TWO-DIMENSIONAL SHIELDING ANALYSES OF THE SNS BEAM LINE AND T_0, E_0, AND BANDWIDTH CHOPPERS

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ABSTRACT

Two-dimensional discrete ordinates shielding calculations have been performed for the Spallation Neutron Source (SNS) beam lines. The calculations include simulation of the T_0, E_0, and Bandwidth choppers, and a "generic" straight beam line. The purpose of these calculations was to perform exploratory analyses to estimate the minimum shielding required to reduce personnel doses to ~0.25 mRem/h.

For source distances up to 10 m, a combined steel and concrete shielding thickness of up to ~2 m is required to reduce the dose to ~0.25 mRem/h.

I. INTRODUCTION

The Spallation Neutron Source (SNS) is an accelerator-based neutron source currently under construction in Oak Ridge, Tennessee and funded by the Department of Energy (DOE). When operational, the SNS will provide the most intense pulsed neutron beams in the world for uses in scientific research and industrial applications.

Because of the intensity of the radiation generated, shielding is required throughout the facility. This paper addresses the calculation of shielding required around beam lines through which neutrons are directed. In particular, the results from two-dimensional shielding calculations are presented. These include simulation of a "generic" straight beam line and simulation of components (choppers) designed to filter the beam line neutron energy spectrum. Chopper types include the T_0, the E_0, and Bandwidth (BW) choppers. The overall purpose of these calculations was to perform exploratory analyses to estimate the minimum shielding required to reduce personnel doses to ~0.25 mRem/h which allows unlimited personnel access.

Calculations were based on a discrete ordinates analysis methodology. Separate three-dimensional discrete-ordinates analyses that simulate the components in more detail were also performed.[1]

II. CALCULATION APPROACH

Two-dimensional simulations were performed using the DORT[2] two-dimensional radiation transport code. This approach dictated the use of cylindrical geometry to model beam line and chopper configurations. Accordingly, the rectangular 10 cm by 12 cm beam line opening was approximated in cross-section as a circular opening of equivalent area (radius = 6.2 cm) and the shielding around the beam line or chopper was simulated as an annulus. Choppers or beam-stop components that intercept the beam were simulated as cylindrical "plugs" of an appropriate thickness with a homogeneous material composition.

The purpose of the two-dimensional calculations was to provide exploratory scoping analyses which could be used to support more detailed three-dimensional analyses. Three-dimensional models using the TORT[3] radiation transport code can be used to more accurately simulate a given configuration but in general require considerably more computer time and memory than equivalent two-dimensional calculations. Therefore the two-dimensional calculations could be used to narrow the scope of parameters for the three-dimensional models and also serve as a check on the calculation results.

As an additional measure of simplification and conservatism, these generic models do not simulate beam line curvature found in the design of certain beam lines. Curvature of a beam line results in a larger attenuation of fast neutrons along the length of the line than would otherwise occur in an equivalent straight line. Calculations for specific curved beam lines are in progress.

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All two-dimensional discrete ordinates calculation models developed for these analyses used a P_5 Legendre scattering order. Except for certain calculations in which a higher order of quadrature was required, the S_{10} angular quadrature was used.

The 88-group HILO[4] (66 neutron groups, 22 gamma groups) cross-section set was used. The group structure of this cross-section set has a maximum neutron energy of 400 MeV and a maximum gamma energy of 20 MeV.

A. Limitations and Strategy

For most calculations, the shielding was divided into two material regions. Region 1 (nearer the beam line axis) contained carbon steel. Region 2 initially contained concrete. The general approach was to first minimize the steel/concrete shield thickness to achieve a specified dose rate. Then, with the steel thickness determined, the effects from replacing the concrete with borated concrete were determined.

The "target dose" rate was 0.25 mRem/h. This value was adjusted in two ways. The dose was lowered initially to ~0.14 mRem/h to allow for dose contributions from adjacent beam lines. In addition, the target dose at locations within the model was increased by a factor of ~1.7 because of reflection effects within the model from material at radii greater than the radius where the dose was evaluated. (It is necessary to increase the target dose since the calculated dose is higher than it would be if the additional shielding were not present.) Thus, the final target calculated dose was ~0.23 mRem/h which was essentially identical to the initially assumed value.

B. Neutron Source Simulation

The source terms for the transport calculations were based on the energy and angular dependent neutron leakage from the SNS moderator faces. Leakage from the moderator faces was calculated using the MCNPX[5,6] code employing a fairly detailed model of the Hg target, cold and ambient moderators, inner and outer reflector regions, inner beam tube channels, and the innermost sections of the target monolith shielding.

The above source terms were normalized to 1.24×10^{16} protons/s, i.e., 2 milliamps. In the 88-group HILO energy structure, all neutrons above 400 MeV were placed in the highest energy group (375 to 400 MeV) with a weight equal to the ratio of the neutron energy to the group midpoint energy (387.5 MeV). As an example, an 800 MeV neutron would be treated as 2.06 (800/387.5) neutrons.

It was decided early on that a point source was adequate for the two-dimensional calculations. However, it was not practical to use a point source directly in the DORT models for the following reasons. Because the source neutrons must be transported along a narrow channel (the beam line opening), a very high-order angular quadrature would be required to provide sufficient angular resolution in the channel. Also, to explicitly include the source in the model, it would be necessary to model the entire geometry including the source region. For a location on the beam line five or more meters from the source, this approach would result in a model with an excessive number of mesh cells and would require an unacceptably long time to achieve numerical convergence. The approach used, therefore, was to model only the region of interest (e.g. chopper, or section of beam line) and to use a semi-analytic methodology to transport the point source neutrons to a "first site of collision" in that model. These interactions were then input as the source for subsequent DORT discrete ordinates transport calculations. The GRTUNCL[7] code, which semi-analytically determines these first-collision events, was used to calculate the first-collision source.

Figure 1 shows a generalized model of an SNS beam line in which the beam is stopped by a 1-m steel plug at a distance of 10 m (face of the plug nearest the source) from the source. The model includes a 5-m length of the beam line. (Specific models and results are discussed in Section III.) GRTUNCL was used to semi-analytically transport the source neutrons along the beam line opening to the section that was modeled. A region of "black" material (a cross-section mixture consisting of a single material (aluminum), but with an extremely high atomic density, e.g. 1.0×10^{20}, which stops all particles) was located on the face of the geometry toward the source. This approach prevented source particles from being transported directly to the modeled geometry other than through the beam line. In effect, the black material replaced the shielding material in that region.

Because some scattered radiation does enter the modeled section through the shielding region not included in the model, it was necessary to make an estimate of this additional scattered radiation and add it back into the original source. This approach was implemented by explicitly modeling the beam line from the source to the entrance of the T_0 Chopper at a distance of 5 m from the source. The calculated leakage, S, from the end of the model was normalized and included as an additional source contribution, S*, to the original point source.

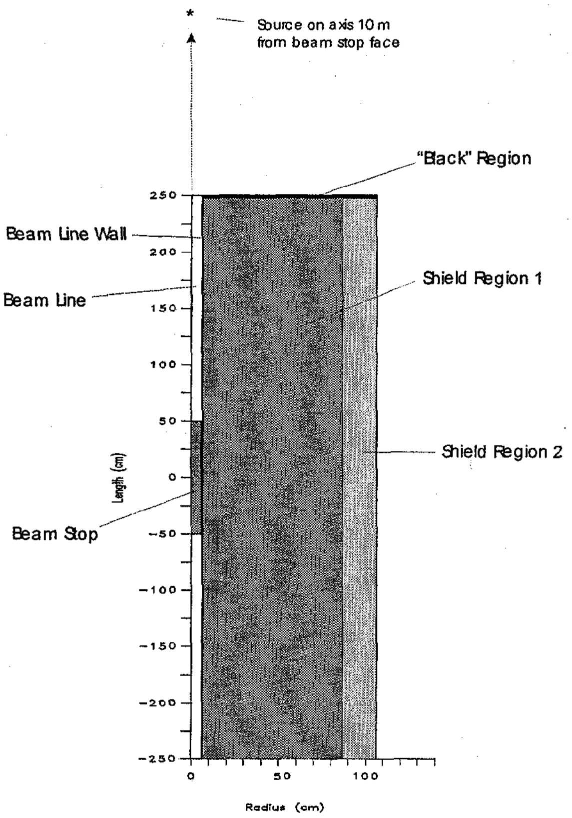

Figure 1. Two-dimensional shielding model for generic beam line.

This additional source was therefore seen by the model in the sense that particles passed through the opening in the black material barrier. The normalization equation is as follows:

$$S^* = (4 D^2 / R^2) S$$

where D = distance from the source to the end of the model (500 cm) and R is the radius of the beam line opening (6.02 cm). On average, the additional source contribution was ~5% per group, but was as great as ~14% in some high-energy neutron groups.

S^* provides a conservative estimate of the additional collided particles passing through the entrance to the T_0 chopper. For the E_0 and BW choppers, the additional source term was doubled for each group to remain conservative.

GRTUNCL and DORT use the same calculation model, except that the black material was removed in the DORT calculation (where it served no purpose) and replaced with a void to prevent numerical convergence problems.

III. BEAM LINE SHIELDING

Two approaches were considered for the two-dimensional beam line shielding model. In the first approach, shown conceptually in Figure 1, the beam was stopped by a 1-m-long stainless steel plug, which completely filled the beam line cross section, thus completely blocking the beam path. This was considered a conservative approach. The presence of a beam-stop results in the largest dose perpendicular (radial) to the beam line because of the scattering of the radiation from the plug. In the second approach, the beam line cavity was left open. In this case, transport in the radial direction resulted from initial scattering events at small (grazing) angles. For both approaches, a 5-m length of the beam line was modeled. The plug (or the plug replaced by a void in the open line case) was located in the center of the model and the source was located 10 m from the near face of the plug (1050 cm from the center of the plug). The GRTUNCL code was used to semi-analytically transport the source particles to the model and a layer of black material was used to channel the neutrons through the voided tube. The source, as described in Section 2.2, contained an approximation of the additional contribution from scattered radiation.

A. Calculation Results (Stopped Beam)

Optimization calculations were performed with the beam stop in place for a combination shield of steel and concrete, and the steel was varied until a minimum total thickness shield was determined. Table 1 summarizes the results.

Table 1. Shielding required for the generic beam line with the beam stopped by a 1-m steel plug

Shield thick. (cm)			Dose rate (mRem/h)		
Steel	Conc.[a]	Tot.	Neut.	Gam.	Tot.
100	100	200	0.319	0.057	0.376
120	80	200	0.169	0.066	0.235
132	68	200	0.119	0.097	0.216
140	60	200	0.103	0.102	0.205
160	40	200	0.097	0.108	0.205
140	44[b]	184	0.189	0.037	0.226
140	56[c]	196	0.186	0.033	0.219

[a] Unborated concrete unless indicated.
[b] Borated concrete.
[c] Borated polyethylene.

For the cases in Table 1 that include unborated concrete, all the values shown are on the outer periphery of the model where the total shielding thickness is 200 cm. On the periphery of the model the target dose of 0.14 mRem/h is used instead of .23 mRem/h because there is no reflection to warrant the additional factor of ~1.7 (see discussion in Section I.A). Thus, a shielding thickness of 200 cm is seen to be slightly inadequate. Results for the cases with steel thickness of 140 and 160 cm are approximately the same. The optimal case is assumed to be the smaller amount of steel, i.e. 140 cm. To achieve a target dose of 0.14 mRem/h, the concrete needs to be increased only by a small amount (~2 cm) for a total shielding thickness of ~202 cm.

Because of the increments of steel available, a near optimal steel thickness of 132 cm (52 in.) (plus an additional ~70 cm of concrete), was also considered, since the results were nearly the same as for the cases with 140 and 160 cm of steel. Figure 2 shows a dose isoplot (contour plot) for this calculation. The source is located in the positive z direction (on the axis above the plot) at a point 10 m from the +50 cm z location.

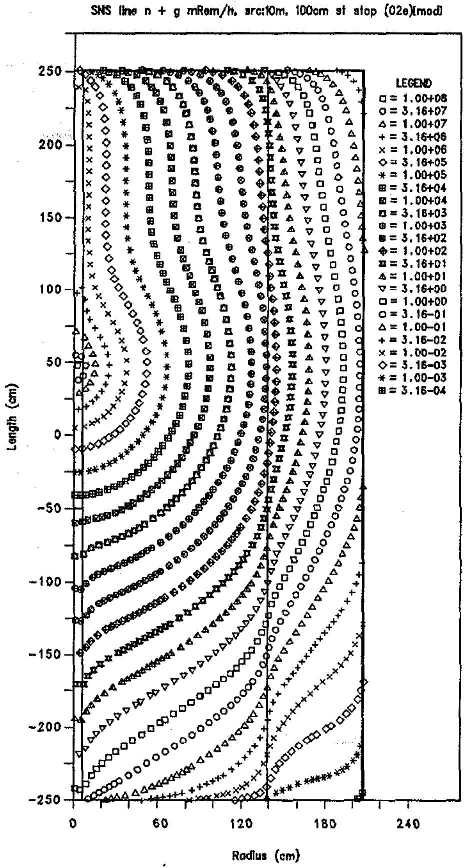

Figure 2. Isoplot of neutron plus gamma dose for beam line model with 1-m beam stop and 132 cm steel + 68 cm concrete shielding.

Table 1 also shows the results of additional runs for the 140-cm steel case with borated (~1.5 wt. %) concrete and borated polyethylene substituted for the concrete. For the borated concrete case, a total shield thickness of 184 cm is required. Thus, a savings of ~18 cm (202 cm – 184 cm) is achieved. For the borated polyethylene substitution, a savings of only about 6 cm is realized.

B. Calculation Results (Open Beam Line)

Additional calculations were also performed using the same model as in the previous section but with the 1-m steel plug removed, thus creating an open beam line. For the case with 132 cm of steel and 68 cm of concrete, the dose at the full 2-m shield is about 20% of that calculated for the "stopped" beam case. Thus, as expected, less shielding is required for the open beam line to meet the target dose rate. In this case, for a steel thickness of 132 cm, the target dose (~.23 mRem/h) is obtained with 50 cm of concrete, for a total shield thickness of 182 cm. Figure 3 shows an isoplot of this case.

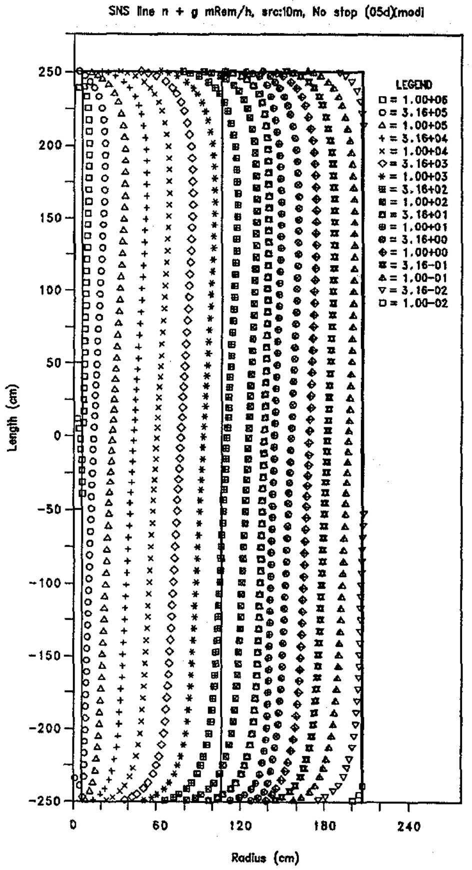

Figure 3. Isoplot of neutron plus gamma dose for beam line open model with 132 cm steel + 68 cm concrete shielding.

C. Steel Shielding Reduction with Distance

If a constant shielding configuration along the length of an open straight beam line is assumed, the dose attenuation at any specified location perpendicular to the beam line axis can be shown to vary with ~$1/D^3$, where D is the distance along the beam line from the source. However, the attenuation varies as ~$1/D^2$ for a stopped beam line. At some distance it is feasible that the shielding thickness can be reduced and the dose still kept at the target dose amount. In particular it is of interest to know at what point the beam line steel shielding can be reduced to the next smaller size (i.e. by an increment of 33 cm (13 in.)).

To investigate this possibility for the open beam line assumption, the steel thickness was reduced to 100 cm from the baseline case of 132 cm. This is a reduction by approximately the 33-cm (13-in.) increment discussed above. Calculations were performed with the source distance set to 10 and 20 m. For the 10 m source distance, the dose calculated for a 50-cm thickness of concrete was 1.79 mRem/h. If $1/D^3$ attenuation is assumed, the 10 m calculation predicts that the dose would be reduced to ~.23 mRem/h for a source distance of ~20 m. The actual calculated dose for the 20 m case was .131 mRem/h, somewhat lower than predicted, but within reasonable agreement if the $1/D^3$ attenuation is regarded as a "rule-of-thumb" approach.

This estimate and approach is valid only for a straight line. Several of the SNS beam lines are curved and will have greater attenuation along the beam line length.

IV. CHOPPER MODEL CALCULATIONS

Cylindrical R-Z DORT models were used to simulate the T_0, E_0, and BW choppers. It is not within the scope of this paper to describe the purpose and details of each of the choppers. From a shielding standpoint, a chopper is a material which blocks a beam line and therefore introduces a source of scattered radiation. Thus, The models were similar to each other and were similar to the plugged beam line model discussed earlier. In each case, the beam line section was approximated as a 2-m-long cylindrical and the chopper was modeled as a cylindrical plug of appropriate thickness. Table 2 summarizes the material, size (thickness), and source distance for each chopper.

Table 2. Chopper model parameters.

Chopper	Materials	Size[a] (cm)	Source Dist.[b] (cm)
T_0	Inconel 750	30	576
E_0	boron, aluminum	10	1000
BW	aluminum, cadmium	2.67	750

[a] Thickness of chopper on model Z-axis.
[b] Distance from source to center of chopper.

The approach using the GRTUNCL and DORT codes as described in the previous section, was used for each chopper model. A similar shielding optimization approach was also used in each case.

In each case, calculations were performed with the chopper exposed to the "full" source. No credit was taken for attenuation of the source by another chopper closer to the source. However, additional calculations were performed for the E_0 Chopper for which the source was initially attenuated by a T_0 Chopper (see Section IV.B).

A. Calculation Results

A shielding optimization was performed for each chopper model in a manner similar to the stopped beam line. Optimization calculations were performed for a combination shield of steel and concrete, and the steel was varied until a minimum total thickness shield was determined. The concrete was then replaced with borated concrete. Table 3 summarizes the results for the three choppers.

Table 3. Shield optimization calculations for T_0, E_0 and BW choppers.

Chopper	Source Distance[a] (cm)	Optimal Shielding Thickness[b] (cm)		
		Steel	Concrete	Total
T_0	576	160	62	222
		160	38[c]	198
E_0	1000	120	76	196
		120	60[c]	180
BW	750	100	93	193
		100	76[c]	176

[a] Distance from source to center of chopper.
[b] For target dose.
[c] Borated concrete.

Figure 4 is an isoplot of the total dose for the T_0 Chopper with a 160-cm-thick steel and concrete shield. For this model the source is located toward the "bottom" or –Z dimension, 576 cm from the center of the chopper along the Z axis. Plots for the other choppers are similar in appearance and orientation with regard to the source.

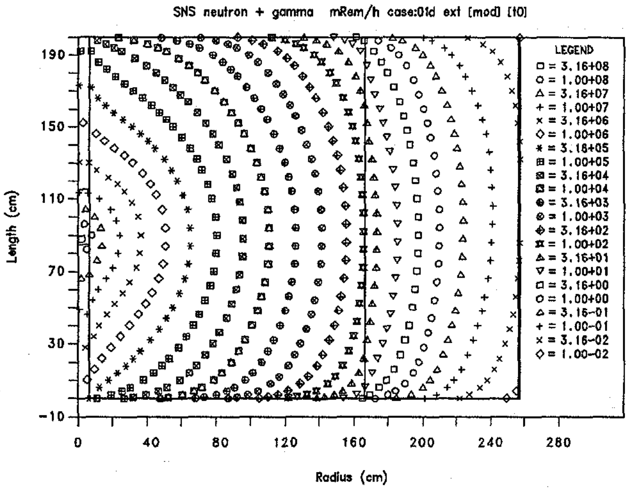

Figure 4. Isoplot of neutron plus gamma dose for T_0 Chopper with 160 cm steel + 90 cm concrete shielding.

Results from Table 1 show that the optimum steel shielding thickness varies over a significant range, depending on the chopper considered. However, selection of the optimal thickness was somewhat arbitrary, since the total shield thickness required tended to vary only a small amount for a significant variation in the steel thickness. For the T_0 Chopper, the total required shield thickness with anywhere from 140-cm to 200-cm of steel only differed by approximately 5 cm. Therefore, it would be feasible to select an amount of steel somewhat more or less than 160 cm (with less or more concrete to make up the difference). An appropriate practical steel thickness for the T_0 chopper could be 165 cm which would correspond to a multiple of 33 cm (13 in.), i.e. 5 x 33 cm = 165 cm (65 in.).

For each chopper, the use of borated concrete reduced the total shield required. This reduction was 24, 16, and 17 cm respectively for the T_0, E_0, and BW choppers.

B. Chopper Model Calculation Results for Source Attenuated by a T_0 Chopper

Additional calculations were performed for the E_0 Chopper, in which the source was attenuated through the T_0 Chopper. The model used for these calculations included both the T_0 and the E_0 choppers. This model used the largest quadrature set readily available for the DORT code (315 angles, forward biased) to suitably represent neutrons exiting the T_0 Chopper towards the E_0 Chopper along the beam line. The shielding configuration was as follows:

T_0 Chopper	160 cm steel, 40 cm concrete
Beam line	130 cm steel, 70 cm concrete
E_0 Chopper	120 cm steel, 80 cm concrete

The steel shielding assumed for the T_0 Chopper, Beam line, and E_0 Chopper were approximately the optimized amounts for the "full source" calculations. The reason for this calculation was to estimate the reduction in shielding if credit could be taken for the T_0 Chopper attenuation.

Results from the E_0 chopper calculation indicate that the target dose is achieved with ~125 cm of shielding, that is, the 120 cm shielding plus a small thickness (~5 cm) of concrete (this amount may be less with optimization). Thus, if credit can be taken for attenuation by the T_0 Chopper, the shielding requirements are approximately 50 to 70 cm less than for the full source case in which steel and either borated or unborated concrete is used.

Because the chopper is approximated as a homogeneous material, the above results do not account for the low energy neutrons that in actuality are allowed to pass through the T_0 Chopper unimpeded. However, additional calculations show that only ~35 cm of steel is necessary to reduce doses to the target dose level for low energy source neutrons (~ < 22.6 eV). Thus, the additional dose from low energy neutrons that pass through the T_0 Chopper unimpeded can be ignored in light of the amount of shielding otherwise required.

V. CONCLUSIONS

Two-dimensional shielding calculations have been performed and results presented for the SNS choppers and generic straight beam line configurations. The results are of a scoping and preliminary nature and are intended to provide guidance rather than specific design information. It is expected that comparison with more detailed three-dimensional calculations and the analysis of results from calculations that more accurately model specific beam lines will provide the final required design information. Results thus far show that for source distances of 5 m to 10 m, a total shielding thickness of up to ~2 m is required to reduce the dose to ~0.25 mRem/h.

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