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Shielding Design of the Spallation Neutron Source (SNS)

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Abstract

The shielding design is important for the construction of an intense high-energy accelerator facility like the proposed Spallation Neutron Source (SNS) due to its impact on conventional facility design, maintenance operations, and since the cost for the radiation shielding shares a considerable part of the total facility costs. A calculational strategy utilizing coupled high energy Monte Carlo calculations and multi-dimensional discrete ordinates calculations, along with semi-empirical calculations, was implemented to perform the conceptual design shielding assessment of the proposed SNS. Biological shields have been designed and assessed for the proton beam transport system and associated beam dumps, the target station, and the target service cell and general remote maintenance cell. Shielding requirements have been assessed with respect to weight, space, and dose-rate constraints for operating, shutdown, and accident conditions. A discussion of the proposed facility design, conceptual design shielding requirements, calculational strategy, source terms, preliminary results and conclusions, and recommendations for additional analyses are presented.

1. Introduction

The Department of Energy initiated a conceptual design study[1] for the Spallation Neutron Source (SNS) and has given preliminary approval for the proposed facility to be built at Oak Ridge National Laboratory. The conceptual design of 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 4 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, and because the costs associated with incorporating the results of the radiation transport analysis comprise a significant part of the total facility costs. A strategy utilizing coupled Monte Carlo and multi-dimensional discrete ordinates calculations, along with semi-empirical calculations has been implemented to perform the conceptual design shielding analysis.

1.1 SNS Facility Description

The complete accelerator system consists of a front end ion source, a linac, an accumulator ring, and the associated transfer lines required to link the complete system together. The primary function of the front end systems is to produce a beam of H^- ions to be injected into the linac at 2.5 MeV. This facility consists of the ion source, the low energy beam transport (LEBT) line, and the medium energy beam transport (MEBT) line . Details of the front end systems design can be found in Section 2 of Ref. 1.

The linac is coupled to the MEBT, accepts beam from the front end system, and accelerates it from 2.5 MeV to 1.0 GeV. The linac consists of a drift-tube linac (DTL) that accelerates the H^- beam to 20 MeV, a coupled-cavity drift-tube linac (CCDTL) that further accelerates the H^- beam to 93 MeV, and a coupled-cavity linac (CCL) that accelerates the H^- beam to 1.0 GeV. The total length of the linac is approximately 492 meters. A detailed discussion of the considerations that went into the design choices and the operating parameters for the various linac components is given in Section 3 of Ref. 1.

The remainder of the accelerator system is made up of the high energy beam transport (HEBT) system from the linac to the ring, the accumulator ring, and the ring to target beam transport (RTBT) system. The lengths of these three components are 165 m (HEBT), 221 m (Ring), and 167 m (RTBT). The HEBT system provides the beam transport between the linac and the accumulator ring. The ring accumulates beam pulses from the linac and bunches them into intense short pulses for delivery to the target. A 1 millisecond pulse of H^- ions is delivered to the ring, passed through a stripping foil to convert it to protons, wrapped around the ring circumference approximately 1200 turns, kicked out in a single turn making a sharp pulse of approximately 0.5 μs to be delivered to the mercury target. This process is repeated 60 times per second. The RTBT accepts the extracted beam from the accumulator ring and transports it to the mercury target. A detailed discussion of considerations leading to design choices and design parameters for the beam transport and accumulator rings can be found in Section 4 of Ref. 1.

The SNS target system has the basic function of converting the short pulse (<1 μs, 60 Hz, 17 kJ/pulse), high-average power (1 MW), 1 GeV proton beam delivered via the RTBT into 18 lower-energy (<1 eV), short-pulsed (~ tens of μs) neutron beams optimized for use by neutron scattering instruments. The proton beam target is liquid mercury flowing inside a stainless steel container. The proton beam enters horizontally at 2 meters above the floor level. The target is positioned within a layered iron 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 reflector region. The core region which includes the target, moderators, and beryllium reflector, is contained inside a 2 meter diameter vessel filled with nickel and a helium atmosphere. Water cooling is used to cool the mercury, shielding, vessels, reflectors, and other assemblies inside the shielding monolith. The target is designed to be installed and removed horizontally using an adjacent service cell. The target service cell is located behind the target assembly and measures 10 meters wide by 17.8 meters long by 7.5 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 a second service maintenance cell adjacent to the target service cell. The general maintenance cell will be used to maintain the moderator/reflector/plug, proton beam window, neutron guide tubes and shutters. This cell measures 10 meters wide, 10.9 meter long and 9.5 meters high. 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 choppers with a vertical access hatch positioned at a radius of 7 meters. More detailed discussions of the selection criteria and design considerations for the target systems in general are contained in Section 5 of Ref. 1.

1.2 Conceptual Design Shielding Criteria

The conceptual design phase of a project typically includes preliminary data on requirements for instruments and equipment that have safety-related functions. During this design phase, potential hazards are identified and mitigation procedures are described. Also, the hazard level for each major part of the facility (e.g., linac, ring, target station, etc.) is determined. The top level document for accelerator safety regulation, DOE Order 5480.25 - Safety of Accelerator Facilities[2], provides a framework for evaluating the safety of the SNS and the initial shielding assessment. More specifically, this document provides guidance in preparing the preliminary and final safety assessment documents (PSAD and FSAD), determining the facility hazard categorization (low, moderate, or high), and the possibility of segmenting the facility to allow for an optimum graded approach to hazard mitigation.

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 SNS and 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, the following shielding/radiation policy was set for the conceptual 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. During postulated beam control accidents, the shield thickness should reduce the dose rate on accessible outside surfaces of the shield to less than 1 rem/h in non-controlled areas of the facility and less than 25 rem/h in areas under access control. Shielding requirements relating to meeting or extending equipment lifetimes are determined on a case by case basis and typically within personnel shielding requirements. Achieving these accident shielding goals without reliance on automatic beam shut-off systems will justify a "low hazard" category rating for the SNS accelerator.

2. 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. MCNP is a general purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron-photon-electron Monte Carlo transport code system. 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 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 conceptual design shielding analyses, three approaches were implemented.

One approach shown in Figure 1, was to couple HETC96 with the ANISN one-dimensional discrete ordinates deterministic transport code[5] to analyze the deep penetration shielding requirements. In this analysis, the HILO86 coupled 66-neutron, 22-gamma-ray cross-section library[6] was used. A second approach (Fig. 2) used the Computer Aided Shield Layout (CASL) code[7] developed at KFA Julich. The HETC96 and MCNP codes have the advantage of containing state-of-the-art physics treatments and cross-section data. However, they require considerable set-up and computing times. The CASL code has general source, material, and geometry capabilities but needs minimal computer and set-up time. CASL uses approximate, semi-empirical physics treatments to provide sufficient accuracy in the SNS conceptual design for many of the practical shielding problems. Finally, to address the shielding for shutdown activation sources, the procedure shown in Fig. 3 was adopted. 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 for 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 generation (buildup) time and depletion (decay), for input into the ANISN or DORT discrete ordinates deterministic transport codes.

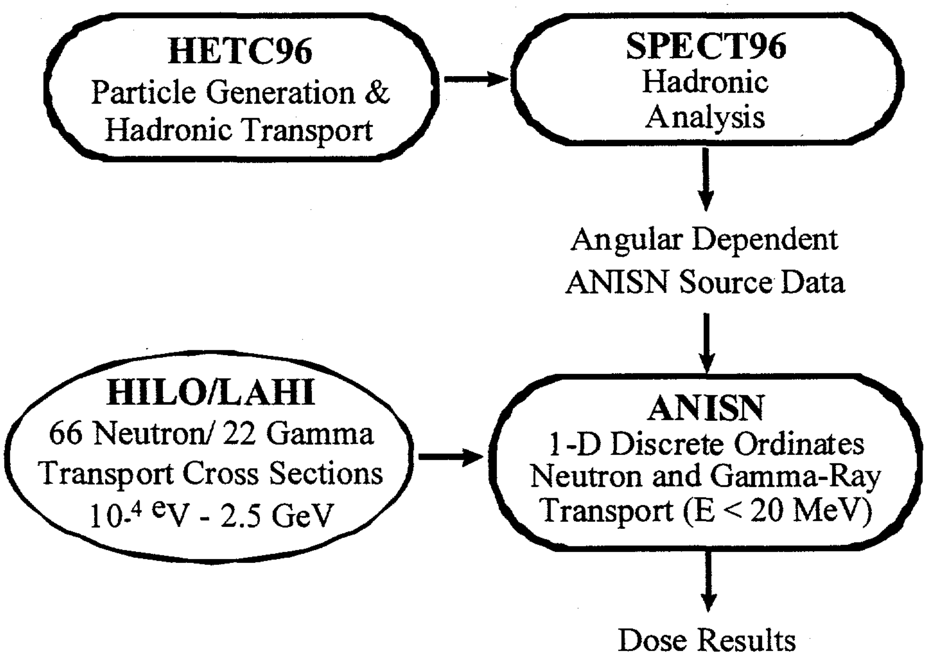

Fig. 1. Schematic diagram of the coupled HETC96 and ANISN shielding analysis procedure.

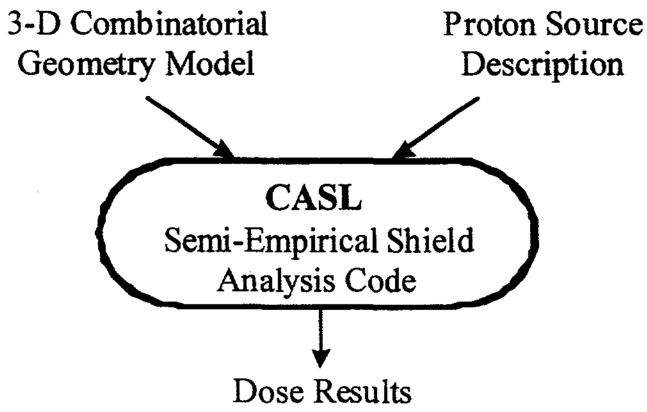

Fig. 2. Schematic diagram of the CASL code system shielding analysis procedure

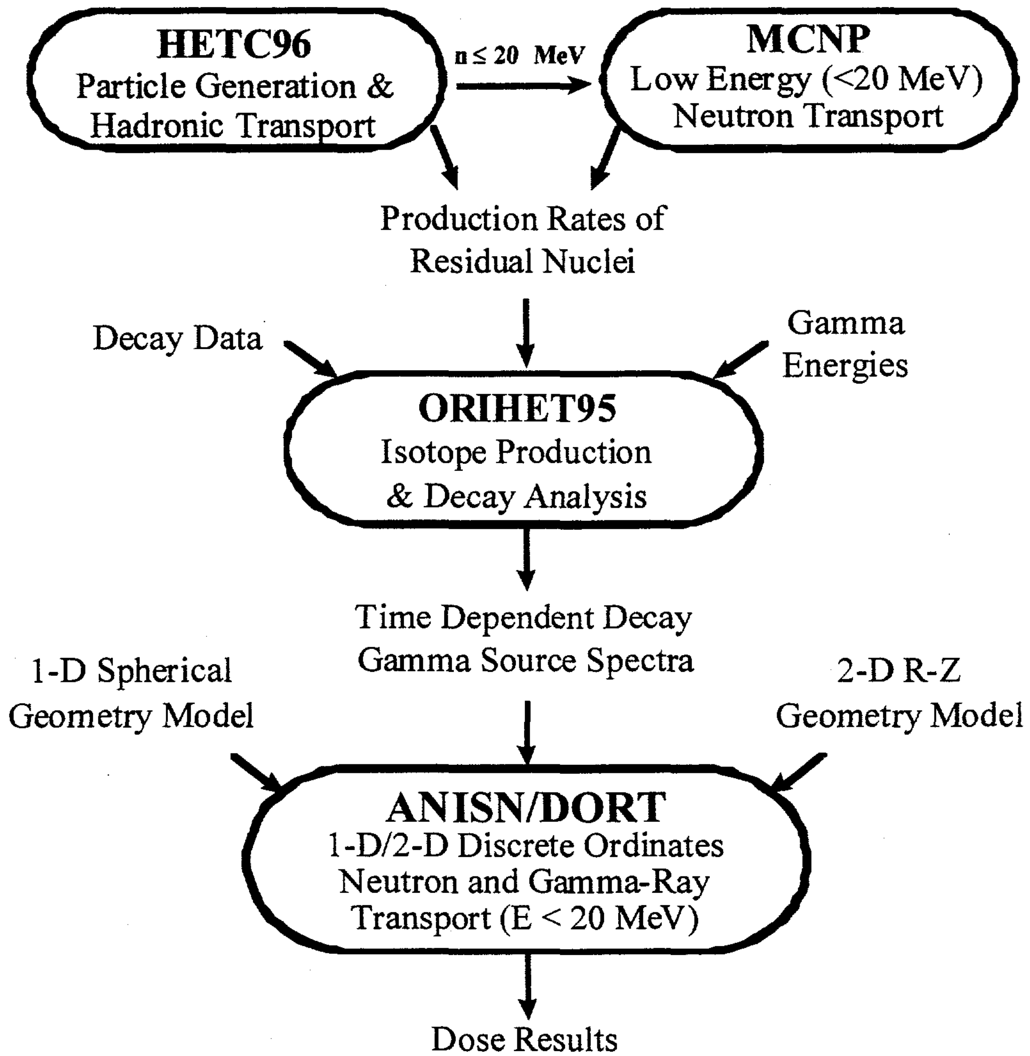

Fig. 3. Schematic diagram of the shutdown activation source shielding analysis procedure

3. Geometry Models

To perform the shielding and activation analysis on the linac and ring tunnels, klystron building and linac service road, a simplified model was constructed. For the linac components, a section of the tunnel was modeled as a cylindrical shell of concrete 2300 mm in radius, 460 mm thick, and 20 m long. The tunnel was filed with air and surrounded by approximately 9 m of earth berm for shielding. A 150 mm diameter by 1000 mm cylinder of copper was modeled in the center of the geometry to simulate the interaction of the proton beam with accelerator components. An equivalent model for the ring tunnel was constructed except the radius of the concrete shell was 3200 mm. Activation analyses were performed with these models to assess the potential radioactive byproducts generated as a function of normal operation of the SNS facility and shielding calculations were performed using the methodology discussed in Section 2 to determine earth berm shielding thickness requirements for normal operation and design basis accident scenarios.

A geometry model of the target station design (Section 5, Ref. 1) was constructed to determine the energy deposition, material damage, activation, radiation flux spectra, and shielding requirements for the entire target station including the biological shielding. In this geometry, the mercury target was represented with a simplified model and the moderator assemblies and associated neutron beam tube design from an earlier target assembly model was incorporated. All core components were modeled in sufficient detail to determine the component activation, cooling requirements, and bulk shielding requirements.

The initial design of the SNS employs three beam dumps. All three beam dumps use an 80% copper/20% water target approximately 600 mm in diameter and 750 mm in length. The central target is surrounded by a water cooled steel central core, followed by a sufficient amount of slab steel shielding to prevent significant activation of the surrounding soil or groundwater. The steel monolith is encased in a steel lined 460-mm-thick concrete enclosure to contain leaks. The linac tune dump, ring tune dump, and ring injection dump are all to be shielded to operate at 200 kW. This power level and the required groundwater and soil activation constraints will determine the required amount of steel shielding for each dump.

For the target service cell and general maintenance cell, the rooms were typically modeled using a one-dimensional spherical model. The mercury spill case was modeled with a two-dimensional cylindrical model. The models were comprised of spherical or cylindrical room equivalent volumes surrounded by one-meter-thick concrete walls. A candidate decay gamma radiation source term was placed in the center of the models. The models contain representative volumes of the different components from which the gamma-ray sources were derived so as to take into account attenuation by the components.

4. 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.

For spallation reactions, energy effects are divided into two regions: low-energy (< 20 MeV) and high-energy (> 20 MeV). This energy cutoff is convenient because the continuous-energy cross-section libraries used by MCNP have evaluated cross sections up to 20 MeV. Low-energy neutron production from a target is the low-energy spallation neutron production plus the net production from low-energy "(n,xn)" reactions. These low-energy neutrons are emitted isotropically and cause shielding problems similar to that of fission reactors. High-energy neutrons resulting from nucleon-nucleon reactions have a strong angular dependence. At 0° to the proton beam direction, high-energy neutrons can have energies up to the incident proton energy. As the angle increases with respect to the proton beam, the high-energy neutron spectrum softens significantly.

The presence of these high-energy neutrons and their strong angle-dependence complicate spallation source shielding. Shielding a spallation source is further complicated by the fact that different neutron leakage spectra are produced depending on target thickness and material. Furthermore, in a spallation neutron source, high-energy neutron attenuation generates more low energy neutrons and creates an additional secondary gamma-ray source, i.e., the shield itself becomes a neutron source. Typically, the high-energy neutrons plus their progeny dominate the dose at the shield surface. Iron combined with concrete is required to shield the high-energy neutron component at a spallation neutron source, whereas, concrete or water is an effective neutron shield for a fission neutron source.

Consequently, the iron-concrete high-energy neutron shield at a spallation source is also an effective shield for the low-energy spallation neutron component.

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, and the target service cell, general remote maintenance 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 1 were utilized for the sequence of calculations to be performed for each SNS facility component.

A summary of the shielding analyses, source terms, and calculational methodologies used to support the conceptual design of the SNS is given in Table 1. For each analysis, a summary of the dose criteria, SNS conceptual shield design, calculated minimum required shielding and representative dose rate results are presented in Table 2. These results were extracted from tabulated shielding data used to support the SNS conceptual design and represent the calculation of maximum dose or minimum required shielding to meet the SNS shielding criteria specified in Section 1. Detailed discussions of the analysis assumptions and preliminary results are presented in each of the following subsections. From this sequence of calculations, preliminary shield designs have been integrated into the overall facility design and optimized to achieve as low as reasonably achievable dose to the facility personnel, visiting experimentalists, and sensitive electronic equipment. The intention is to build the SNS facility in stages and each stage will approximately double the delivered beam power. To ensure that there will be no fundamental impediments in the design for the later stages of the project, all calculations in support of the SNS conceptual design were based on the final maximum beam power of 4 MW unless otherwise noted.

4.1 Linac, Ring, Klystron Building And Linac Service Road Shielding Analyses

For the purpose of determining the dose rates associated with normal operation and postulated catastrophic design basis accidents of the accelerator system, the linac and ring models described in Section 3 were employed in coupled HETC - ANISN calculations and semi-empirical CASL calculations using the shielding policy guidelines discussed in Section 1. HETC directionally dependent sources were generated for the high energy neutrons leaking out of the simulated copper accelerator component. One-dimensional traverses through the concrete tunnel structure and earth berm were analyzed for the anticipated normal operational loss terms and design base accident loss terms for the maximum anticipated maximum operating levels of the SNS.

The results of the linac shielding analyses indicate the conceptual design of the SNS accelerator system has sufficient shielding to meet both normal operation dose rates and postulated catastrophic beam loss accident dose rates. In all cases, the shielding analyses were performed to a dose rate constraint approximately equal to one-half of the required maximum dose rate to allow for a factor of two uncertainty in the modeling assumptions and calculational methodology. In the klystron gallery and linac service road analyses, the shielding berm thickness was chosen equal to the calculated minimum required shielding thickness for the 1 GeV linac tunnel catastrophic beam loss accident.

4.2 Target Station Shielding Analyses

For the purpose of determining the dose rate at the biological shield surface, the target station, described in detail in Section 5 of Ref. 1, was modeled using the shielding guidelines outlined in Section 1 and the calculational methodology outlined in Section 2. The amount of shielding above the target was fixed by limiting the biological dose rate in the high bay area of the target station building while the accelerator is operating. Equipment activation above the target is also a concern. However, a shield that is sufficiently thick enough to protect personnel will generate negligible equipment activation. The shielding beneath the target station was governed by nuclear heating in the concrete support structure. In future design efforts, other criteria may dominate the SNS target station shield design such as component activation (which affects maintenance and plant availability) or soil and groundwater activation. One-dimensional traverses through the bulk shielding were analyzed for the forward, backward, transverse (side), upward, and downward directions of the target station relative to the incident proton beam direction. In the forward direction, one traverse was modeled through the mercury target plug assembly, and a second traverse was modeled through the bulk shielding adjacent to the target plug. Corresponding CASL calculations were also performed for each of the ANISN calculations.

The results of the analyses indicate the target station model shield design satisfies the shielding requirements by a factor of two or more except in the downward direction. In this direction, the results show more bulk iron shielding is needed to reduce the amount of energy being deposited in the concrete and ultimately the ground. This has resulted in additional iron shielding being added below the target and increasing the thickness of the concrete. It should be noted that beam-line penetration streaming through the bulk shield is beyond the scope of this analysis and has not been calculated.

4.3 Linac And Ring Beam Dump Shielding Analyses

The SNS accelerator ring proton transport system will require three beam dumps for normal operation of the facility. The linac tune dump will be located at the end of the linac beyond the linac to ring transfer tunnel. This beam dump will be required to operate at 100 kW incident proton beam power. The ring facility will require two beam dumps. The ring tune dump will be required to operate at 50 kW incident proton beam power, and the ring injection dump will be capable of 200 kW of power operation. The proton beam footprint on the linac tune dump and ring injection dump will be approximately 50 to 60 mm in diameter with a gaussian distribution. The proton beam footprint of the ring tune dump will be equivalent to the footprint for the target station, i.e. 70 mm x 200 mm parabolic with a 2 to 1 peaking factor.

For the preliminary shielding analysis, all three dumps are assumed to operate at 200 kW incident proton beam power and are to be similar in design. Furthermore, the beam dumps should be capable of sustaining full beam power for a few pulses without catastrophic failure. Since beam dumps are basically low power target stations, a similar analysis was initiated for the three beam dumps as that performed on the target station models. Within this analysis, the steel shielding required to obtain a dose rate of 0.125 mrem/h on the outside of the concrete encasement was determined. This stringent dose rate criterion was established to ensure the beam dumps did not make a significant contribution to the ground and/or groundwater activation.

The results for the beam dump analysis indicate all three dumps require approximately 8.2 to 8.7 meters of steel per side to obtain dose rates on the external surface of the concrete of approximately 0.125 mrem/h. This low dose rate insures insignificant activation in the ground due to beam dump operations, and the length per side is within the SNS conceptual design of 9 meters.

4.4 Target Service Cell, General Maintenance Cell, And Miscellaneous Shielding Analyses

For the purpose of determining the dose rates associated with normal operation and postulated catastrophic design basis accidents for the target service cell, general maintenance cell, and utility vault, the models described above were employed in coupled HETC - ANISN calculations and semi-empirical CASL calculations using the shielding policy guidelines discussed in Section 1. Candidate decay gamma radiation source terms were placed in the center of the models. The models contain representative volumes of the different components from which the gamma-ray sources were derived so as to take into account attenuation by the components. The source terms were determined from the ORIHET95 activation and were calculated for 4 MW operation of the target station for 1 year. The gamma-ray spectra calculated for immediately after the facility shutdown was used as the source term. For most source terms, this yields an approximate equilibrium spectrum.

For the target service cell, the target SS-316 jacket, which holds the mercury target, was selected as a source term to simulate a repair or replacement operation of this component, while the target mercury source was used for the analysis of the mercury spill case. Utilizing these sources, the required concrete wall thickness was determined. The results further indicate the heavy concrete thickness of one meter satisfies the dose rate limit for normal operation scenarios. In the case of a catastrophic accident like the mercury spilling out onto the floor, the heavy concrete thickness of one meter, however, does not satisfy the shielding requirement and 1.20 meters of heavy concrete will be required.

The two most activated components from the inner reflector assembly, i.e., the beryllium/D_2O reflector assembly, and the nickel inner reflector plug assembly, were modeled in the center of the general maintenance cell, in separate calculations, and the dose rate was determined at the external surface of the concrete wall. The results indicate at least 1.20 m of heavy concrete is required for the most activated component, the Be/D_2O reflector. This shielding thickness is greater than the conceptual design thickness of one meter. It should be noted that standard operations will involve lifting the entire safety vessel and all the interior components and placing this assembly in the remote maintenance cell for servicing. The dose rate associated with this assembly will be significantly greater than the dose rates from either of the two components analyzed individually in this study. Additional analyses to seek possible alternative procedures in the general maintenance cell operations may be required to reduce the dose rates for more realistic operations. Multi-dimensional analyses using multi-component sources will also be necessary for further design of the cell shielding.

The shielding analyses for the utility vault and the transfer cask were performed in a manner similar to that used in the target and general maintenance cell calculations. The results for determining the amount of steel shielding for the target station inner reflector process water loop in the utility vault indicate approximately 0.63 m of steel shielding is required to meet the 0.5 mrem/h dose requirement. If space constraints limit the shielding, options for declaring this area a "high" or "extremely high" radiation zone will relax the dose requirements and reduce the shielding. In the gamma-ray spectrum for the water coolant, high energy gamma rays from ^{16}N, which are produced by the $^{16}O(n,p)^{16}N$ reaction, and whose half life is 7.12 seconds, are dominant. If the target water coolant could be stored in a shielded tank for ~1 minute, the required additional steel thickness would be reduced to approximately 0.42 m for a source 1 minute after shutdown. For determination of the steel thickness for the transfer cask for activated target components, the Be/D_2O reflector assembly was used as a source term to demonstrate the shielding requirement. The results indicate 0.44 m of steel is required to obtain 77.2 mrem/h at the surface of the transfer cask. The dose rate requirement for the transfer cask is 100 mrem/h at the surface of the cask.

5. Conclusions And Recommendations

A preliminary shielding analysis of the proposed SNS was performed for the target station and associated maintenance cells and utility areas, accelerator and ring tunnels, and the accelerator system beam dumps. Analyses were performed utilizing coupled HETC-ANISN calculations and CASL 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 those areas of concern. Future analyses need 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. Furthermore, alternative procedures for operations of the general maintenance cell, will be required for a more detailed design of the maintenance systems for the construction phase of the NSNS project

References

1. Oak Ridge National Laboratory, "National Spallation Neutron Source (SNS) Conceptual Design Report," Volume 1, NSNS/CDR-2/V1.
2. U. S. Department of Energy, *Safety of Accelerator Facilities, DOE Order 5480.25*, U S DOE, Washington DC, (1992).
3. T. A. Gabriel, et al., "CALOR: A Monte Carlo Program Package for the Design and Analysis of Calorimeter Systems," Oak Ridge National Laboratory, ORNL/TM-5619 (1977).
4. J. F. Briesmeister, Ed. "MCNP-A General Purpose Monte Carlo Code for Neutron and Photon Transport," LASL Report LA-7396-M, Rev.2 (Sept. 1986).
5. W. W. Engle, Jr., "A User's Manual for ANISN: A One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering," Union Carbide Nuclear Division Report K-1693 (1967).
6. R. G. Alsmiller, Jr. and J. Barish, "HILO Neutron-Photon Multi-group Cross Sections for Neutron Energies < 400 MeV," Oak Ridge National Laboratory, ORNL/TM-7818 (June 1981).
7. T. W. Armstrong, "CASL - A Computer Aided Shield Layout Code," unpublished, (1985).
8. P. Cloth, et al., "HERMES, A Monte Carlo Program System for Beam Material Interaction Studies," KFA Jülich, Report Jul-2203 (1988).

Table 1. Summary of shielding analyses, source terms, and calculational methodologies used to support the conceptual design of the SNS proton beam transport and target station facility components.

SNS facility	Shielding analysis	Source term	Calculational methodologies
Linac Tunnel			
333 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
	Component Activation	Activated Copper	HETC/MCNP/ORIHET/ANISN
667 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
	Component Activation	Activated Copper	HETC/MCNP/ORIHET/ANISN
1 GeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
	Component Activation	Activated Copper	HETC/MCNP/ORIHET/ANISN
Klystron Building			
333 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
667 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
1 GeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
Linac Service Road			
333 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
667 MeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
1 GeV	Normal Operation	10 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	4 MW Point Loss	HETC/ANISN, CASL
Ring Tunnel			
1 GeV	Normal Operation	1 nA/m Beam Loss	HETC/ANISN, CASL
	Catastrophic Accident	2 MW Point Loss	HETC/ANISN, CASL
	Component Activation	Activated Copper	HETC/MCNP/ORIHET/ANISN
Beam Dumps			
Linac Tune	Normal Operation	100 kW Beam Power	HETC/ANISN, CASL
Ring Injection	Normal Operation	200 kW Beam Power	HETC/ANISN, CASL
Ring Tune	Normal Operation	50kW Beam Power	HETC/ANISN, CASL
Target Station			
	Normal Operation	4 MW Beam Power	HETC/ANISN, CASL
Target Service Cell			
	Normal Operation	Activated Target SS-316	HETC/MCNP/ORIHET/ANISN
	Target Mercury Loop	Activated Mercury	HETC/MCNP/ORIHET/ANISN
	Target Cooling Loop	Activated Water	HETC/MCNP/ORIHET/ANISN
	Hg Spill Accident	Activated Mercury	HETC/MCNP/ORIHET/DORT
	Beam Trip Failure	1 MW Proton Beam	CASL
General Maintenance Cell			
	Normal Operation	Activated Be Reflector	HETC/MCNP/ORIHET/ANISN
	Normal Operation	Activated Ni Reflector	HETC/MCNP/ORIHET/ANISN
Utility Vault Pipe Chase			
	Normal Operation	Activated Cooling Water	HETC/MCNP/ORIHET/ANISN

Table 2. Summary of dose criteria, minimum required shielding, and dose rate analysis results used to support the conceptual design of the SNS proton beam transport and target station facility components.

SNS Facility	Shielding Analysis	Dose Criteria	CDR shield Design	Calc. min. req. Shielding	Dose rate or Comment
Linac Tunnel					
333 MeV	Normal Op.	0.125 mrem/h	9.14 m berm	6.40 m berm	0.060 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	5.99 m berm	12.29 rem/h
667 MeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.47 m berm	0.056 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	6.93 m berm	12.18 rem/h
1 GeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.92 m berm	0.077 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	7.49 m berm	12.00 rem/h
	Comp. Act.	NA	NA	NA	264 rad/h at 1 m
Klystron Bldg.					
333 MeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.49 m berm	4.24e-03 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	7.49 m berm	0.334 rem/h
667 MeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.49 m berm	2.62e-02 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	7.49 m berm	2.520 rem/h
1 GeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.49 m berm	6.29e-02 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	7.49 m berm	5.680 rem/h
Linac Srvc. Rd.					
333 MeV	Normal Op.	0.05 mrem/h	9.14 m berm	7.49 m berm	2.02e-03 mrem/h
	Catst. Acc.	1 rem/h	9.14 m berm	7.49 m berm	0.082 rem/h
667 MeV	Normal Op.	0.05 mrem/h	9.14 m berm	7.49 m berm	1.76e-02 mrem/h
	Catst. Acc.	1 rem/h	9.14 m berm	7.49 m berm	0.711 rem/h
1 GeV	Normal Op.	0.05 mrem/h	9.14 m berm	7.49 m berm	4.14e-02 mrem/h
	Catst. Acc.	1 rem/h	9.14 m berm	7.49 m berm	1.640 rem/h
Ring Tunnel					
1 GeV	Normal Op.	0.125 mrem/h	9.14 m berm	7.92 m berm	0.068 mrem/h
	Catst. Acc.	25 rem/h	9.14 m berm	8.61 m berm	12.15 rem/h
	Comp. Act.	NA	NA	NA	25.3 rad/h at 1 m
Beam Dumps					
Linac Tune	Normal Op.	0.125 mrem/h	9 m Steel	8.48 m Steel	0.123 mrem/h
Ring Injection	Normal Op.	0.125 mrem/h	9 m Steel	8.70 m Steel	0.124 mrem/h
Ring Tune	Normal Op.	0.125 mrem/h	9 m Steel	8.22 m Steel	0.122 mrem/h
Tgt. Station					
	Normal Op.	0.125 mrem/h	5 m Steel + 1 m Conc.	5 m Steel + 1 m Concrete	6.26e-02 mrem/h
Tgt. Srvc. Cell					
	Act. Tgt. SS316	0.125 mrem/h	1 m Hvy Conc	1 m Hvy Conc	4.98e-10 mrem/h
	Tgt. Hg Lp.	10 rad/h at 0.5 m	To Be Determined	0.20 m Steel	9.70 rad/h
	Tgt. H2O Lp.	10 rad/h at 0.5 m	To Be Determined	0.10 m Steel	9.94 rad/h
	Hg Spill Acc.	0.125 mrem/h	1 m Hvy Conc	1 m Hvy Conc	1.82e-04 mrem/h
	Bm. Trp. Fail.	25 rem/h	1 m Hvy Conc	1 m Hvy Conc	Redesign Target Plug
Gen. Maint. Cell					
	Act. Be Refl.	0.125 mrem/h	1 m Hvy Conc	1.20 m Hvy Conc	0.08 mrem/h
	Act. Ni Refl.	0.125 mrem/h	1 m Hvy Conc	1.08 m Hvy Conc	0.07 mrem/h
Utility Vault					
	Normal Op.	0.5 mrem/h at 0.3 m	To Be Determined	0.42 m steel	0.469 mrem/h With 1 min Decay Source