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The SNS Target Station Preliminary Title I Shielding Analyses

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The Department of Energy (DOE) has given the Spallation Neutron Source (SNS) project approval to begin Title I design of the proposed facility to be built at Oak Ridge National Laboratory (ORNL). During the conceptual design phase of the SNS project, the target station bulk-biological shield was characterized and the activation of the major target station components was calculated. Shielding requirements were assessed with respect to weight, space, and dose-rate constraints for operating, shutdown, and accident conditions utilizing the SNS shield design criteria, DOE Order 5480.25, and requirements specified in 10 CFR 835. Since completion of the conceptual design phase, there have been major design changes to the target station as a result of the initial shielding and activation analyses, modifications brought about due to engineering concerns, and feedback from numerous external review committees. These design changes have impacted the results of the conceptual design analyses, and consequently, have required a re-investigation of the new design. Furthermore, the conceptual design shielding analysis did not address many of the details associated with the engineering design of the target station. In this paper, some of the proposed SNS target station preliminary Title I shielding design analyses will be presented. The SNS facility (with emphasis on the target station), shielding design requirements, calculational strategy, and source terms used in the analyses will be described. Preliminary results and conclusions, along with recommendations for additional analyses, will also be presented.

KEYWORDS: Spallation Neutron Source, protons, neutrons, shielding, target station, mercury target, streaming

I. Introduction

The Department of Energy initiated a conceptual design study[1] for the Spallation Neutron Source (SNS) and has given approval for the facility to be built at Oak Ridge National Laboratory. The SNS consists of an accelerator system capable of delivering a 1 GeV proton beam with 1 MW of beam power in an approximate 0.5-μs pulse at a 60 Hz frequency into a single target station. The SNS will be upgraded in stages to a 2 MW facility with two target stations (a 60 Hz station and a 10 Hz station). The radiation transport analysis, which includes the accelerator and target station neutronics, shielding, and activation analyses, is important for the construction of the SNS because of its impact on conventional facility design, maintenance operations. Furthermore, the shielding costs for the SNS comprise a significant part of the total facility costs. A strategy utilizing coupled Monte Carlo and multi-dimensional discrete ordinates calculations has been implemented to perform the preliminary Title I design shielding analysis.

1. SNS Target Station Facility Description

The basic function of the SNS target system is to produce 18 lower-energy (<1 eV), short-pulsed (~ tens of μs) neutron beams optimized for neutron scattering instruments from a short pulsed (<1 μs, 60 Hz, 17 kJ/pulse), high-average power (1 MW), 1 GeV proton beam. The proton beam target is liquid mercury flowing inside a stainless steel container. The target is positioned within a layered iron, lead, and concrete shielding monolith approximately 12 meters in diameter. Two ambient water moderators are positioned under the target and two supercritical hydrogen cryogenic moderators are positioned above the target. The moderators are surrounded by a heavy water cooled beryllium inner reflector region and lead outer reflector region. The core region, which includes the target, moderators, and beryllium/lead reflector, is contained inside a 3.5-meter diameter vessel. The target is to be installed and removed horizontally into an adjacent service cell using a target cart assembly. The target service cell is located behind the target cart assembly and measures 6 meters wide by 31 meters long by 12 meters high. Work will normally be performed via remote handling techniques behind a one-meter thick heavy concrete wall. The other core components are designed to be removed vertically and serviced in the target service cell. There are 18 neutron beam lines viewing the moderators, nine on each side, and equally spaced in angle. Each beam line has an independently operable shielding shutter controlled by the experimentalists. The beam lines are located at two levels; nine lines directed at the ambient water moderators under the target, and nine at the cryogenic hydrogen moderators above the target. The shielding extends to a radius of ~8 meters at the beam line level to provide a region for the neutron beam T0 choppers.

II. Shielding Design Criteria

The preliminary safety assessment of the SNS recognizes the unique nature of accelerator safety hazards. This assessment indicates the SNS has no credible potential to affect public safety, and that the greatest hazard to worker safety will be prompt radiation during operation of the proton beam. Furthermore, the SNS target station does not have sufficient decay heat to drive the release of spallation and/or activation products and consequently represents a minimal risk to the environment and public health. To insure a low hazard rating for the

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SNS and to potentially have the SNS evaluated as an "accelerator" facility versus a "nuclear" facility, the design of the SNS will rely on passive safety features (shielding) to as large an extent as economically feasible. With that as a goal, and using DOE Order 5480.25[2], and requirements specified in 10 CFR 835, the following SNS shielding/radiation policy was set for the SNS shield design analysis. During normal operation the shielding should be designed such that the dose rate on accessible outside surfaces of the shield is less than 0.05 mrem/h in non-controlled areas and less than 0.125 mrem/h in areas under access control. Furthermore, beam control/focus requirements will be designed to keep activation of structure low enough to allow hands-on maintenance in the linac and ring tunnels. Shielding requirements relating to meeting or extending equipment lifetimes are determined on a case by case basis and typically within personnel shielding requirements.

Part of the guidance provided by DOE directive 5480.25 is to mitigate worst case design basis beam control faults. These faults should be demonstrated not to cause a radiation dose exceeding 25 rem to any individual worker, or a dose exceeding 1 rem to any member of the public, (no credit is taken for automatic beam cutoff systems). The philosophy behind this approach is that the prevention of radiation injury should be insured by passive, highly reliable means — such as the thickness of massive shielding material. The 5480.25 guideline dose limits (i.e., 25 rem and 1 rem) for design basis beam control accidents do not imply an acceptance of rem-level doses. The SNS conceptual design, consistent with other DOE accelerators, includes very rapidly-acting and highly-reliable automatic systems that cut off the beam when it is not in its desired path (or if personnel access to the tunnel is attempted during operation of the beam). The automatic beam cutoff would function to limit worker exposures to a small number of millirem even for worst-case beam-control accidents.

III. Calculational Methodology

The CALOR[3] code system was the main calculational tool used for the radiation shielding studies. The three-dimensional, multimedia, high-energy nucleon-meson transport code HETC96 was used to obtain a detailed description of the nucleon-meson cascade. This Monte Carlo code takes into account the slowing down of charged particles via the continuous slowing-down approximation; the decay of charged pions and muons; and inelastic nucleon-nucleus and charged-pion-nucleus (excluding hydrogen) collisions through the use of a multitude of high energy physics models. The MCNP Monte Carlo transport code[4] was coupled to HETC96 to obtain the proper source for the low energy ($E < 20$ MeV) neutron transport. For the shielding design of high power spallation targets and hadron accelerators with energies up to 1 GeV, it is beneficial to use deterministic methods for the shielding calculations instead of Monte Carlo methods because deep penetration problems require very high particle numbers to obtain good statistics, and high particle numbers typically lead to high computational times. For the SNS target station shielding analyses, two approaches were implemented. One approach was to couple HETC96 with the ANISN[5] one-dimensional or DORT[6] two-dimensional discrete ordinates deterministic transport codes to analyze the deep penetration shielding requirements. In this analysis, the HILO86 coupled 66-neutron, 22-gamma-ray cross-section library[7] was used. To address the shielding for shutdown activation sources, the HETC and MCNP codes provide the required input data for the isotope generation and depletion code, ORIHET95[8], which utilizes a matrix-exponential method to study the buildup and decay of activity for any system in which the nuclide production rates are known. The combination of these two sources yield the radionuclide concentrations, radioactivity, and time dependent decay gamma source spectra, as a function of buildup and decay time.

IV. Shielding Analysis

Shielding a spallation neutron source is more difficult than shielding a reactor neutron source because spallation neutrons have higher energies than fission neutrons. For a spallation neutron source, the highest-energy cascade neutrons approach the energy of the incident proton beam. These high-energy neutrons are extremely penetrating, and well-designed shielding is needed to prevent them from causing excessive biological dose rates. Shielding design calculations have been performed for all sections of the SNS facility. Biological shields have been designed and assessed for the proton beam transport system and associated beam dumps, the target station, the target service cell, and utility vault. Calculations have been performed for normal operation, catastrophic accident scenarios, and shutdown activation sources. The appropriate shielding design criteria outlined in Section II were utilized for the sequence of calculations to be performed for each SNS facility component.

1. Target Station Monolith Shielding Options

As originally envisioned, the SNS target station monolith shield was to be constructed mainly of steel except for regions closest to the Hg target that are 0.8 m of 80% Pb-20% H_2O followed by 0.7 m of 80% Carbon Steel (Fe+5%C)-20% H_2O. The high cost of both material and fabrication for this configuration prompted designers to seek a less costly option having equivalent shielding performance. The availability of large quantities of lead prompted replacement of the steel with lead. One-dimensional ANISN radiation transport calculations were performed to determine optimum configurations with both lead and lead mixtures replacing the steel. A fourteen-region, one-dimensional model of the monolith and surrounding concrete biological shield summarized in **Table 1** was used in the analysis. The source for the ANISN calculations was the forward directed leakage from the Hg target in a 0 to 20 degree cone. This represented the hardest neutron source spectrum to be shielded.

In the original configuration, the regions labeled "XXX" were comprised of carbon steel (CS). The merits of replacing these with Pb and lead mixtures were assessed. In the CS configuration, the total ($n+\gamma$) contact dose rate at the outside surface of the concrete biological shield was calculated to be 5.3 μrem/h. (At 1 mA proton beam current.) Replacing CS in regions 6, 9, and 12 with pure Pb and maintaining the same compositions elsewhere, increased the dose rate to 0.11 mrem/h.

Table 1 One-Dimensional Model of the Target Monolith and Biological Shield

Region	T (m)	Material
1	0.20	Void
2	0.80	80% Pb-20%H_2O
3	0.75	80%SS-20%H_2O
4	0.05	SS
5	0.025	SS
6	1.05	XXX
7	0.025	SS
8	0.025	SS
9	1.05	XXX
10	0.025	SS
11	0.025	SS
12	1.05	XXX
13	0.025	SS
14	1.00	Concrete

The increase is due to higher production of secondary gamma rays from low energy neutron reactions in lead and poor attenuation of the low-energy neutrons ($E_n \leq 20$ MeV).

Several materials were proposed to replace the CS in regions "XXX". These included Borated Pb (0.5% ^{10}B), Cadmium Loaded Pb (0.5% Cd) and combinations of Cement (Borated and Non-borated) and Pb shot. Replacing the SS structure (regions 4, 5, 7, 8, 10, 11, and 13) with Borated SS was also evaluated. The Borated and Cadmium-loaded Pb options, though neutronically advantageous, are impractical because of the difficulty to obtain homogeneous mixtures.

The recommended configuration in terms of cost and fabrication consists of pure Pb in regions 6 and 9, a Borated Cement-Pb shot (65%Pb) in region 12 and Borated Concrete in the biological shield. The contact dose rate outside the biological shield was calculated to be 2.3 µrem/h. When voids, gaps, and manufacturing tolerances are taken into account, the contact dose rate increases by a factor of ~3 but is still well below the allowed dose rate. Shields using other combinations of materials were also shown to be neutronically effective but were either difficult to fabricate or impossible to make with uniform consistency.

2. Dose Rate Outside the SNS Target Maintenance Cell From Radiation Streaming through the Clearance Gaps Surrounding the Target Carriage

Insertion and withdrawal of the SNS target carriage into and out of the target monolith requires clearance gaps between the carriage surfaces and the monolith walls, ceiling, and floor to facilitate movement of the carriage. During accelerator operation, neutrons produced in the Hg target and surrounding materials will migrate through the moderator-reflector and shielding surrounding the target. The transmitted neutrons and secondary gamma rays will impinge on the front face of the carriage. The shielding provided by the carriage itself reduces the radiation leaking into the posterior target-maintenance cell. The dose rate outside the cell walls is less than 0.25 mrem/h. SNS designers are concerned about the impact of radiation streaming through these gaps on the dose rate outside the maintenance cell.

It was assumed that the target carriage is a solid assembly surrounded on all sides by a 7-mm-wide gap. The carriage cross section is 1.72m x 1.72 m over the entire 5-m length of the assembly. Neutrons produced from the reactions of 1-GeV protons in the Hg target were calculated previously by R. A. Lillie and J. M. Barnes [9], using the High Energy Transport Code, HETC. Neutron emission in the angular intervals between 0° and 20° was used as the source term for this analysis. Only the neutrons and gamma rays that leak out of the iron shield in the forward direction will have a chance of entering gaps. The forward emitted component of the angular flux in the interval between 0 and 3° calculated using the leakage source was taken as the source incident on the mouth of the gap. A sequence of bootstrapped one-dimensional ANISN calculations coupled to a series of analytic calculations was utilized to transport the leakage from the moderator-reflector-shield assembly incident on the target carriage assembly. The calculations determined the uncollided flux exiting the gaps into the maintenance cell. The lateral width of the gap will result, however, in uncollided neutrons exiting the gap at directions other than normal to the shield face. The maximum angle is ~19° and therefore these neutrons are incident on the surrounding concrete wall at "grazing" angles. The maximum "straightahead" thickness of concrete the neutrons traverse before exiting the 100-cm–thick concrete maintenance wall is ~300 cm. Neutrons that are scattered while traversing the gap emerge at larger angles but these will be of lower energy and will be more rapidly attenuated in the concrete. The dose rate behind 300-cm of concrete is 0.53 µSv/h for a neutron source strength of 7.4 x 10^{15} n/s.

The approximations made for this analysis lead to a conservative estimate of the dose rate outside the maintenance cell. The assumption that the radiation entering the gap corresponds to the forward directed (0 to 3°) component of the angular flux is an overestimate. This corresponds to the most intense component of the high-energy angular flux. The flux decreases a factor of ten or more for a small increase in angle. The angular distribution of the low energy neutrons is nearly constant with angle and, though the intensity is greater than the forward peaked component, the contribution to the dose rate outside the maintenance cell is small. Modeling the radiation incident on the gaps in this way overestimates the dose rate by at least an order of magnitude. The assumption that the width of all gaps is the same increases the streaming flux by ~30%. Since the carriage is also narrower than it is tall, the angle at which the neutrons strike the sidewalls of the cell is smaller so the forward directed flux traverses a greater thickness of concrete. In the actual carriage configuration, there are offsets in the gaps along the top and sides of the assembly that provide an additional factor of 2 to 5 reduction in the dose rate. The calculated dose rate is less than the recommended dose rate level of 0.25 mrem/h. Including the conservatism implied above, the impact of streaming through the clearance gaps on the dose rate outside the maintenance cell is tolerable.

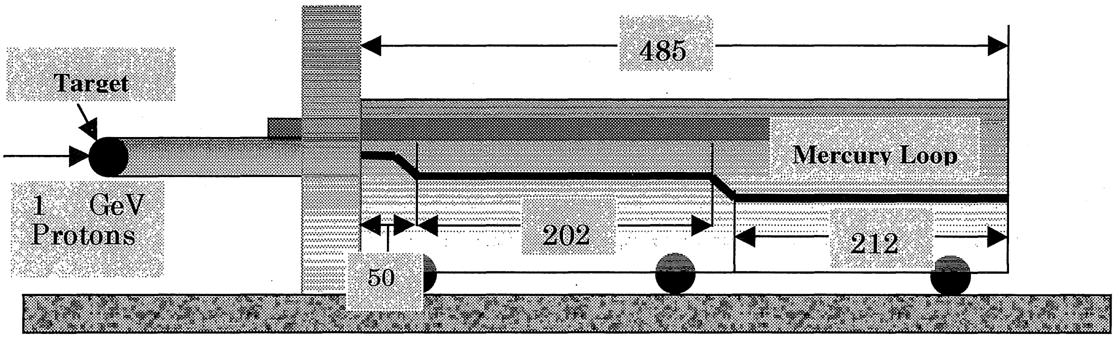

Fig. 1 Schematic Diagram of the Target Carriage and Mercury Loop

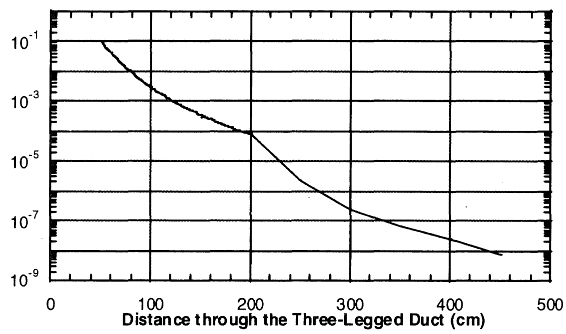

Fig. 2 Estimated Attenuation in the Three-Legged Duct

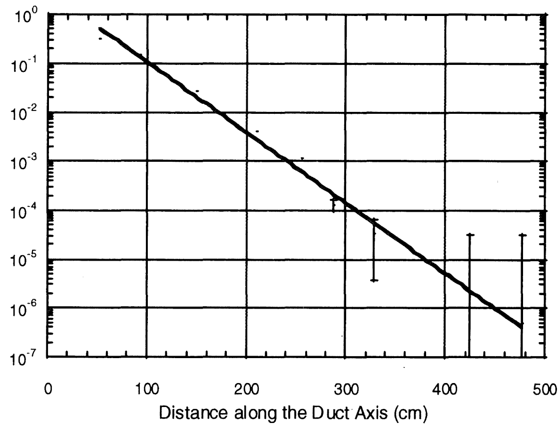

Fig. 3 Calculated Attenuation through the Three-Legged Duct

3. Radiation Streaming through the Mercury Loop in the SNS Target Carriage

Mercury is supplied to the SNS target through a pipe assembly that passes through the target carriage. The pipe assembly, shown in **Fig. 1**, referred to as the mercury loop is configured as a three-legged duct to reduce the radiation leaking through the pipe during a loss-of-mercury accident. In a loss-of-mercury accident, 1 GeV protons can stream through the loop and react in the pipe and the carriage materials at the first bend producing charged particles and secondary neutrons. These particles, particularly the neutrons, can migrate through the pipe and leak from the rear of the carriage into the target maintenance cell. For this work, it was assumed that the mercury loop consists of a 6.25-cm-radius pipe imbedded in a 4.85-m-long solid steel block. For the case when the pipe is filled with mercury, it is assumed that the radiation attenuation provided by the block and the filled pipe meets SNS shielding criteria. The two straight sections of the pipe are 202 and 212 cm long, respectively. The length of the pipe through the second 45° bend is ~30 cm. The straight sections of the pipe are separated by ~3 pipe radii.

A series of Monte Carlo calculations using the High Energy Transport Code, HETC, to estimate neutron streaming through a two-legged pipe (one bend) configuration were carried out previously [9] and showed that a 450-cm-long duct following the initial bend reduces the incident radiation by five orders of magnitude. The results of this analysis was used to roughly estimate the attenuation through the three-legged duct (two bends; see Fig. 1). The result is shown in **Fig. 2** and indicates introducing the second bend in the pipe produces approximately seven orders of magnitude total attenuation.

A Monte Carlo calculation was also performed to estimate the neutron population and energy spectra as a function of distance along the duct axis. In this analysis, the target carriage-mercury loop was modeled in detail. A line beam of 1-GeV protons was taken to be incident on the mouth of the pipe. Neutrons produced from proton reactions in the iron were tallied as a function of location in the duct. Tally surfaces were positioned along the duct axis to score neutrons passing through the iron structure and the open duct. The cross-sectional area of the duct opening is <1% of the cross-sectional area of the carriage. One million source particles and their progeny were transported to achieve good statistical sampling particularly through the front elements of the duct. The neutron population, energy, and angular distribution were tallied. The energy was recorded in eight energy bins between 0 and 700 MeV while their angular distributions were scored in two broad bins between $-1<\mu<0$ and $0<\mu<1$.

The attenuation of the neutron current for all energies inside the duct with $0<\mu<1$ is shown in **Fig. 3**. The curve is an exponential fit to the calculated data. The attenuation is approximately seven orders of magnitude. The error bars reflect the Monte Carlo standard deviation of the neutron population. The large attenuation of the bulk shielding material and the small opening of the duct lead to poor sampling of the neutron population at long distances through the loop.

V. Conclusions and Recommendations

A preliminary shielding analysis of the proposed SNS was performed for the target station monolith and associated maintenance cell and utility areas, accelerator and ring tunnels, and the accelerator system beam dumps. Analyses were performed utilizing coupled HETC-ANISN calculations for both normal operating conditions and catastrophic design base accident scenarios. Results of the present analysis demonstrate the bulk shielding of the SNS conceptual design meets the shielding requirements specified in DOE Order 5480.25 for almost all scenarios. Design modifications have been made to address areas of concern. Future analyses are needed to refine the shielding models to account for penetrations and streaming gaps in the bulk shield, and determine mitigation measures to reduce and/or eliminate the dose from these penetrations.

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