped save considerable time. In each of the four test days

Table 2
Test target matrix for December 2001

Target ID	Target type/description	No. of beam pulses	Front flange material/ configuration	Rear flange material/ configuration
LE5	LE with **thick** flanges	200	316SS CW & Kolsterized	Annealed 316SS
LE6	LE with **thick** flanges	200	Stellite	Nitronic 60 – CW
LE7	LE with conical, **thick** front; **thin** rear	100	Cone with **thick** flat, 316SS annealed	316SS annealed, **thin**
RECT1	Rectangular body (75 × 125 mm), **thick** flanges, dual front window	200	Nitronic 60 CW (inner window: Nitronic CW)	Nitronic 60 CW
LE8	LE with **thin** flanges	20	316SS annealed & Kolsterized	316SS annealed
CROSS1	6-way vacuum fitting w/ring flanges and disk diaphragms	20	316SS annealed, **thin** disks five locations	Annealed nickel conflat seal
PB1	Lead Bismuth target, LE with **thin** wall flanges	200	316SS annealed, **thin**	316SS annealed, thin

Note: CW = Cold worked. All Nitronic 60 material was 20% CW; LE5 front flange was 50% CW.

provided, two targets were irradiated. A day's session would begin with irradiation with one of the 20 pulse targets, or with 50 pulses on target LE7. With relatively low activation, these could be moved aside quickly and one of the 200 pulse targets put in place. The 200 pulse targets were left in place until the next day to allow for more decay time. LE7 was irradiated over two days for a total of 100 pulses.

Temperatures were monitored during irradiation. Maximum temperatures in the mercury targets were below 80 °C, having started around 25 °C. The lead bismuth target began irradiation at 150 °C and increased to about 175 °C during its 100-minute test.

Sound recordings were made using a high quality audio microphone with pre-amplification and a digital sound recorder. An assessment of sound intensity was made after returning to Oak Ridge. Fig. 13 shows a segment of a recording taken from a pulse on LE7. The microphone was inside the secondary container roughly 10 cm from the target body. There is an indication that the recording equipment was clipping the sound for some initial period. Nevertheless, the maximum sound pressure level is 6 Pa, corresponding to 109 db, indicating a substantially loud sound. One could infer the actual maximum might be 10 Pa or 114 db.

Decontamination work began in late February 2002. Lessons learned during the decontamination work from the July test helped expedite the cleaning process significantly. A sequence of ultrasonic baths in a mercury-active cleaning solution (HgX), a water-based detergent (Branson IS), and Branson Oxide Remover, followed by washing with isopropanol was very effective. No heating was employed. Nineteen pieces were cleaned for inspection in about the same time it took to clean four flanges from the July test. A few of the 19 required an additional cleaning step with acetone.

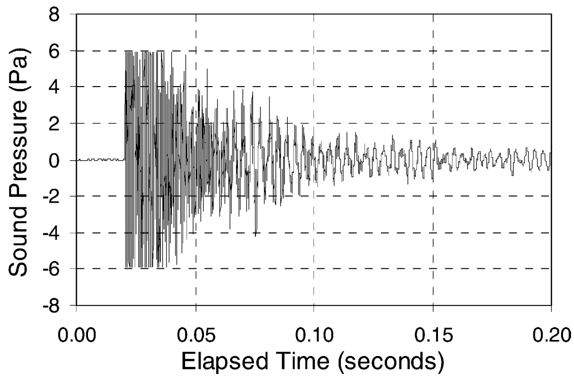

Fig. 13. LE7 Track4 sound pressure waveform.

A summary of damage visible with the unaided eye is given in Table 3. Damage was found on all 200-pulse cylindrical target surfaces except the Kolsterised front flange of LE5. The Stellite flange (LE6 front) had a prominent cluster of large pits. Examination by SEM showed pit size ranging from 150 to 200 μm across. Unlike other test pieces there was not a distribution of pit sizes down to the few m level. The Nitronic 60 flange (LE6 rear) also had visible damage, and an assessment of the damage area indicated four times worse damage than the annealed 316SS flange on LE5. This result is difficult to understand in view of Nitronic's superior cavitation damage resistance over 300 series austenitic

Table 3
Visible damage summary for cylindrical targets

Target/Mat.	No. of pulses	Front flange material/ thick or thin	Visible pits?	Rear flange material/thick or thin	Visible pits?
LE6/Hg	200	Stellite 6B/thick	Yes	Nitronic 60–20% CW/thick	Yes
LE5/Hg	200	Kolsterised 316SS – 50% CW/ thick	No	316SS – annealed/thick	Yes
LE 4/Hg[a]	200	316SS – annealed/thin	Yes	Kolsterised 316SS – annealed/ thin	Yes
LE8/Hg	20	Kolsterised 316SS – annealed/ thin	No	316SS – annealed/thin	No
PB1/Pb-Bi	200	316SS – annealed/thin	Yes	316SS – annealed/thin	Yes

Note: Visible pits means visible by unaided eye.
[a] From July 2001 test.

steels in research done for water cavitation erosion. Results from the LE4 target (July test) are included in Table 3 to highlight the observed damage on its thin, annealed and Kolsterised rear flange.

Taken together, the main point of these cylindrical mercury target results are that the combination of small strain, stronger/harder substrate, and hard surface treatment eliminated all pits for 200 pulses. A serious question remains as to how well this combination would hold up a prototypic number of pulses, i.e., 200 million. If the surface treatment should eventually fail, the substrate would be unprotected. Optimistically, one could hope the irradiation hardening would provide improved damage resistance by that time. This remains to be demonstrated.

The rectangular target results were interesting as well. Fig. 14 is helpful in identifying surface locations, with surface 1 being closest to the beam and surface 4 furthest away. Large visible damage clusters were found on surfaces 1 and 2, while no visible damage was found on surfaces 3 and 4. SEM examination has identified only a few small pits on surfaces 3 and 4. This might suggest the rectangular geometry avoided the radial focusing that enhances cavitation conditions in the cylindrical targets. But how was the damage on surfaces 1 and 2 caused? One theory is that the acoustic impedance mismatch at the air/steel interface causes rarefaction that propagates back into the first mercury layer thus leading to cavitation. The rarefaction is reduced as it travels through the intermediate window towards the bulk mercury region, or the thin cavitating mercury layer attenuates the rarefaction. Conclusions are difficult to draw at this point. If the thin mercury layer were not present, would surface 3 be damaged in a rectangular geometry? Or if the thin mercury layer were replaced by water, could damage be entirely avoided? These questions are to be addressed in 2002 target tests.

The lead bismuth target showed visible damage on both front and rear flanges. During testing, strain measurements were indicating maximum levels roughly 20% that of comparable mercury target tests. This was puzzling since the difference in material properties would indicate the lead bismuth strains should be about 70% that of a mercury filled target. It was surmised at the time, and verified by later examination of the solidified target, that the target was not completely filled. Using the measured void of the opened, frozen target, and accounting for the contraction from the temperature change and solidification, is it estimated the void space during test was 1% of the target volume. This may be the cause of the lower strains, but conditions still led to visible cavitation damage.

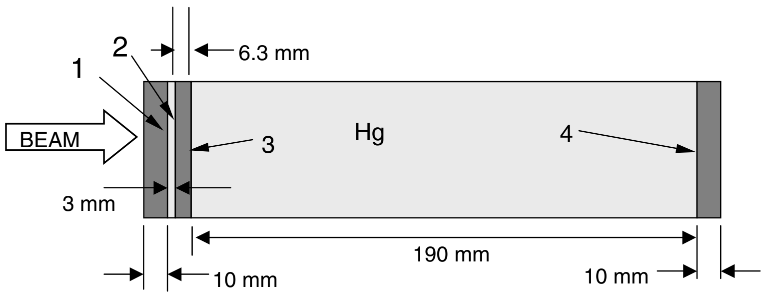

Fig. 14. RECT1 target surface locations.

Activation foils placed directly on the targets for the December tests provide another piece of information. Analyses locating the actual (average) beam centers have been done on the foils for targets LE5, LE6, RECT1 and PB1. For LE5, LE6 and RECT1, which have thick flange components, the large damage clusters were located coincident with the beam centers. For PB1, which had thin flanges, the large damage clusters were opposite the beam center location, i.e., across the geometric center. This result was similar to the thin flange targets tested in July.

The coincident beam-damage locations observed on the thick flange targets is consistent with the concept of an acoustic mechanism leading to damage. It is less clear what the thin flange results with opposite beam-damage locations suggest. Perhaps the compliant thin boundary somehow mitigates the acoustic effect, but another mechanism(s) then comes into significance. Damage opposite the beam location is consistent with a radial reflection/focusing effect off of the cylindrical target walls. In fact, the Stellite flange did have a faint cluster opposite the dominant cluster (and beam location). But an alternate theory might be that the thin flanges undergo an asymmetric deformation that leads to cavitation damage opposite the beam location.

4. Summary

Two important experimental test campaigns were conducted in 2001 by the SNS Target Systems group. Using the 800 MeV proton beam at the LANSCE – WNR test facility at the Los Alamos National Laboratory, a series of mercury filled test targets were irradiated under proton intensity conditions relevant to SNS operation for a limited number of pulses. The first of these test campaigns verified that cavitation damage could be caused by the proton induced pressure conditions, and that the damage could severely limit the lifetime of the SNS target if extrapolation to a relevant number of pulses were unfavorable. The second test investigated both target material and geometry issues as a first step in finding directions to pursue for finding a solution to this cavitation damage.

Several key findings should be noted. The use of Stellite, a material highly ranked for damage resistance in water cavitation research, failed to prevent damage. Although Stellite is not suitable for the SNS target for various reasons, the failure of this extreme material case indicates the problem is not likely to be solved solely by change of the SNS target vessel material.

A test component of thick, cold-worked 316LN type stainless steel with its surface hardened by the Kolsterising process showed no damage after 200 WNR pulses. Another Kolsterised test component made of thin, annealed 316LN steel showed some damage, but considerably less than comparable untreated pieces. It is not clear which of the differences, base material condition or thickness, mechanical strain or deformation, account for the observed difference in damage. Regardless, a serious question remains how well the treatment will survive under prolonged irradiation (several dpa).

Target geometry does have an effect on observed damage. The results have led to some insight into the mechanisms leading to cavitation damage conditions. Some of the mechanisms under consideration include acoustic wave theory and wave focusing effects of the geometry. Nevertheless, a thorough understanding is not in hand and will take substantial effort to achieve. Unfortunately, the time and cost of such experiments limit the opportunities to study the impact of these features.

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