THERMAL-SHOCK ASSESSMENTS FOR NATIONAL SPALLATION NEUTRON SOURCE TARGET SYSTEM

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ABSTRACT

A perspective overview is provided on preliminary observations from simulations of thermal shock in the National Spallation Neutron Source (NSNS) at various power levels. Significant damage potential to structures may be present only at high (~ 5-MW) power levels which may require inclusion of mitigative features. The simulation framework being utilized and under development is presented. Focused experiments are being conducted to derive key benchmarking data for the simulation framework as also for timely resolution of key design and operational-safety issues.

INTRODUCTION

The National Spallation Neutron Source (NSNS) is a user facility providing high flux neutron beams for material research, isotope production, etc. The US Department of Energy has designated Oak Ridge National Laboratory (ORNL) to prepare a conceptual design for a next-generation, short-pulse spallation neutron source. This effort is working towards commencement of operation of the NSNS facility in 2004, with a cooperative effort between multi-national laboratories including ORNL, Lawrence Berkely National Laboratory (LBNL), Los Alamos National Laboratory (LANL), Brookhaven National Laboratory (BNL) and Argonne National Laboratory (ANL). General information related to NSNS is provided in a companion paper.[1] This paper concentrates primarily on operational safety-related work dealing with thermal-shock issues.

For spallation neutron sources, powers in the 1 MW range (time-average) are close to current technology limits resulting in the storing of around 1 to 2 x 10^{14} protons in each pulse. Designing targets for these high powers is very difficult. It is generally believed that, the shock loads, radiation damage and heat dissipation requirements on a multi-MW-level target are thought to require designs beyond today's state-of-the-art.

The reference target design of the NSNS incorporates mercury as its reference target material. The mercury target design configuration, shown in Figure 1, has a width of 400 mm, a height of 100 mm, and a length of 650 mm. The mercury is contained within a structure made from 316-type stainless steel. Mercury enters from the back side (the side furthest from the proton beam window) of the target, flows through a 224 mm x 8 mm rectangular passage in the middle of the target to the front surface (proton beam window), and returns along the two side walls. The target window (i.e., portion of the target structure in the direct path of the proton beam) is cooled by mercury which flows through the passage formed between two walls of a duplex structure. In this way, the window cooling and transport of heat deposited in the bulk mercury are achieved with separate flow streams. This approach is judged to be more reliable and efficient (minimal pressure drop and pumping power) than using the bulk mercury to cool the window. Also, the duplex structure used for the window has significant structural advantages that help to sustain other loads. Beside serving as flow guides, the baffle plates used to separate the inlet and outlet flow streams are also important for maintaining the structural stability of the target. A safety container is provided around the mercury target to guide the mercury to a dump tank in the event of a failure of the target container structure. The safety container is a water-cooled duplex structure made from austenitic, probably 316-type, stainless steel.

The mercury target and its enclosing structure must be designed to sustain the time-averaged power loads as well as the nearly instantaneous power deposition during single pulse operation. These time-averaged and single pulse loads for a 1-MW design are defined in Table 1. Since about 60% of the proton beam power is deposited in the mercury and balance into the surrounding structures, the thermal-hydraulic system for the target is designed to remove a time-averaged power of 0.6 - 1.2 MW corresponding to proton beam powers of 1 - 2 MW. For a pulse frequency of 60 Hz, the amount of energy deposited in the target during a single pulse is 10 - 20 kJ.

The interaction of the energetic proton beam with the mercury target leads to very high heating rates in the target. Although the resulting temperature rise is relatively small (a few ^{o}C), the rate of temperature rise is enormous (~10^{7} ^{o}C /s) during the very brief beam pulse (~1 μs). The resulting compression of the mercury leads to the production of large amplitude pressure waves in the mercury that interact with the walls of the mercury target, and the bulk flow field. Safety-related operational concerns exist in two main areas, viz., (1) possible target enclosure failure from impact of thermal shocks on the wall due to its direct heating from the proton beam and the loads transferred from the mercury compression waves, and (2) impact of the compression-cum-rarefaction wave-induced effects such as fluid surging and potential cavitation.

This paper describes ongoing and planned experimentation and analyses to establish the feasibility of using a liquid target (mercury) in the intense thermal load environment expected for the NSNS target system.

MODELING AND ANALYSIS FRAMEWORK

The capability to understand and predict the propagation of the pressure pulses in the target (either liquid or solid) is considered to be critical for establishing the feasibility of constructing and safely operating such a device. The CTH code system[2] is being used as a basis for developing the appropriate simulation framework. CTH is a three-dimensional (3-D), shock-physics code, sometimes loosely referred to as a hydrocode. This code and associated technology base have been used extensively to simulate explosive processes (such as molten metal-water vapor explosions, and hydrogen detonation) in enclosed fluid-structure systems.[3-5] It is now being adopted for characterizing the current thermal-shock process in a coupled manner, simultaneously accounting for localized compression pulse generation due to rapid heat deposition, the transport of the compression wave through the mercury, interaction of this wave with the surrounding structure, feedback to the mercury from these structures, and multi-dimensional reflection patterns including rarefaction-induced material fracture (or possible cavitation phenomena in fluids).

Modeling and analysis work are being performed in several areas. Modeling is conducted in a staged manner starting with a simple two-dimensional (2-D) geometry, followed by full-scope 3-D model development.

Initial modeling efforts have examined the effects of rapid heat deposition in an idealized axisymmetric target geometry with only an axially-varying transient heat deposition profile in mercury and steel. 5 MW of axially-varying energy deposition occurs over 0.58 μs. Two dimensional modeling was performed with simple geometry of the cylinder with a hemispherical dome filled with mercury (as shown in Figure 2). Resulting transient pressures in the mercury and principal stresses in the target structure are shown in Figure 3 for selected locations. It should be noted that the negative pressures in mercury shown in Figure 3 at a time of about 35 μs after the pulse imply that the mercury can support a rarefaction process. This result is an artifact of assuming a solid-like equation-of-state (EOS) for mercury (Mie-Gruniesen form)[6] and the presumption that liquid mercury will not cavitate. Developing a more realistic EOS model for mercury in the regime expected in the NSNS target and simulation of more realistic geometry are required to improve our understading and predictive capabilities.

The minimum principle stress shown in Figure 3 for the stainless steel container in the region near the location with peak heating shows several characteristic time scales. The small amplitude, short period (~ 1 μs) variations are associated with the characteristic time scale for transfer of pressure waves through the thickness of the stainless steel structure and resulting "ringing" type effect. The longer time scale variations (tens of microseconds) are due to the transport of pressure waves from the mercury to the container.

The resulting peak tensile stress in the stainless steel structure is found to be about 200 MPa. This is roughly equal to the yield strength of solution annealed 316-type stainless steel. The acceptability of this stress level is not clear, although it is likely too high, and a concern. This stress must be examined in combination with other stresses. The dynamic (short duration) and cyclic (more than 10^8 cycles per month) nature of this stress must be appropriately considered along with the effects of irradiation-induced embrittlement. Similar evaluations conducted for a 1 MW beam power rating revealed tensile stresses in steel which were significantly below yield stress values for steel. At 1 MW, the cyclic stress loads were found to be below allowable fatigue limits as suggested in the well-known ASME Boiler & Pressure Vessel Code. In a high irradiation field, it is known that the materials will show some embrittlement due to gas generation and atomic displacements. The failure mechanism (and therefore life limitation) may then progress due to crack propagation. However, data taken by M. Grossbeck at ORNL indicates little reduction (< 20%) upon irradiation in cyclic stress limits for SS-316.[7]

Based on understanding and experience gained from 2-D simple geometry modeling, three-dimensional (3-D) CTH model has been developed. In this simplified 3-D model, only a quarter of the target has been included assuming symmetry conditions. This model is currently being exercised to obtain more realistic estimates of induced stresses in the liquid and structures, and also for assessing onset of phenomena such as cavitation, flow surging, and flow reversal.

EXPERIMENTATION

The thermal shock test program and related efforts are focused on derivation of key benchmarking and validation data. The program is divided into four major elements including: (1) pressure pulse tests, (2) particle beam experiments, (3) measurement of cavitation threshold of mercury, and (4) thermal shock mitigation tests and analyses. These elements are explained below.

- <u>Pressure Pulse Tests</u>

  Pressure pulse tests are designed as a means to provide benchmark data for the thermal/mechanical models of the CTH code used to predict the transport of pressure waves through mercury. Also demonstrated will be the fluid/structure interaction model to predict the stresses/strains in the structure walls containing mercury. A well characterized elastic wave is generated from a (pneumatically driven piston) projectile striking a target plate that is made of the same material (i.e., steel). For reference, about 1 m/s of projectile velocity produces pressure pulses with ~20 MPa in magnitude which is similar in magnitude to initial pressure levels produced in mercury for a 1 MW NSNS. The other side of the target plate faces mercury contained in a cylinder. The test arrangement is depicted schematically in Figure 4(a).

  Associated, follow-on tests are to be conducted to characterize interaction of the pressure waves in a flowing medium to derive data related to flow surging and reversal. One concern is that mercury flowing at a velocity of 0.6 - 0.8 m/s for a 1 MW design and 3 - 4 m/s (for a 5 MW design) in the NSNS target system may not have enough inertia to overcome high compression/rarefaction pressures resulting from waves generated by rapid deposition of high energy proton beam pulses and magnified by their interaction with bounding target structures. Momentarily (the time span of which is under investigation), mercury may not be able to flow through the target system as designed to carry away the heat generated and to serve as target material to produce spallation neutrons. With 60 Hz of the beam cycle, a proton beam will come into the target every ~16 msec. Unless the mercury flow recovers within this time frame, the target system may experience significant heat-up and reduction in neutron generation. To understand such interaction behavior between the shock and flowing mercury, a test section is being designed to introduce shock waves in a flowing mercury field. Flow reversal and its duration (recovery time) will be characterized as a function of initial shock strength and inertia of flowing mercury. This behavior will be simulated using the CTH code for validation.

- <u>Experiment with particle beam volumetric energy deposition</u>

  In this experiment shown schematically in Figure 4(b), volumetric thermal energy deposition-induced pressure waves are to be used instead of impact-induced pressure waves, to characterize the wave interaction with mercury and the surrounding container walls. These pressure waves will be produced in a similar manner as the pressure waves expected in the NSNS target system. As shown in the figure, this is done by exposing a mercury-filled steel-can to particle beams. The electron beam used for such a test in the Oak Ridge Electron Linear Acceleratory (ORELA) is characterized as 160 MeV, 6 A and 30 nsec of pulse width. The beam diameter is ~1 cm. The electron beam will dissipate its power at 132 MW/cm in mercury (using stopping power of 22 MeV/cm), or ~4 J/cm for each 30 nsec pulse. This experiment is also being utilized to benchmark the relevant design-related modeling framework.

- <u>Measurement of Cavitation Threshold of Mercury</u>

Liquids (like solids) rupture or cavitate when subjected to tension (due to rarefaction waves) in excess of their tensile strength. As may be expected, the thermal hydraulics of flowing mercury could be completely different if such cavitation occurs in the target system. Also cavitation is well known to cause pitting and wearing of target structures as a result of the collapse of bubbles generated due to cavitation near solid surfaces. If it occurs, cavitation damage to structures in mercury can be about 90 times greater than that in water (because of differences in material density, and the surface tension which provides the main driving force for bubble collapse, is much larger in mercury than in water).[8] On the other hand, cavitation bubbles (especially gaseous versus vaporous cavitation bubbles) may act as a significant shock absorbing medium, resulting in reduced shock magnitudes in the target system. Therefore, we need to determine whether cavitation occurs in the NSNS target system, and the associated need to characterize its behavior, if it should occur. This experiment is planned, therefore, aiming to find cavitation thresholds for mercury under various conditions. As shown schematically in Figure 4(c), the test section is fabricated in a diamond shape made of either acrylic or Pyrex tubing filled with mercury to set levels. At the base of this diamond-shaped tube, a motor is attached to spin the apparatus. Liquid level positions before and after potential fracture are depicted in Figure 5(c). Cavitation (fracture) onset is monitored visually and via microphone.

Clean liquids can withstand a surprisingly high tensile stress before a macroscopic bubble forms. Estimates of the intrinsic tensile strength of pure water at room temperature and pressure give values in excess of 150 MPa. However, such a threshold drops to ~1 - 10 MPa in untreated water containing dissolved gas and other contaminants behaving as nucleation sites. Therefore, such a spin test will be conducted not only with relatively pure mercury but also with mercury with well-characterized contaminants in it.

Cavitation can occur in the bulk of the mercury nucleated by radiation under pressures low enough to cause significant tension in the liquid. An energetic proton particle slowing down in the mercury transfers kinetic energy to the mercury molecules. If sufficient heat is deposited in a small enough volume, the mercury vaporizes locally, forming a tiny bubble which provides the nucleation sites that can grow to a macroscopic bubble. When a sufficiently large rarefaction wave comes in, such bubbles can grow. In addition, recoil nuclei also provide nucleation sites for bubble formation. Therefore, tests are also to be conducted via exposing the central bulb region of the apparatus to proton pulses.

Overall data obtained from these focused tests will then be used to refine the EOS for mercury and the modeling framework developed with the CTH code system.

- Thermal Shock Mitigation Tests and Analyses

If the cyclic stresses in the target structure are found to be excessive, techniques to mitigate the effects of thermal shock will be developed. One such approach entails injection of a non-condensable gas (e.g., He) stream into the mercury. Gas bubbles in theory would act as shock absorbers and prevent any significant pressure pulse generation. Details of assessment will have to await recognition of the need for such mitigation, in the first place. Currently, no work is planned in this area.

Instrumentation consists of rapid-response (<< 1μs rise time) PVDF pressure transducers, accelerometers, and optical gages, along with a variety of so-called virtual instruments for high-speed data acquisition developed using the well-known LabView system.

SUMMARY AND CONCLUSION

To summarize, preliminary assessments for thermal shock in the NSNS have indicated the possibility of excessive stress levels in structural components for power levels in the 5-MW range, but not at the 1-MW operating power level. These evaluations have also indicated the possibility of inducing significant tensile stresses in the fluid space. Coupled with the intense radiation environment these negative stress states in the fluid may result in onset of cavitation, which may or may not represent significant damage potential to the surrounding structures (such as pitting, erosion, etc.). Several other areas related to impacts on the fluid field have been identified such as possible flow surging, enhanced mixing, etc.

A simulation framework has been developed which utilizes the CTH code system, along with development of an appropriate EOS for mercury based upon non-equilibrium thermodynamics. A staged approach is being taken wherein key insights are derived via 2-D simulations of wave propagation and mercury-steel interactions, followed by detailed 3-D simulations for actual design support. Bench-marking is to be conducted via comparisons against focused experiments covering cavitation (with and without radiation fields), pressure pulse propagation and fluid-structure interactions using either mechanical impact or direct volumetric energy deposition. The presentation at the conference will highlight recent data obtained in the above-mentioned key areas.

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Table 1. Power loads on the NSNS mercury target

Parameter	Value
Energy of protons (GeV)	1
Pulse duration (μs)	0.5
Pulse frequency (Hz)	60
Percent of beam power deposited in mercury target (%)	60
Time-Averaged Loads	
Beam current (mA)	1 - 2
Total proton Beam Power (MW)	1 - 2
Peak current density on target (A/m^2)	0.14 - 0.28
Peak beam power flux on target (MW/m^2)	140-280
Peak volumetric heating rate in mercury (MW/m^3)	400 - 800
Peak volumetric heating rate in window (MW/m^3)	50 - 100
Loads During a Single Pulse	
Energy per pulse (kJ)	10 - 20
Peak energy density in mercury (MJ/m^3)	6.7 - 13
Peak energy density in window (MJ/m^3)	0.83 - 1.7

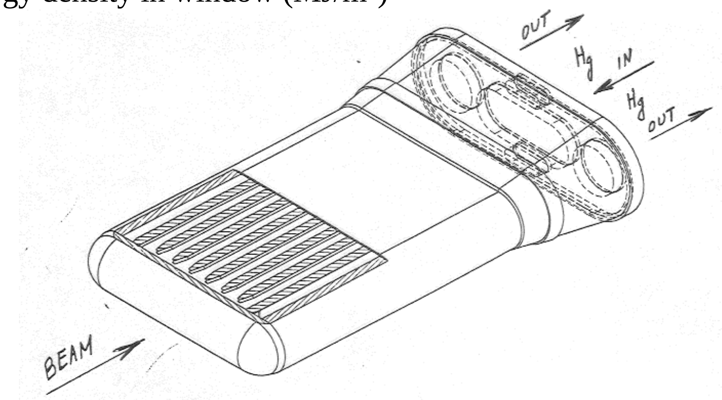


Figure 1. Schematics of NSNS Target System

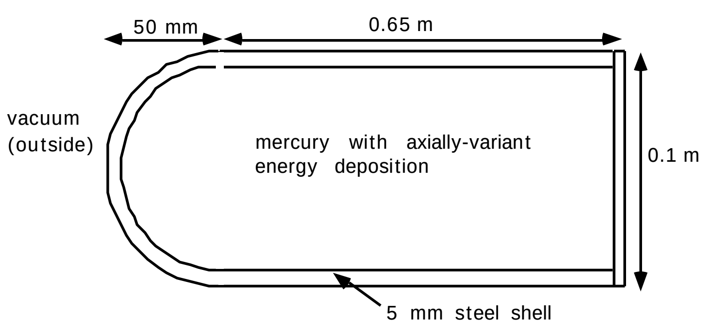


Figure 2. CTH 2-Dimensional Model for NSNS Target

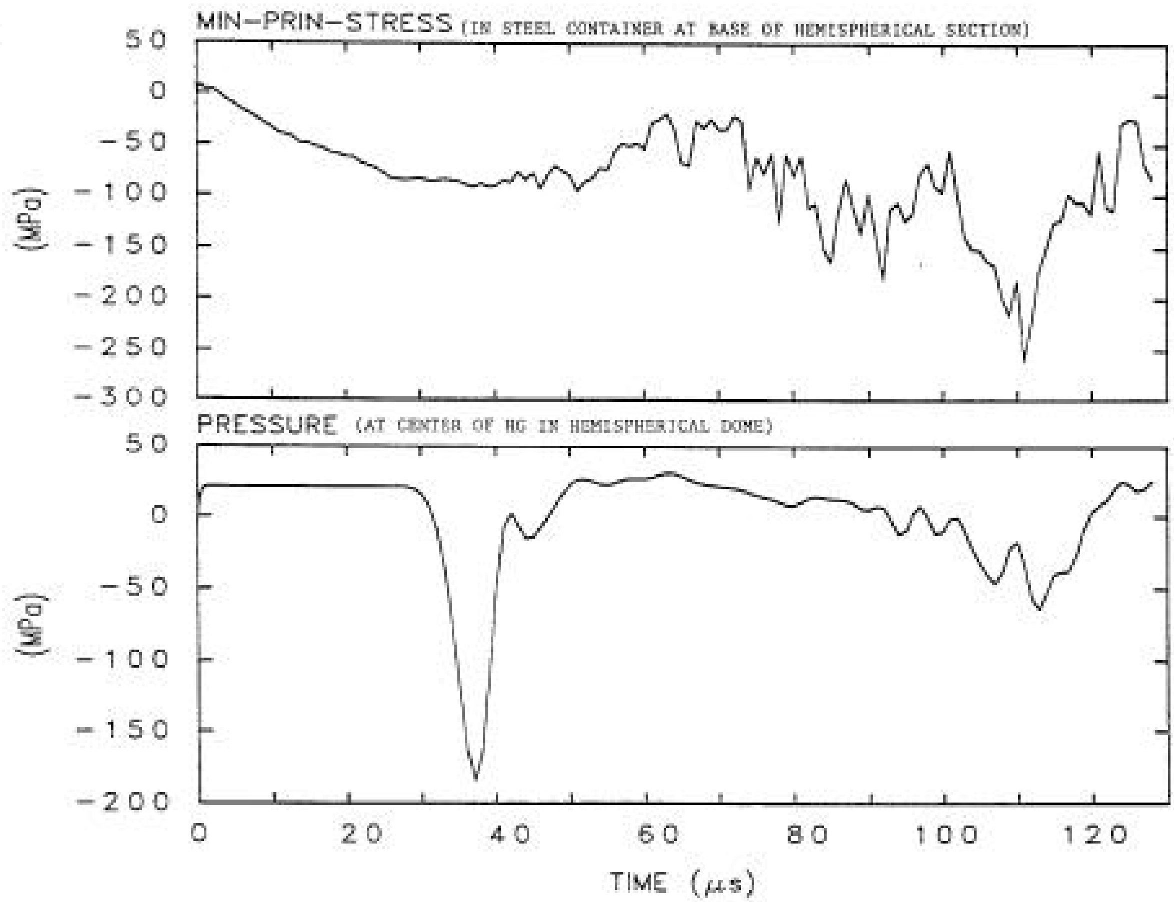
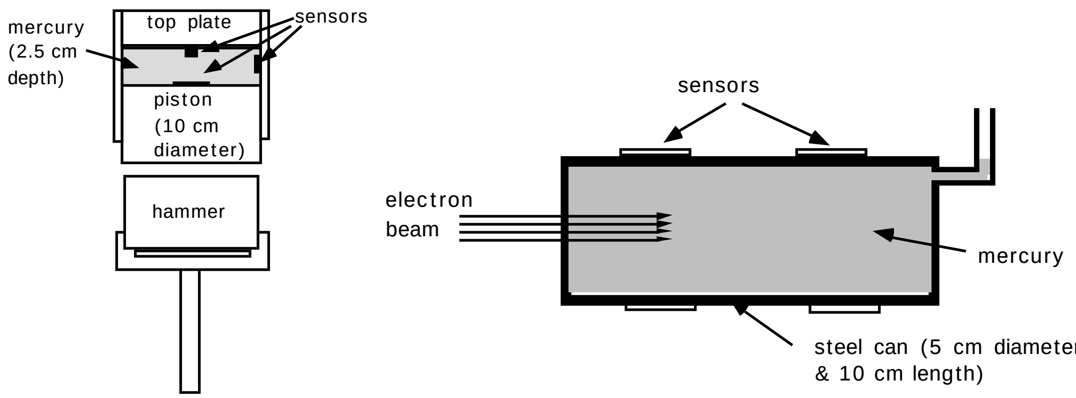
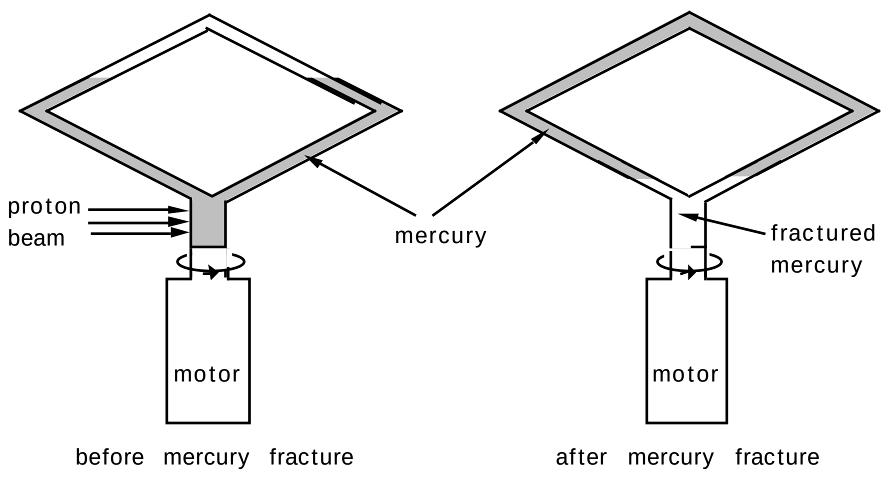


Figure 3. Transient Pressures & Stresses in Selected Location Following Single Beam Pulse



(a) Pressure Pulse Test (b) ORELA Test



(c) Cavitation Threshold Measurement Test

Figure 4. Schematics of Experiment Apparatus for Thermal-Shock Study of NSNS Target System