THREE-DIMENSIONAL SHIELDING SIMULATIONS AND ACTIVATION CALCULATIONS OF THE SNS NEUTRON BEAM LINES, T_0, E_0 AND BANDWIDTH CHOPPERS

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ABSTRACT

Three-dimensional (3-d) radiation transport simulations have been performed to define the shielding requirements of a generic neutron beam line and generic T_0, E_0 and bandwidth choppers for the Spallation Neutron Source (SNS). In these analyses, the beam line and chopper models were located between 5 m and 10 m from the moderator face, at their closest likely positions relative to the moderator. From these calculations the maximum required shielding is determined for each chopper. A baseline shield concept comprised of carbon steel and standard concrete was defined and the optimum shield thickness for each material was determined from 2-d and 3-d calculations. The principal shield configuration that was evaluated was composed of a thick inner layer of carbon steel with a thinner outer layer of standard concrete. The optimum thickness of the steel was generally found to be 75-85% of the total shield thickness, with concrete making up the balance. To achieve tissue doses of 0.25 mrem/h, a shield thickness on the order of 2 m is required in the T_0 chopper. The total required shield thickness varies between chopper types from about 120 cm to 230 cm depending on the composition of the scattering material within the chopper and its distance from the moderator. Over the distances examined in these calculations, the total required shielding thickness decreased at approximately $1/d^3$, where d is the distance from the moderator. Replacing standard concrete with either borated or heavy concrete reduces the required thickness of the outer shield material but doesn't significantly reduce the total thickness.

Chopper motors, bearings, seals, instrumentation and other components are essentially unshielded from neutrons scattered within the chopper. Degradation and activation of components are concerns since they determine maintenance and repair scenarios and schedules. Cooling water, required for motors and bearings, will become activated and could pose a risk to personnel. Water line shielding requirements for each chopper type, in its worst-case location, have been determined.

I. INTRODUCTION

The Spallation Neutron Source (SNS) will provide an intense source of low-energy neutrons for experimental use[1]. Low-energy neutrons are produced by the interaction of a high-energy proton beam (1.0 GeV) on a mercury target and slowed down in liquid hydrogen or light water moderators[2].

Individual beam lines transport neutrons from the moderators to specific instruments and may contain one or several beam choppers to modify the neutron energy spectrum of the transmitted beam. Beam choppers are designed to intercept neutrons within a particular range of energies, preventing them from reaching the instrument. The neutrons and gammas scattered in each chopper require significant amounts of shielding to isolate adjacent beam lines from each other and to ensure personnel safety in the vicinity. A target dose of 0.25 mrem/h outside of the shielding is chosen since it would allow unlimited personnel access.

The beam line, T_0 chopper and bandwidth (BW) chopper will be exposed to the direct, unfiltered neutron source, while the E_0 chopper operates only in conjunction with a T_0 chopper or curved beam line, which remove essentially all high-energy neutrons before they reach the chopper.

A large number of two-dimensional (2-d) shielding calculations were performed to determine the approximate optimum shield thickness for various shield material

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compositions[3]. Based on these results, 3-d simulations provided additional details that could not be represented in the simpler 2-d models. In general the results from 2-d and 3-d simulations were in very good agreement, with the 3-d models almost always predicting somewhat higher doses for the equivalent geometry.

The majority of 3-d shielding simulations evaluated neutron and gamma dose levels outside of the radiation shielding, comparing the predicted tissue dose levels to the criteria for unlimited personnel access. The potential benefit of a more complexly layered shield was not investigated, although the effect of replacing standard concrete with borated or heavy concrete was evaluated in a few cases. In addition, an all-borated heavy concrete shield was considered for the T_0 chopper.

II. NEUTRON BEAM SOURCE MODEL

The Monte-Carlo radiation transport code MCNPX[4,5] was used to simulate the SNS proton beam, mercury target and moderators to provide an angular and energy dependent neutron spectrum radiating from the moderator face. This spectrum was used as a point source for all calculations and was placed at the relative location of the moderator, approximately 5 m from the input to the T_0 chopper model[6]. The GRTUNCL3D first-collision source code[7,8] was used to calculate the transport of neutrons from the point source to the chopper model and create distributed sources at the locations of "first collision" of source neutrons within the model. Using this distributed source, the TORT[9] three-dimensional discrete ordinates radiation transport code simulated radiation transport through the shielding and structures, ultimately calculating the neutron and gamma flux spectra at each point within the model.

The GRTUNCL3D code helps avoid unmanageably large models by allowing placement of the source a long distance from the model itself. It also helps avoid computational problems associated with neutron propagation through long ducts. Ray effects occur when particles preferentially stream along discrete directions and are common in discrete ordinates calculations because of the finite set of quadrature angles that are used. Without utilizing the GRTUNCL3D code, an extremely large number of angles, and a model with extremely fine meshes, would be required to maintain sufficient angular resolution in the TORT calculation.

Because the beam line section, leading from the moderator to the input boundary of the TORT model, is not included in the GRTUNCL3D or TORT calculation, scattering in this portion of the beam line is not part of the first-collision source calculated by GRTUNCL3D. To account for this additional contribution to the source seen by a chopper or beamline, a series of 2-d calculations was performed to quantify the scattering in a generic section of beam line. The calculated spectrum of scattered neutrons in a beam line, was transformed back to the original point source position and added to the moderator leakage spectrum, which was then used as an input to the GRTUNCL3D code. The magnitude of the scattered term, at all energy ranges, was a factor of 10 or more below the level of the principal source term.

III. BEAM CHOPPER DESIGNS AND MODELS

Three basic types of beam choppers have been simulated in these calculations: T_0, E_0 and Bandwidth choppers. All three chopper types are designed to pass a particular range of low energies. The range of energies allowed to pass through each chopper, varies with its particular design and operational parameters. In all chopper shielding calculations, the low-energy particles, as well as high-energy particles, interact with the chopper. While this is inconsistent with actual chopper operations, it makes a negligible affect on shielding results.

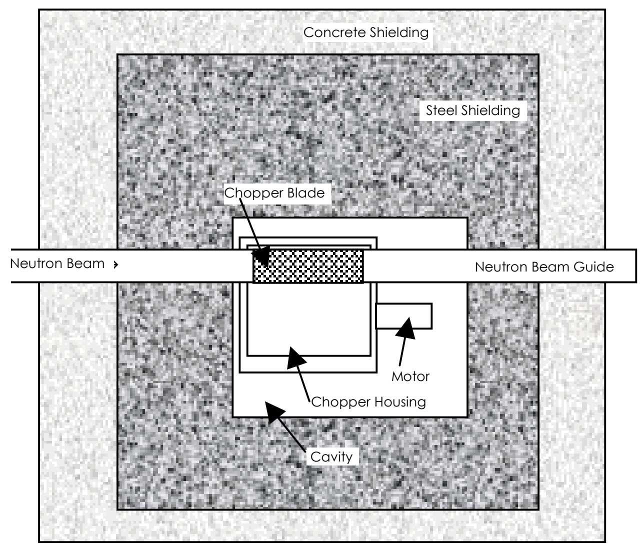

Figure 1. Vertical cross section of T_0 chopper, showing typical chopper components included in the model.

The T_0 chopper is designed to remove all particles with energies above a few eV by absorbing and scattering them in a thick block of Inconel 750, which is synchronously rotated through the beam. The Inconel block is 10 x 12 x 30 cm long and effectively removes high-energy neutrons from the beam. In the T_0 chopper model, the Inconel 750 block is represented as a separate region and is not homogenized with other components. A schematic cross section of the T_0 chopper model is shown in Figure 1.

The E_0 chopper operates in conjunction with a T_0 chopper and selects neutrons within a narrow band of energies from the bulk of the low-energy pulse exiting the T_0 chopper. This is accomplished by rotating a laminate, comprised of alternating aluminum and boron plates, through the beam. The plates are curved and the assembly rotated at a speed to let only neutrons with the proper energy pass through the aluminum plates without being absorbed by the boron plates. In the E_0 chopper model the laminate of boron and aluminum plates is represented as a homogenized region within the beam line. A schematic cross section of the E_0 chopper model is shown in Figure 2.

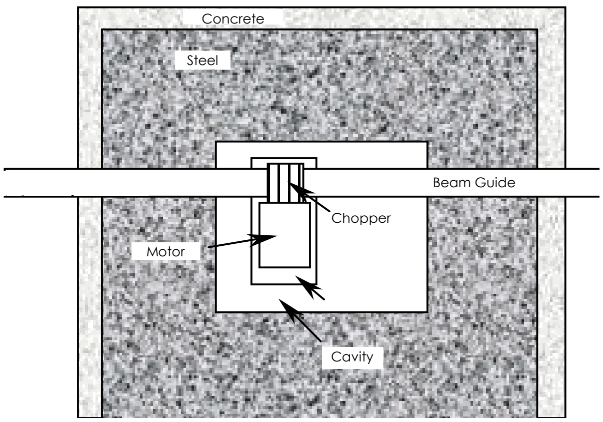

Figure 2. Schematic cross section of the E_0 chopper model, showing principal components. The chopper is a laminate of boron and aluminum plates.

A schematic cross section of the Bandwidth chopper is shown in Figure 3. The Bandwidth chopper consists of a pair of thin aluminum disks coated with a layer of cadmium. The disks have a notch whose width along with the rotational speed of the disk, determines the energy width of the neutron pulse, which can pass through. The aluminum and cadmium are homogenized in a region thicker than the actual plate to keep the size of meshes within reasonable bounds. The density is reduced proportionately to compensate for the artificial thickening of the chopper plate in the model.

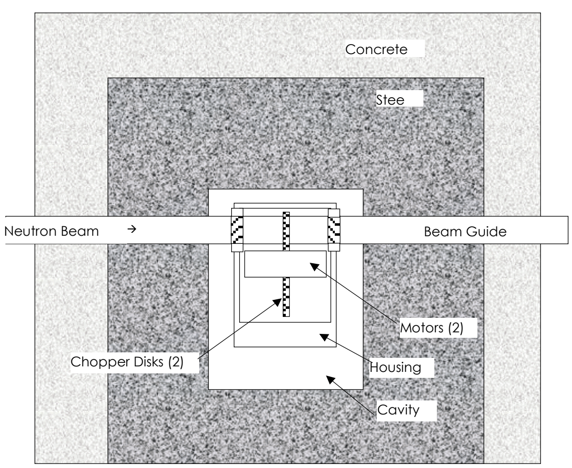

Figure 3. Schematic cross section of bandwidth chopper model showing principal components. Chopper is Cd-coated aluminum disk.

Results from a series of 2-d DORT[10] simulations provided a starting point for the 3-d simulations reported here[3]. The 2-d simulations were based on a cylindrically-symmetric approximation to the beam line and chopper geometries. Three-dimensional TORT models represent the geometry more accurately but still make simplifications in the representation of particular objects. Motors, bearings, and associated structures were all represented as homogenized regions with the correct external dimensions and approximately correct isotopic composition, but with a simplified geometry.

In each of the chopper models, the distinct regions which are represented in the model are the chopper blade or disk, the drive motor, chopper housing, chopper cavity, steel shielding, concrete shielding, beam line opening, some diagnostic regions and a super-absorbing "black" region to prevent source particles from entering the model except through the beam line opening. In each of the three chopper types, motors, housings, cavities, and other regions all have dimensions, compositions and locations specific to the design of that chopper type.

IV. SHIELDING DESIGNS

The baseline shielding design for beam lines and choppers is a thick layer of carbon steel with a thin outer layer of standard concrete. The effect of replacing standard concrete with borated concrete was explored in some calculations. Shielding blocks are expected to be available in multiples of 33 cm (13"), with the primary size being 66 cm (26") thick. Because of the available size of steel shielding blocks 132 cm of carbon steel was used in many of the models, with a varying amount of concrete to achieve the desired personnel radiation dose. Since the radiation dose to individuals was of primary importance in these simulations, the principal quantity that was evaluated was tissue dose, although silicon dose and flux above 1 MeV were also calculated. For unrestricted personnel access, a requirement for a maximum dose of 0.25 mrem/h was presumed. For the various choppers 100-175 cm of steel was required along with 18-55 cm of standard concrete. These values do not include any additional shielding to account for inaccuracies, assumptions or design margin.

The baseline shielding design for each of the models is a thick layer of carbon steel, close to the axis of the beam line, and a layer of standard or borated concrete on the outside. For the various choppers, 100-180 cm of steel was required along with 18-56 cm of standard concrete. Chopper shielding results are summarized in Table 1.

Table 1. Summary of chopper shielding thickness and resulting dose.

Type	Steel Thickness (cm)	Concrete Thickness (cm)	Tissue Dose[a] (mrem/h)
T_0	175	55	0.1
E_0	100	18	0.1
BW	132	42	0.2

[a]Contributions from nearby beam lines are not included.

V. BEAM LINE

Simulations of a generic beam line were conducted with a steel shielding thickness, below the beam line, of 100 cm and a steel shielding thickness, to the sides of the beam line, of 132 cm. The concrete floor and wall thickness were varied to achieve the desired dose level. The beam line model includes a 5 m long segment, beginning at the target monolith outer surface, 5 m from the moderator. Two symmetry planes were utilized to reduce the computational model size. A schematic cross-section of the model is shown in Figure 4. Using standard-sized steel blocks (66 cm), a layer of steel 132 cm thick was modeled to the sides of the beam line, while only 100 cm

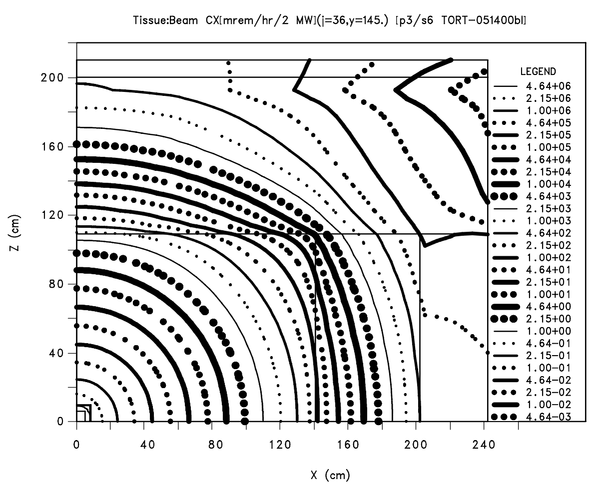

Figure 5. Vertical cut plane through beam line model, showing dose contours (mrem/h). Location is approximately at maximum. Lower and left edges are symmetry planes, floor is at top and side wall is to right.

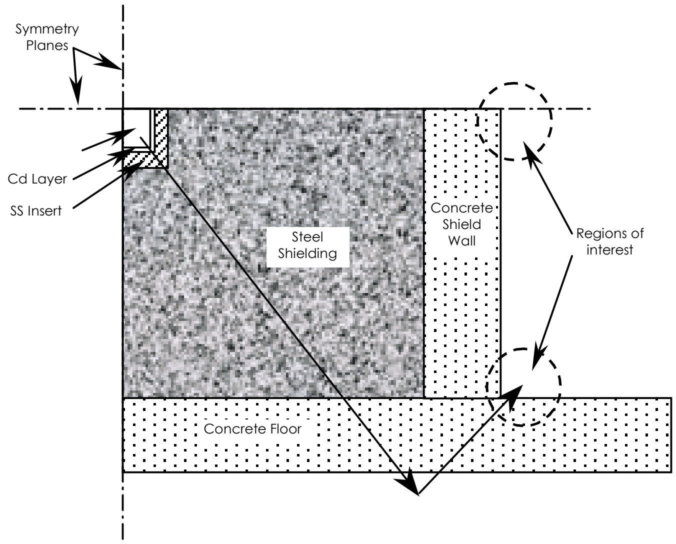

Figure 4. Schematic cross section of the TORT 3-d beam line model. The left-hand and upper boundaries are symmetry planes.

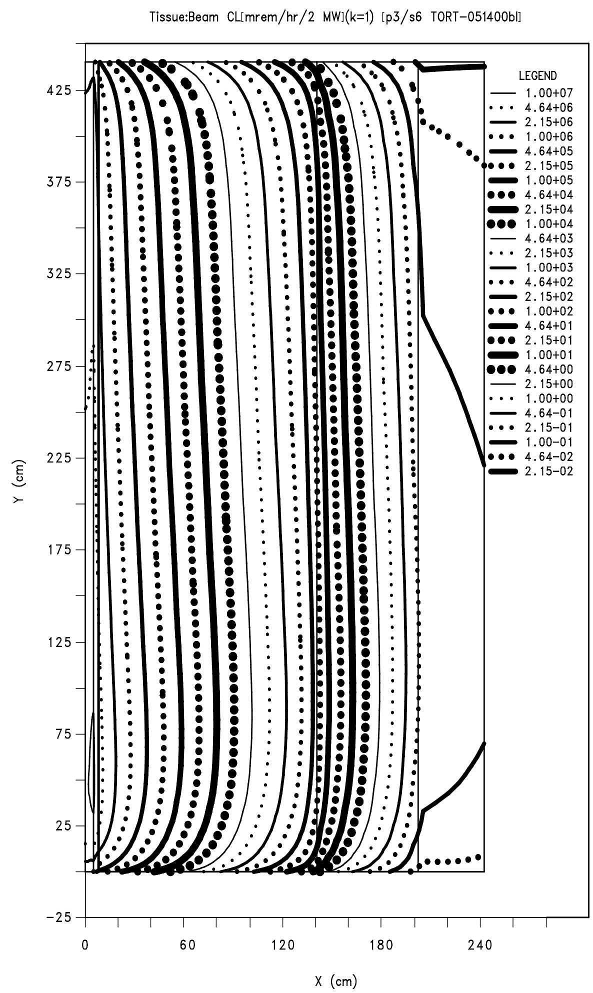

Figure 6. Tissue dose contours (mrem/h) on a horizontal plane through the beam line centerline. Left edge is the symmetry plane and center of the beam.

of steel could be accommodated between the beam line and the floor. Tissue dose contours on a vertical plane through the beamline model are shown in Figure 5. To achieve a dose of 0.2 mrem/h, 66 cm of concrete were required in the side shield walls making a total shield thickness of 198 cm. Contours of tissue dose on a plan view of the beam line model, cut through the center of the beam are shown in Figure 6. Note from the figure that at the beginning and end of the model the contours are significantly modified by the boundary conditions at the ends. By exploring models of different lengths, it was determined that almost 100 cm of the model at either end is perturbed by the boundary conditions and that a model at least 3 m long was required to obtain accurate results at the center point.

VI. 3-CAVITY T_0 CHOPPER MODEL

To investigate the effects of adjacent beam lines, a model of three adjacent T_0 chopper cavities was constructed with a symmetry plane along the centerline of the active beam line. The model represents a set of five contiguous beam lines. Symmetry and superposition can be applied to the results from this model to predict the impact of one operating beam line on its neighbors and the total dose from up to five operating beam lines. The angle between centerlines of actual beam lines is approximately 14^{o}, but varies somewhat, depending on which moderator the beam lines originate from. With each T_0 chopper located as close as possible to the target-shielding monolith, the distance between centerlines of adjacent beam lines can be as small as 104–126 cm. As a worst-case, these separations are used in the 3-cavity T_0 chopper model. In the 3-cavity T_0 model the angle between beam lines is neglected and beamlines are modeled as parallel. A plan view of the 3-cavity chopper model is shown in Figure 7. The dose contours calculated for this model are shown in Figure 8, with a summary of the peak values given in Table 2. A total tissue dose, in the center of a non-operating beam line, of 6.4×10^{5} mrem/h would exist if all neighboring beam lines were operating. We conclude that, in the worst case, at least three beam lines on either side would need to be shut down in order to perform maintenance on a single non-operating T_0 chopper.

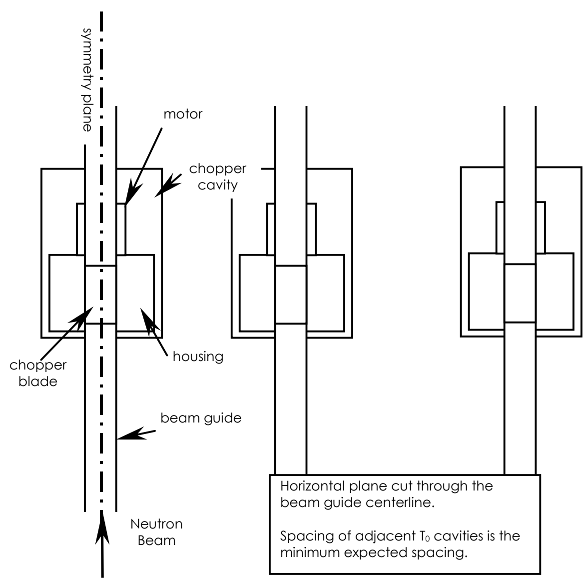

Figure 7. Schematic plan view diagram of 3-cavity T_0 chopper model. Left-most chopper is active. Symmetry boundary is on centerline of left chopper and beamline.

Table 2. Summary of dose results from the 3-cavity T_0 chopper model.

Chopper Number	On Plane of Beam Centerline	
	Pk Dose (mrem/h)	Dose at Centerline (mrem/h)
#1 (operating)	1.0×10^{7}	1.0×10^{7}
#2 (non-operating)	3.2×10^{5}	8.0×10^{4}
#3(non-operating)	1.0×10^{3}	2.5×10^{2}
Total dose in a non-operating beam line from 4 neighboring beam lines		6.4×10^{5}

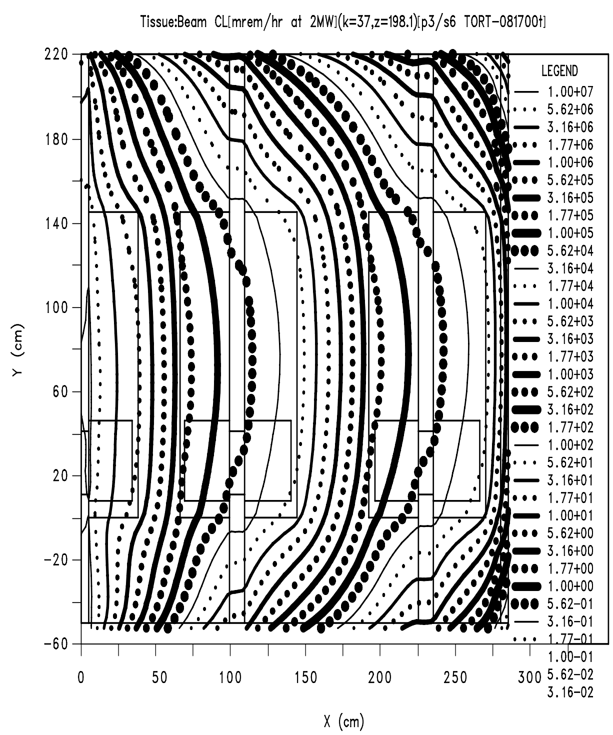

Figure 8. Dose contours (mrem/h) on a horizontal plane through the center of the 3-cavity T_0 chopper model.

VII. COOLING WATER ACTIVATION

Activation calculations have been performed for the water used to cool chopper motors and bearings, in each chopper type used in SNS. Cooling water will be cyclically exposed to a radiation environment each time it circulates through the chopper region. Shielding requirements for water lines serving each type of chopper have been determined for their particular radiation environment and water flow characteristics. Table 3 lists the water volume and flow parameters in each type of beam chopper. A total water circulation time of 240 s is assumed in all cases.

Table 3. Water flow parameters for the drive motors used in each chopper type.

Type	Water Residence Time (s)	Fractional Residence Time	Flow Rate (cm^3/s)	Water Volume (cm^3)
E_0	5.7	0.02	63	354
T_0	10	0.04	45	445
BW	7.5	0.03	72	535

Models of each chopper were constructed in their "worst-case" locations, as listed in Table 4. These locations are their closest likely positions relative to the moderator. The T_0 chopper model was located immediately outside of the target-shielding monolith, 5 m from the moderator face. While the T_0 and bandwidth choppers see the full beam from the moderator, the E_0 chopper will only operate in conjunction with a T_0 chopper or curved beam line, both of which remove essentially all high-energy particles from the beam. As seen from the shielding calculations, elimination of high-energy neutrons from the beam prior to reaching the E_0 chopper, greatly reduces the shielding requirements of this chopper. Likewise the activation of its cooling water will be significantly less than in the other two chopper types.

Table 4. Source characteristics and locations.

Chopper Type	Neutron Beam Characteristics	Moderator Distance (m)
T_0	full beam	5.0
E_0	chopped beam	10.0
BW	full beam	7.5

The average neutron flux spectrum in each chopper motor, is shown in Figure 9. A significant depression of the flux level within the E_0 chopper motor is seen over a wide energy range, and is the result of the attenuation of the incident neutron beam by a T_0 chopper.

Neutron and gamma flux spectra, averaged over the motor volume, were used in calculations with ORIHET95 to calculate the build-up and decay of nuclide concentrations and radioactivity in the chopper cooling water during a single cooling water cycle. The cross-section set used for

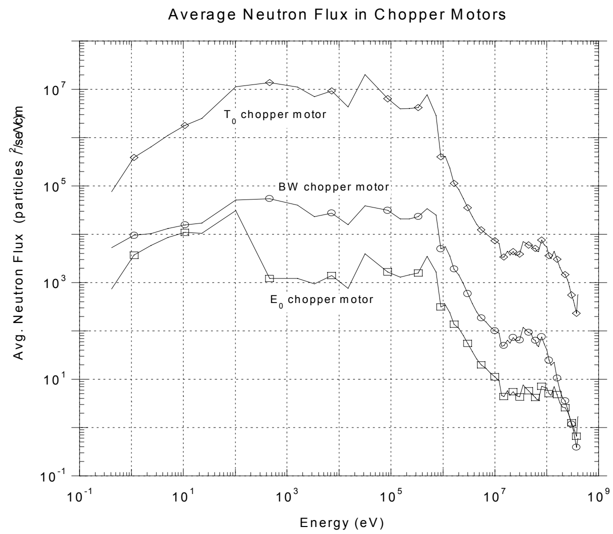

Figure 9 Neutron flux spectrum in the motors of each chopper type, at their respective "worst-case" locations.

these calculations is valid up to 400 MeV. Reaction rates for nuclides generated by higher-energy interactions, are estimated from MCNPX simulations of a similar geometry[11].

Nuclides are generated in the cooling water with a wide range of half lives and concentrations and some will continue to build over very long times. Of particular concern is ^{7}Be, because of its relatively long 53-day half-life. The formation of ^{7}Be is a result of high-energy collisions between scattered beam neutrons and oxygen atoms in the cooling water. Analytic methods, based on isotopic half-lives, are used to calculate scaling factors to account for radioactivity build-up during cyclical exposure and decay. Using the calculated scaling factors, summarized in Table 5, predictions of steady-state nuclide concentrations are obtained. Nuclides, which build significantly over one year, include ^{3}H, ^{7}Be, ^{14}C, ^{14}O and ^{15}O. Of these, the only nuclides that impact the shielding requirements are ^{7}Be and ^{14}O. Tritium also builds over time to high levels but does not drive the choice of shielding materials or shield thickness, although it is a concern in maintenance, repair and accident scenarios.

Table 5. Ratios of long-term nuclide production rates to single-cycle rates in the T_0 chopper cooling water. Values are given for 1-yr and 10-yr operational periods.

Atomic #		Mass #	Nuclide production rate ratio to one-cycle	
Z	Element	A	1 yr	10 yrs
1	H	3	1.20×10^5	9.46×10^5
4	Be	7	2.58×10^4	2.60×10^4
6	C	14	1.24×10^5	1.24×10^6
7	N	16	1.0	1.0
7	N	17	1.0	1.0
7	N	18	1.0	1.0
8	O	14	1.09	1.09
8	O	15	1.30	1.31
8	O	19	1.0	1.0

Water line shielding calculations were performed with the 1-d transport code ANISN for an infinitely long, 1.0 cm radius water line, using the nuclide production rates calculated with ORIHET95, for low-energy interactions, and with MCNPX for high-energy interactions.

A set of possible water line shielding designs were defined and evaluated for each chopper type. Figure 10 shows typical tissue dose results for the T_0 chopper. In this figure distances are measured from the center of the 1-cm radius water line. It can be seen from Figure 10 or from the summary presented in Table 6 that to achieve a maximum dose level of 0.25 mrem/h, approximately 7 cm of carbon steel is required at the output of the T_0 chopper. Without shielding, a dose of 12.4 mrem/h would result from contact with the water line.

Table 6 Water line shield compositions and thickness to achieve a dose of 0.25 mrem/h for the T_0 chopper.

Water line shield composition	Total shield thickness (cm)
7 cm steel	7
10 cm gap, 2.5 cm steel, 4 cm concrete	16.5
10 cm concrete, 9.5 cm gap	19.5
10 cm gap, 10 cm concrete, 1 cm gap	21
46 cm gap	46

The choice of an optimum water line shield design depends on whether space or material is the primary consideration. Many reasonable water line installation designs would automatically provide most of the separation required for a safe personnel dose level.

While the T_0 chopper water lines require 7 cm of steel shielding, the E_0 chopper water lines will require no shielding. Direct contact with a water line, at its hottest location, will result in a dose of 0.1 mrem/h, well below the limit. The bandwidth chopper water lines may not require shielding either, if a 3 cm separation can be guaranteed. Direct contact with the hottest location on the water line would result in a dose of 0.9 mrem/h, above the limit but requiring very little shielding.

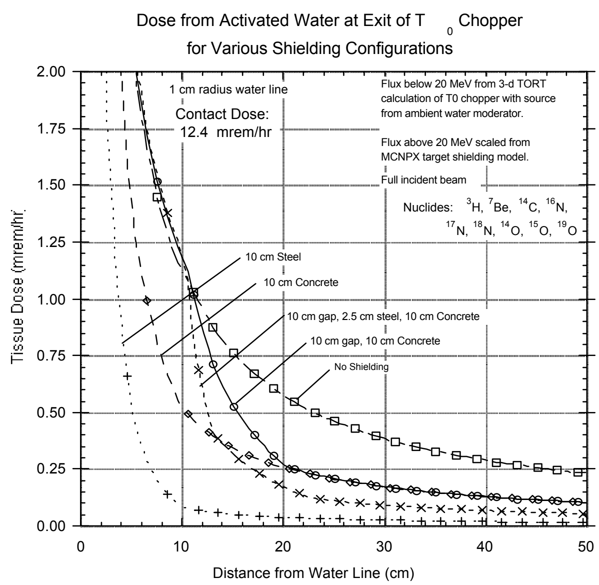

Figure 10 Tissue dose as a function of distance, from a T_0 chopper water cooling line, with various shielding configurations.

IIX. POWER DEPOSITION IN CHOPPER BLADES

The calculated neutron and gamma flux spectra, averaged over the volume of the Inconel blade used in the T_0 chopper, are used to calculate heating of each constituent material. Neutron and gamma flux spectra are each folded with the kermas for the material constituents, yielding a total heating contribution for each material. Nickel experiences the greatest heating from both neutrons and gammas. Heating from neutrons deposits a total of 0.12 W in the Inconel 750 chopper blade while gammas deposit a total of 0.41 W, for a total average heat load of 0.53 W. While the total T_0 chopper blade heating is not large, the heat is very hard to remove since it is deposited in a material with extremely poor thermal conductivity which operates in a vacuum environment. Heat removal, except by radiation to a cooled outer case, must be through the drive shaft, making efficient shaft bearing cooling essential.

IX. SUMMARY

A series of 3-d shielding calculations have been performed for the SNS beam choppers and beam line to evaluate their radiation shielding requirements. A shield composition and thickness for each chopper type has been determined. For beam lines and choppers, shields composed primarily of carbon steel with concrete outer layers have been defined with total shield thickness of 110–210 cm.

Cooling water activation, and water-line shielding calculations have been performed. Water lines, carrying activated water from chopper cavities, are expected to require 0-7 cm of steel shielding to maintain an acceptable personnel radiation dose level. It is not expected that the actual final design of water lines will require shielding if adequate separation of water lines from habitable spaces can be maintained.

The results of these calculations support the design process for the Spallation Neutron Source and provide reasonable starting points for simulations of specific beam line designs, which are underway.

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