PRELIMINARY SHIELDING ANALYSIS AND DESIGN OF THE REMOTE MAINTENANCE CELLS FOR THE PROPOSED NATIONAL SPALLATION NEUTRON SOURCE (NSNS)

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ABSTRACT

Radiation shielding analysis and design calculations were performed for remote maintenance cells of the proposed National Spallation Neutron Source (NSNS) facility. In the analysis, a calculational strategy utilizing coupled high energy Monte Carlo calculations and multi-dimensional discrete ordinates calculations was implemented to perform an activation analysis and shielding assessment of the NSNS remote handling cells. A general description of the remote maintenance cells, the methodology employed, and preliminary results of the shielding analysis and recommendations are presented.

I. INTRODUCTION

The Department of Energy (DOE) has initiated a conceptual design study for the National Spallation Neutron Source (NSNS) and given preliminary approval for the proposed facility to be built at Oak Ridge National Laboratory (ORNL). The conceptual design of the NSNS initially consists of an accelerator system capable of delivering a 1 GeV proton beam with 1 MW of beam power in an approximate 0.5 μ s pulse at a 60 Hz frequency onto a single target station.

Optimization of operating availability and predictability, while protecting personnel, is the primary goal of the remote maintenance systems for the NSNS. Towards this end, the liquid mercury target system activation analysis is important for the design of the target service cell and general maintenance cell due to its importance on conventional facility design, maintenance operations, and facility availability.

The As Low As Reasonably Achievable (ALARA) principle was used as guidance for all personnel and contamination control operations in the NSNS. Furthermore, the top level document for accelerator safety regulation (DOE Order 5480.25, Safety of Accelerator Facilities)[1] and the associated guidance were utilized in the shielding assessment. Taking into account these guidelines, shielding analyses were performed for the entire NSNS facility. In this paper, attention was focused on the analysis for the remote maintenance cells. An overview of the preliminary shielding analysis for other parts of the NSNS can be found in a companion paper.

II. REMOTE MAINTENANCE CELLS

Several techniques proven in successful facilities throughout the world have been applied in the NSNS design to assist the operators in meeting optimization of operating availability and predictability, while protecting personnel. It is important to design operating equipment in the earliest stages of design to reduce the need for remote handling and packaging. Furthermore, attention should be given to designing operating equipment in modular assemblies designed to be replaced with on-site spares. This enables operations to continue while time-consuming repairs are performed in off-line facilities. Maintenance concepts for the NSNS neutron source system can be divided into two types, those associated with the mercury loop, and those involving the shielding and neutron beam systems. In the first case, both the activation and contamination levels will be very high and attention must be given to isolate maintenance operations from the environment and personnel. In the

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later case, components will normally not have significant amounts of contamination and therefore emphasis will be placed on protecting personnel from activation. For radiation control operations in the NSNS, the ALARA principle shall be used as guidance. Therefore, activated and contaminated equipment should be shielded for transport around the facility and to the permanent storage site. Areas of potential contamination will be isolated by seals and valves. Repair and replacement of active components will be accomplished in the hot cells associated with the target station. As for the radiation shielding guideline in normal operation of the facility, average dose rates should be less than 0.05 mrem/h for general employees and visitors and 0.125 mrem/h for radiation workers. In case of catastrophic accident such as release of mercury and contaminated cooling water into the shielding region, dose rates should not exceed 25 rem/h outside any shielded enclosure.

A. Target Service Cell

A target service cell will be located behind the target assembly for the purpose of maintaining the highly activated target components (Fig. 1). It will measure 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 concrete shielding wall. The dose rate criteria behind the shielding wall is 0.125 mrem/h. Lighting and viewing are critical features of hot cell operations. Considering the radiation resistance of components inside the hot cell, the cell background is required to be kept less than 10 rad/h during normal plant operation. To meet this requirement, the target cooling water loop and mercury loop must be shielded in the target service cell.

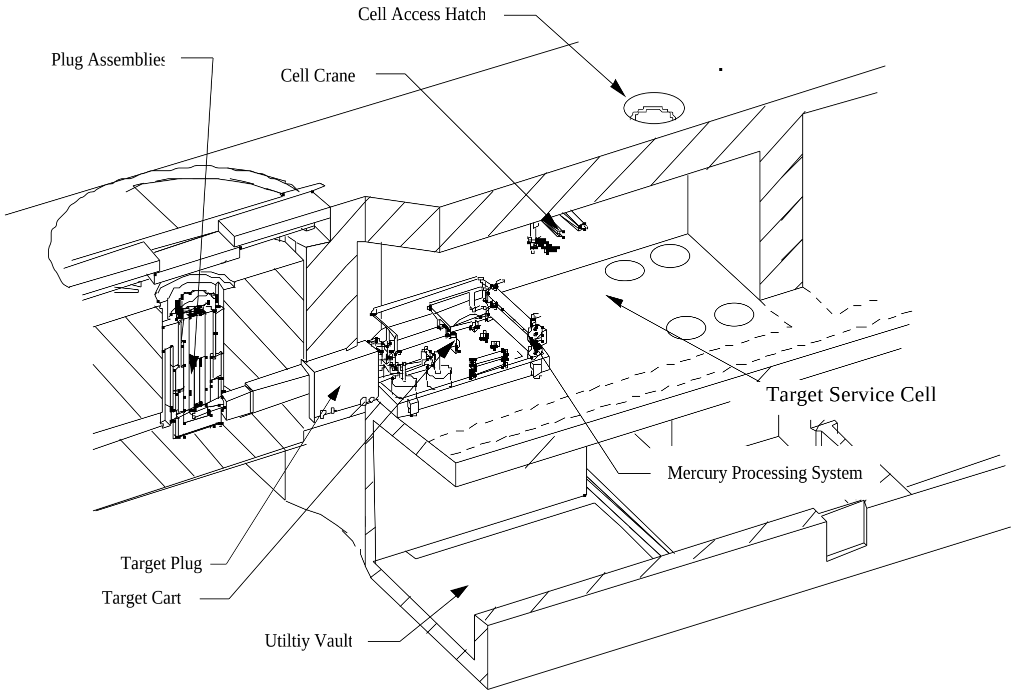

Fig. 1. Target service cell with target cart assembly in operating position.

B. General Maintenance Cell

A general maintenance cell will be located behind the target cell to maintain the moderator/reflector/plug, proton beam window, neutron guide tubes and shutters.

This will measure 10 meters wide, 10.9 meter long and 9.5 meters high (Fig. 2). The dose rate criteria behind the shielding wall for the general maintenance cell is also set at 0.125 mrem/h.

C. Utility Vault and Transport Cask

The cooling water used in the inner reflector regions is activated from the harsh radiation environment in the target station. This water flows through a piping chase in the utility vault area which is accessible during normal operation of the target station. The dose rate criteria for shielding purposes was set to 0.5 mrem at 0.3 meters from the piping.

A cell transfer system will be installed to transfer the shielding transport cask between the target service cell and the general maintenance cell. The dose rate criteria at the surface of the transport cask was set to 100 mrem/h. Determining the required shield thickness was one of the objectives in this study.

III. METHODOLOGY OF RADIATION SHIELDING ANALYSIS

The CALOR96[2] code system was the main calculational tool for the numerical radiation transport studies. The three-dimensional, high-energy nucleon-meson transport code HETC96 was used to obtain detailed descriptions of the nucleon-meson cascades. In HETC96, the intranuclear-cascade-evaporation model and the intranuclear-cascade pre-equilibrium evaporation model are used. Transport of neutrons which are produced with energies below 20 MeV was accomplished using MCNP[3]. The MCNP code was coupled to HETC96 in order to provide the proper source for the low energy ($E < 20$ MeV) neutron transport.

For the activation and decay heat analysis, the procedure as shown in Fig. 3 was adopted. The HETC and MCNP codes provide the required input data for the

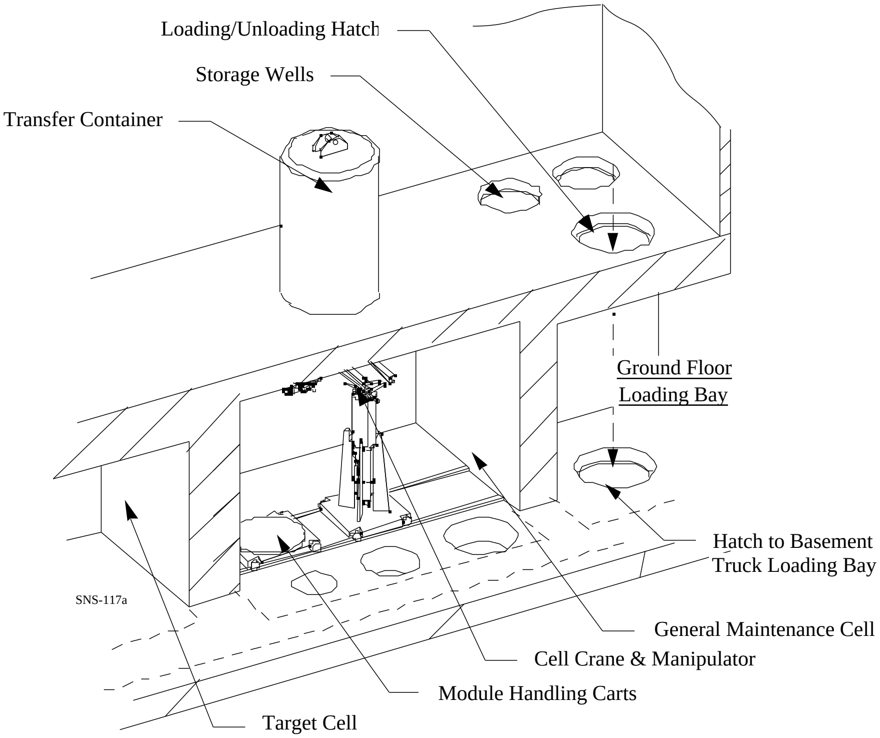

Fig. 2. General maintenance cell and loading bay.

Fig. 3. Flow diagram of the activation and decay heat analysis procedure.

isotope generation and depletion code, ORIHET95[4], which was modified from the original ORIGEN[5] code. ORIHET95 utilizes a matrix-exponential method to study the buildup and decay of activity for any system for which the nuclide production rates are known. In the NSNS analyses, the nuclide production rates from the HETC96 code are fed directly into the ORIHET95 code, and fluxes calculated by the MCNP code are folded with the FENDL Activation Library[6] to generate the nuclide production rates due to low energy neutron interactions. The combination of these two sources yield the radionuclide concentrations, radioactivity, and decay heat data as a function of generation (buildup) time and depletion (decay).

For the shielding design of the NSNS facilities, including the target station, accelerator, and remote maintenance cells, a deterministic method was used instead of the Monte Carlo method 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 shielding analysis of the remote maintenance cells, the ANISN[7] one-dimensional or DORT[8] two-dimensional discrete ordinates deterministic transport code was used to analyze the shielding requirement. The HILO86[9] cross section library was used for the discrete ordinates calculations. HILO86 is a 66-neutron, 22-gamma coupled multi-group library. The ANSI/ANS-6.1.1-1977[10] standard was used in the flux-to-dose rate conversion factors. The decay gamma-ray spectrum calculated from ORIHET95 was used for the gamma-ray source for the deterministic transport codes.

IV. RESULTS OF SHIELDING ANALYSIS OF REMOTE HANDLING CELLS

A. Target Service Cell

For the target service cell, four different types of analyses were performed to determine; (1) required concrete thickness of the room, (2) additional steel shielding around the target cooling water, (3) additional steel shielding around the mercury piping loop, and (4) required concrete thickness in case of a mercury spill from the target. For the first three cases, the room was modeled using a one-dimensional spherical model while 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. The source terms were determined from the activation analysis discussed in section III. Although the initial power proposed for the NSNS facility is 1 MW, the possibility upgrading the facility to 4 MW exists, therefore, all source terms 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. Results of this analysis are summarized in Table 1. The results shown in Table 1 indicate ordinary concrete will not satisfy the dose rate requirement of 0.125 mrem/h on the external surface of the concrete. 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.

Table 1. Shielding Analysis For The Target Service Cell

Calculational Methodology	**Activation Source**	**Dose Rate Criteria**	**Required Shielding**	**Dose Rate**
HETC/MCNP-ANISN	Target SS-316 Jacket	0.125 mrem/h	Ordinary Concrete	1.19E+01 mrem/h
HETC/MCNP-ANISN	Target SS-316 Jacket	0.125 mrem/h	Heavy Concrete	7.90E-02 mrem/h
Target SS-316 jacket requires 1.00 meters of heavy concrete to obtain 0.08 mrem/h on the outside.				
HETC/MCNP-ANISN	Target Cooling Water	10 rad/h @ 0.5 m	0.10 m Steel	9.94E+00 rad/h
HETC/MCNP-ANISN	Target Mercury	10 rad/h @ 0.5 m	0.20 m Steel	9.70E+00 rad/h
HETC/MCNP-DORT	Target Mercury Spill Case	0.125 mrem/h	Heavy Concrete	1.33E+00 mrem/h
Target mercury requires 1.20 meters of heavy concrete to obtain 0.07 mrem/h on the outside.				
Target service cell walls = 1.0-meter-thick Activation sources are for 4 MW operation of target station				

Table 2. Dose Rate Versus Distance in Target Service Cell for Activated Mercury Loop

Distance From Target Cart Shielding (m)	Dose Rate (rad/h) No Added Steel Shielding	Dose Rate (rad/h) 0.2 m Added Steel Shielding
0.0	4.39E+04	3.43E+04
0.5	9.35E+03	9.70E+00
1.0	4.05E+03	4.20E+00
1.5	2.35E+03	2.40E+00
2.0	1.50E+03	1.60E+00
Dose rate criteria for required additional steel shielding = 10 rad/h @ 0.5 meters Target service cell walls = 1.0-meter-thick concrete Mercury activation source is for 4 MW operation of target station Attenuation through mercury accounted for in model		

The amount of additional steel shielding, which is required around the mercury loop and mercury target cooling water loop to maintain a dose rate in the room of less than 10 rad/h at 0.5 meters from the surface of the shield, was also determined. These results are also shown in Table 1. The results indicate 0.1 meters of steel will reduce the dose rate from the cooling water down to 9.94 rad/h, and 0.2 meters of steel will reduce the dose rate from the mercury flow loop to 9.70 rad/h. The dose rate versus distance in the target service cell for the activated mercury loop is listed in Table 2 with and without the additional shielding

B. General Maintenance Cell

The shielding analyses of the general remote maintenance cell, which is located adjacent to the target service cell, were carried out in a similar way as for the target service cell. The room was modeled as a one-dimensional spherical room, of equivalent volume, with one-meter-thick concrete walls. The two most active components from the inner reflector assembly were modeled in the center of the room, in separate calculations, and the dose rate was determined at the external surface of the concrete wall. From the activation analysis, the beryllium/D_2O reflector assembly, and the nickel inner reflector plug assembly were the two most radioactive sources that would be serviced in the general remote maintenance cell. The results, presented in Table 3, indicate ordinary concrete walls are insufficient to meet the dose rate requirements of 0.125 mrem/h. Though substituting heavy concrete reduced the calculated dose rate, additional heavy concrete shielding is still required to meet the dose rate limit. The results further indicate at least 1.20 m of heavy concrete is required for the most activated component, the Be/D_2O reflector. 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.

C. Utility Vault and Transfer Cask

The shielding analyses for the utility vault and the transfer cask were performed in a manner similar to that in sections III.A and III.B. The results for determining the amount of steel shielding for the target station inner reflector process water loop in the utility vault is shown in Table 4. The results in Table 4 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

Table 3. Shielding Analysis For The General Maintenance Cell

Calculational Methodology	Activation Source	Dose Rate Criteria	Concrete Type	Dose Rate (mrem/h)
HETC/MCNP-ANISN	Be/D_2O Reflector	0.125 mrem/h	Ordinary	3.29E+01
HETC/MCNP-ANISN	Be/D_2O Reflector	0.125 mrem/h	Heavy	6.04E-01
Be/D_2O reflector requires 1.20 meters of heavy concrete to obtain 0.08 mR/h outside the shield.				
HETC/MCNP-ANISN	Nickel Inner Plug	0.125 mrem/h	Ordinary	2.08E+01
HETC/MCNP-ANISN	Nickel Inner Plug	0.125 mrem/h	Heavy	2.01E-01
Nickel inner plug requires 1.08 meters of heavy concrete to obtain 0.07 mrem/h outside the shield.				
General maintenance service cell walls = 1.0-meter-thick concrete Activation sources are for 4 MW operation of target station Attenuation through activation source accounted for in model				

Table 4. Dose Rate Versus Steel Shield Thickness in Utility Vault for Activated Target Station Cooling Water Loop

Thickness of Added Steel Shielding (m)	Dose Rate At 0.3 m From Shield (mrem/h)	
	Shutdown Source	1 Minute Source after Shutdown
0.10	1.38E+04	4.82E+03
0.20	1.24E+04	2.48E+02
0.30	1.15E+03	1.33E+01
0.40	1.08E+02	8.21E-01
0.42	-	4.69E-01
0.50	9.90E+00	
0.52	6.21E+00	
0.54	3.84E+00	
0.58	1.48E+00	
0.62	5.42E-01	
Dose rate criteria for water loop = 0.5 mrem/h @ 0.3 meters Dose rate determined at 0.3 meters from shield		

Activation source is for 4 MW operation of target station
Attenuation through cooling water accounted for in model

in a shielded tank for ~1 minute, the required additional steel thickness would be reduced. Results in Table 4 indicate the additional steel thickness will be 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.

IV. CONCLUSIONS

A shielding analysis of the proposed NSNS was performed for the remote handling cells, including the target service cell and general maintenance cell. Results of the present analysis show ordinary concrete will not satisfy the shielding requirements while the utilization of heavy concrete will meet the requirements. For shielding of the target water loop in the utility vault, storing water in a tank for approximately 1 minute can reduce the pipe chase steel shield by 33%. The present analysis indicates the primary goal of the maintenance system of the NSNS, which is optimization of availability and predictability while protecting personnel, can be achieved.

The present study is a preliminary shielding assessment to confirm radiation shielding safety of the remote maintenance systems of the NSNS. Further analyses, including multi-dimensional discrete ordinates calculations and 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.

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