TARGETS FOR HIGH-INTENSITY PARTICLE PRODUCTION†

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Abstract

The high-powered target development efforts at ORNL for the Spallation Neutron Source and the muon collider/neutrino factory are discussed. Emphasis is given to the technology issues that present the greatest scientific challenges.

1 INTRODUCTION

The need for the development of high-powered targets, which can be used to produce intended beams of various types of secondary particles, is increasing. This is especially true in the production of neutrons. The Europeans, Japanese, and Americans are in the process of developing neutron spallation sources utilizing high-intensity proton beams incident on a flowing Hg target system.[1,2,3] Another area of current interest is in the production of muons also using high-intensity proton beams incident on either a graphite target or Hg target. This effort has a focal point around the international muon collider/neutrino (μ,ν) factory collaboration.

This paper describes the R&D and design associated with the development of these targets and in particular with the efforts that are currently underway at ORNL. Almost all the target development for the Spallation Neutron Source Project is centered at ORNL, contrasting the multi-laboratory and university efforts for the development of the muon collider/neutrino factory target.

2 DEVELOPMENT OF HG TARGET SYSTEM FOR THE SNS

In many areas of physics, chemistry, biology, materials, and nuclear engineering, it is extremely valuable to have a very intense source of neutrons so that the structure and functionality of materials can be studied. One facility under construction for this purpose is the Spallation Neutron Source (SNS). This facility will consist basically of three parts: first, a high-energy (~1 GeV) and high-powered (>1 MW) proton accelerator (60 Hertz, <1.0 μs/pulse, 34 kJ/pulse maximum), second, a target/moderator/reflector/shielding/shutter/utility (Target Systems) assembly, which converts part of the proton beam power to low-energy ($\lesssim$ 2 eV) neutrons through spallation and delivers them to the third part, the neutron scattering instruments. A picture showing the overall facility is given in Fig. 1. LBNL is responsible for the front end; LANL/JLAB, the linac; BNL, the high-energy transport system and accumulator ring; ORNL, Target Systems and Conventional Facilities; and ANL/ORNL, the neutron scattering instruments. This part of the paper deals with the second part of the system, specifically, the R&D associated with the development of the Target.

Figure 1: The site layout of the Spallation Neutron Source in Oak Ridge, Tennessee.

2.1 Thermal Hydraulics & Thermal Shock R&D

The mercury target for the Spallation Neutron Source (SNS) must be designed to sustain the time-averaged proton beam power of 2 MW, which is deposited in nearly instantaneous (~0.7 μs) pulses at a 60 Hz repetition rate. A mercury target development program, aimed at defining a system that can remove the power deposited in the target without excessive temperature or stresses, has been established. Ongoing development activities are focussed on studying the thermal hydraulic, thermal shock (effects of intense power deposition from pulsed-beam), and materials irradiation* and compatibility phenomenon.[4] To conduct these studies, several mercury flow loops are being operated, tests are being performed at accelerator facilities, and computer models are being benchmarked.

2.2 Thermal-Hydraulics R&D

A series of experimental and computational investigations aimed at characterizing the quasi-static power handling behavior of the proposed design for the SNS target have been initiated. To assure reliable and safe operation, several specific areas are being addressed. These include the wettability of liquid mercury on

* These are very important areas, but are not emphasized in this paper.
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stainless steel surfaces with corresponding effects on heat transfer and frictional pressure drops, and the fluid flow characteristics of the bulk flow in the target and cooling jacket regions where the primary proton beam is depositing its energy.

Flow characteristics of the target are being modeled using computational fluid dynamics (CFD) models. Validating and benchmarking these models under the hydraulic conditions of the actual target is necessary to develop confidence limits for application to analysis of target thermal hydraulic performance. Three experimental test facilities are being used to evaluate the thermal hydraulic issues described above and benchmark the CFD models. These facilities, developed at ORNL and shown in Fig. 2, include the Mercury Thermal Hydraulic Loop (MTHL), the Water Thermal Hydraulic Loop (WTHL), and the Target Test Facility (TTF). CFD model development and the three test facilities are described in more detail in the following sections.

2.2.1 Mercury Thermal-Hydraulic Loop

An experimental test facility has been constructed to evaluate heat transfer and wetting characteristics in flowing liquid mercury. The loop components were selected to provide measurements at prototypic heat flux levels and temperatures and flow rates corresponding to those in the passages of the target-cooling jacket. The facility is a closed piping loop, constructed primarily of 316 stainless steel, and designed to circulate liquid mercury at velocities representative of the target-cooling jacket (~3.5 m/s). An electromagnetic pump with variable speed control provides the driving force for circulating the mercury through the test section and heat exchanger.

The loop is instrumented for flow, temperature, and pressure measurements. Several test sections have been used for the mercury inlet temperatures (80 to 220ºC), mercury pressures (from 0.1 to 0.4 MPa) and velocities (from 1 to 4 m/s). As shown in Fig. 3, the measured non-dimensional heat transfer data agrees well with computational fluid dynamics calculations. All tests have achieved excellent heat transfer, and no evidence of reduced heat transfer has been observed.

2.2.2 Water Thermal Hydraulic Loop

The Water Thermal Hydraulic Loop is being used to evaluate flow characteristics in the target bulk flow region, especially recirculation and stagnation regions. A full-scale mockup of the bulk flow within the SNS target assembly has been fabricated using stereo lithography with a molding process to accurately model the interior design details. The front 0.59 m of the target is constructed of transparent plastic to provide access for flow visualization studies and velocity distribution measurements using a Laser Doppler Velocimeter (LDV).

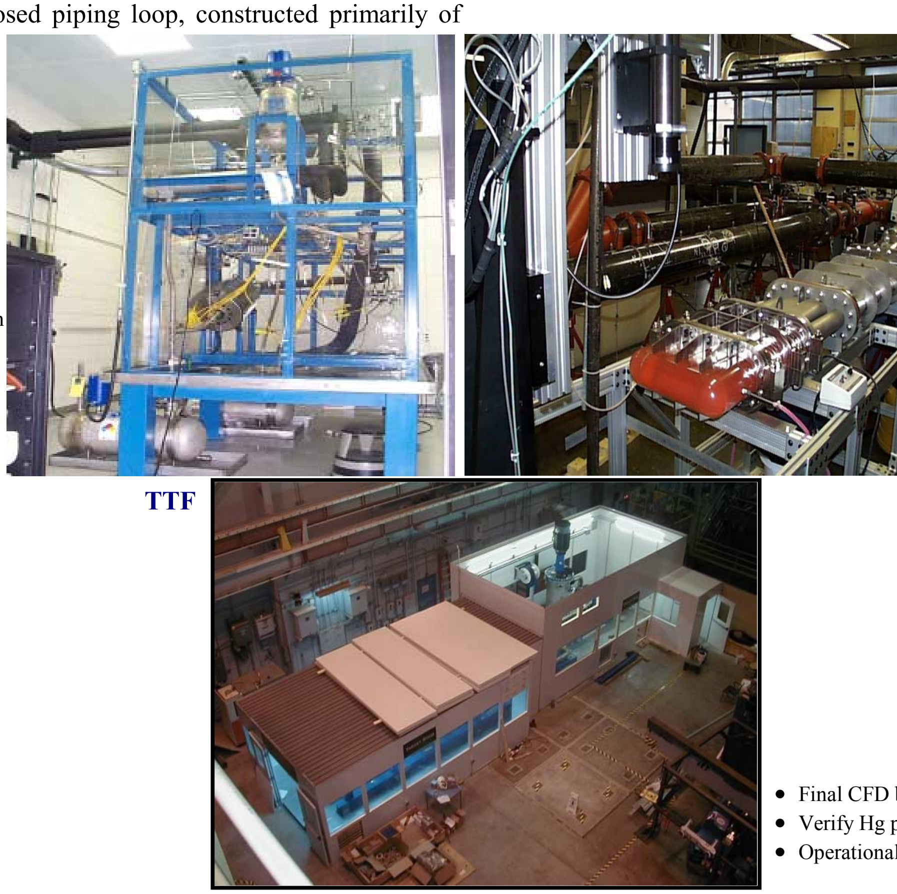


Figure 2: Experimental Facilities which are used at ORNL to carry out CFD and remote handling tests (TTF only): WTHL, MTHL, and TTF.

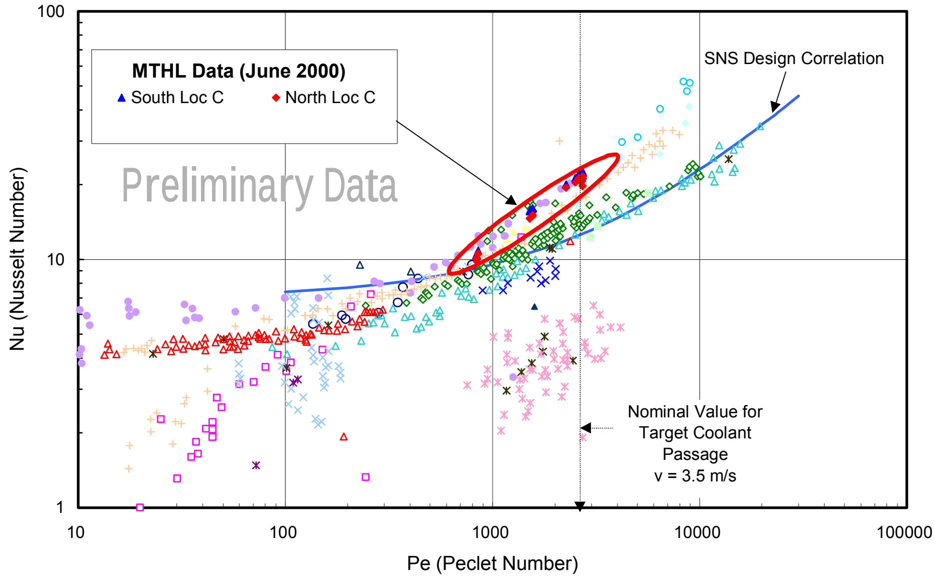


Figure 3. Heat transfer data from MTHL agrees with design correlation predicted from CFD calculations.

Test objectives for the WTHL include benchmarking of CFD code(s), examination of the effect of design changes on the target fluid performance (e.g., baffle location, etc.), and evaluation of diagnostic methods which may be applicable to mercury tests in the Target Test Facility (TTF), which is described later. Measurements that are being made in the WTHL include flow rate for each inlet, pressure drop across the test section, pressure measurements at selected locations in the transparent front section, detailed localized velocities and velocity vectors in the transparent section using a 2-D LDV system, and flow visualization studies using injected dyes and gas bubbles. Very good agreement between the CFD predictions and flow visualization results as well as LDV measurements of the flow field has been demonstrated.

2.2.3 Target Test Facility

The Target Test Facility (TTF) provides a full-scale test bed for confirmatory fluid dynamic tests using mercury. The purpose of the test planned for this facility is to provide confirmation that the full-scale target meets its design requirements with mercury as the fluid. CFD models previously benchmarked in the WTHL using water will be benchmarked for mercury under expected target hydraulic conditions.

Initial tests have been conducted to verify hydraulic performance of the pump and piping system. A second testing phase, currently underway, will use an Ultrasonic Doppler Velocimeter (UDV) to provide measurement of velocity profiles in the bulk flow channel for characterization of flow distributions, including recirculation and stagnation zones. An array of wall pressure taps is also planned for measurement of local pressures. Data will be used to benchmark the CFD codes that are being used for design confirmation.

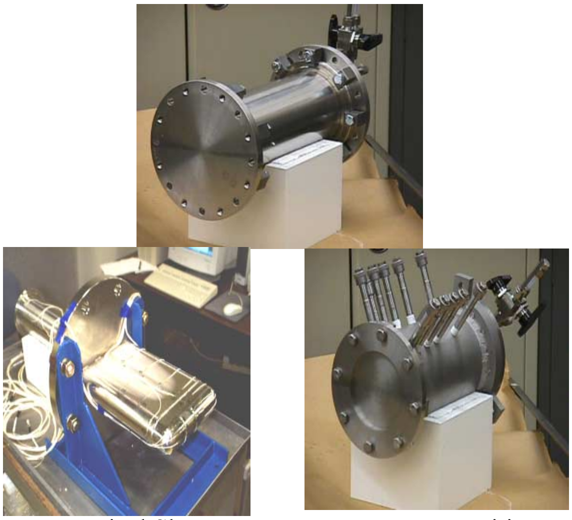
2.3 Thermal Shock R&D

Short pulse-accelerator-driven neutron sources such as the Spallation Neutron Source (SNS) employ high-energy proton beam energy deposition in heavy metal (such as mercury) over sub-microsecond time frames. The interaction of the energetic proton beam with the mercury target leads to very high heating rates in the target. The resulting thermal induced 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.

A series of mercury target tests have recently been completed at LANL in an attempt to gather the data needed to benchmark computer models used to predict thermal shock effects. Fiber-optic based strain sensors have been developed to measure the response of the target vessel to the induced pressure waves in this intense radiation environment. A picture of three of the test targets is shown in Fig. 4. Short pulses (~300 ns) of protons were obtained at the Weapons Neutron Research (WNR) facility at LANL to simulate the SNS environment. The energy density in the Hg was equivalent to that in the SNS but the modules irradiated were much smaller (~1/2 scale). The notable aspects of the data collected during these tests are that the magnitude of the strain is relatively large (as predicted) while the frequency response is surprisingly low (not well predicted).

An explicit dynamic finite element code is being used to simulate the thermally induced wave propagation and resulting dynamic stresses in the vessel. Simulations have been performed on test targets for which experiments have provided some data. As mentioned above, comparisons of simulation results with early test results have indicated over-prediction of maximum stress and dynamic response with higher frequency than measured. The belief is that cavitation of dissolved gas during the response significantly changes the wave propagation, possibly due to changes in compressibility, or to scattering effects of gas bubbles. The most recent tests at the WNR facility have furnished substantial data on new test targets which, when analyzed, will hopefully provide further insight into this issue.

Large Effects Target



Prototypical Shape Target

Energy Deposition Target

Figure 4: Target modules used in the WNR tests for pressure wave analysis.

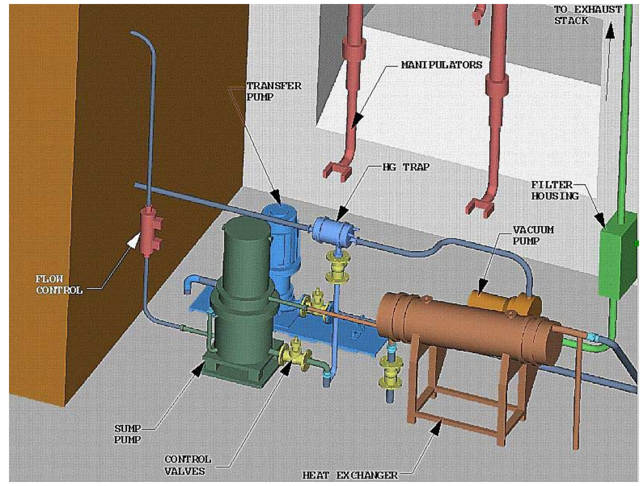


Figure 5: Hot cell arrangement for the mercury target equipment.

3 DEVELOPMENT OF THE TARGET AREA REMOTE HANDLING AND GRAPHITE TARGET FOR THE μ/ν

The development of a high-intensity source of muons that can be used for collider experiments or for the production of high-energy neutrino opens the door for a broad range of physics experiments. A large effort is underway in this country to develop such a source. The concept is to use a high-intensity proton beam (~24 GeV, 1MW, 15 hz) incident on a Hg jet or graphite target to produce pions which decay to give the muons. These muons will be magnetically captured and then accelerated in a collider ring or in a “race track” system. The “race track” itself can be pointed at a detector located many kilometers away. This part of the paper describes some of the target remote handling needs, which are necessary at such a facility,[5] and also on some of the R&D that is underway on the graphite target.

3.1 Remote Handling Associated With the Target Area

Facility design concepts have been developed for graphite and mercury target systems based on the requirements to operate and maintain these different targets. Both systems have highly activated components that must be replaced periodically using remote handling equipment and tools. For the case of a graphite target, overhead access was the preferred approach and the hot cell was located above the target area. For the mercury target, overhead access combined with below-grade access was necessary in order to maintain the mechanical components of the system, i.e., pumps, valves, and mercury storage. These are contained in a below-grade hot cell as shown in Fig. 5.

The various components that make up the target system fall into three categories. Class 1 components are life-limited and require periodic, scheduled replacement during the facility lifetime. They are designed for remote handling and must have minimal impact on operating availability. Class 2 components are ideally life-of-the-facility with activation levels that preclude hands-on replacement, and whose failure shuts down the facility. These components have a probability of at least one lifetime failure and are designed for remote handling. Their replacement could impact operating availability since spare components are generally not on hand. Class 3 components are not expected to fail during the facility lifetime and do not have provisions for remote handling.

Table 1 lists examples of target system components that require remote handling. The table is based on an operating year of 10^7 seconds, which is equivalent to four months of continuous beam line operation. A more detailed writeup can be found in Ref. 5.

Table 1. Maintenance requirements for various target system components.

Component (Class)	Failure Mode	Dose Rate (Rad/h)	Exp. Life (yrs)	Replace-ment Time (days)*
Nozzle Insert (1)	erosion, embrittled beam window	$>10^6$	2-3	11-16
Graphite Target (1)	erosion, fracture	$>10^6$	0.3	6
Bitter Magnet (1)	radiation damage	$10^5 – 10^6$	0.5	7
Supercon-ducting Solenoid (2)	turn-to-turn short	$10^{-1} – 10^0$	20	up to 365**
Beryllium Window (1)	Embrittle-ment	$10^4 – 10^5$	2	7-11
Isolation Valve (1)	mechanical	$10^4 – 10^5$	5-7	8-14
Filters (1)	saturated	Contam.	2	2-3
Pumps, Valves (2)	mechanical	Contam.	7.5	2-3
Heat Exchanger, Piping, Tanks (3)	mechanical	Contam.	> 40	5-8

*Based on assuming either 12-hour or 8-hour maintenance shifts.
**Includes time to fabricate a replacement magnet.

3.2 GRAPHITE ROD TEST AT THE LANSCE-WNR

Graphite rods were instrumented with fiber optic strain gages to measure the dynamic response from the LANSCE 800 MeV proton beam pulses. The energy deposition produced by the protons in the graphite is similar to that anticipated at a muon/neutrino facility. Structural analysis simulations of the response were performed with the finite element code, ABAQUS/ Explicit.[6] The predicted and measured strains at the mid length location compare favorably.

The measured strains indicated the first bending mode of the rod was strongly excited, thereby indicating that the beam was not totally centered on the rod (see Fig. 6). To account for this, the energy deposition in the rod was shifted parallel to the rod axis approximately 5 mm.

Higher order responses observed in the strain correspond to axial wave propagation and radial wave propagation. Displacement results from the simulation also indicate higher bending modes are also excited.

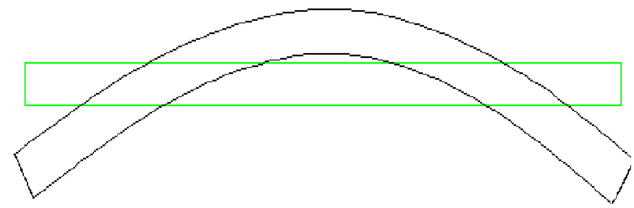


Fig. 6. Deformed shape at 12 ms (10000x) show bending mode character.

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