RADIATION TRANSPORT THROUGH COMPLEX SHIELD PENETRATIONS IN ACCELERATOR ENVIRONMENTS USING HYBRID MONTE CARLO/DISCRETE ORDINATES CALCULATIONS

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SUMMARY

Shielding calculations for penetrations in the SNS accelerator environment are presented based on hybrid Monte Carlo and discrete ordinates particle transport methods. This methodology relies on coupling tools that map boundary surface leakage information from the Monte Carlo calculations to boundary sources for one-, two-, and three-dimensional discrete ordinates calculations.

I. BACKGROUND

Evaluating bulk shielding in accelerator environments is generally an easy task compared to analyzing the radiation transport through complex shield penetrations like mazes, ventilation shafts and vent lines, or egresses. Although there exist a couple of simple hand calculation formula[1,2] developed over the years from the expertise gained at accelerator facilities, these are limited to simple duct arrangements through shields. Monte Carlo transport codes, on the other hand, are able to model radiation fields in complex geometry. However, they consume significant amounts of resources, even with today's computers, and may give solutions with poor statistics even when variance reduction methods are heavily applied.

In the design of the Spallation Neutron Source (SNS),[3,4] hybrid Monte Carlo (MC) and discrete ordinates (DO) methods were applied for many of the complex shielding tasks, building on the Monte Carlo code MCNPX,[5] the discrete ordinates suite of the DOORS[6] system and coupling tools that serve as an interface between the different transport codes. In almost all cases the front-end of the multi-step calculations is performed by MCNPX modeling the proton beam interactions with beam dumps or structural elements. At some distance from the primary interaction area, the high-energy protons and secondary charged particles have interacted or ranged out, and neutrons and photons are the dominant radiation. At this distance neutron and photon boundary leakage terms can be scored and passed as boundary sources to the discrete ordinates codes to continue the radiation transport through bulk shields and/or penetrations. Further coupling between successive discrete ordinates calculations allow, for example, modeling of multiple legged duct arrangements and mazes. It has to be mentioned here that applying discrete ordinates methods in accelerator shielding depends very much on the availability of coupled neutron/photon cross section libraries with an upper energy that is near to that of the beam energy of the particle accelerator. We are fortunate to having the HILO[7] library and the recently developed library HILO2k[8] with upper neutron energies of 400 MeV and 2 GeV, respectively.

The paper will briefly introduce the coupling tools that were developed for the SNS shielding effort, i.e. MTA, MTD and MTT, for coupling MCNPX to the one-, two-, and three-dimensional discrete ordinates codes ANISN,[9] DORT[10] and TORT.[11] Then the paper will focus on presenting typical applications of these tools in the neutronics design of penetrations and mazes at the SNS facility.

II. COUPLING TOOLS

The coupling tools basically sample the event-wise Monte Carlo boundary crossing information into energy bins, angular bins, and spatial bins (if applicable) of the corresponding discrete-ordinates mesh, angular quadrature, and multigroup energy structure[12]. In doing so, they map the Monte Carlo surface crossing information into a boundary source definition to be used by the discrete ordinates codes.

A. Monte Carlo to ANISN (MTA)

The first of the coupling tools is Monte Carlo to ANISN (MTA), which prepares a boundary source for the one-dimensional discrete-ordinates transport code ANISN from surface crossing information written primarily by codes of the MCNP(X)[5,13] series. Recently, an extension was written to be able to read surface leakage data from the MARS[14] code.

MTA can prepare sources for planar, cylindrical and spherical problems. ANISN allows two types of sources, a distributed volume source that is restricted to isotropic angular distributions, and a shell source that is implemented as directional flux step condition at a specified right mesh boundary. Hence the second source type enables any angular distribution within the discrete angular quadrature set. Both source types are supported by MTA.

B. Monte Carlo to DORT (MTD)

The second tool, MTD (Monte Carlo to DORT), prepares a boundary source for the two-dimensional discrete ordinates code DORT, again from surface crossing information written by the Monte Carlo codes MCNP or MCNPX. At the current time, MTD is limited to the preparation of surface sources for the (r,z)-cylindrical-geometry option meaning that sources are allowed on the top and bottom surfaces and on the mantel surface at the outer boundary of the problem, but also at any internal right mesh boundary of constant-z planes or constant-r cylinder mantels.

C. Monte Carlo to TORT (MTT)

Shortly, the coupling tool for the three-dimensional DO code TORT will complete the suit of Monte Carlo to discrete-ordinates coupling tools. First calculations were performed at the time of the preparation of this article.

D. DORT to DORT (DTD)

Similar coupling codes are available in the DOORS package to couple two-dimensional DORT and three-dimensional TORT problems, and two TORT problems with the tools TORSED[6] and TORSET,[6] respectively.

Of particular value for the analysis of penetrations has been the DTD[15] (DORT to DORT) code that couples two cylinder symmetrical problems with arbitrarily lined up cylinder axes. The code performs a spatial and angular transformation to equate the angular fluxes at each radial, azimuthal, and axial boundary mesh point of the perturbed problem to the angular flux at the nearest mesh point and angular direction of the base problem.

III. RADIATION FIELDS IN ACCELERATOR ENVIRONMENTS

In this section three typical applications of hybrid Monte Carlo and discrete ordinates analyses of shielding aspects of the SNS accelerator system are given. Other examples of design calculations are published in earlier articles.[16,17,18] The first problem demonstrates simple applications of MCNPX to ANISN and DORT coupling. The second problem is a multi legged duct application, which is approached with MCNPX coupled to multiple cylindrical DORT analyses. The third problem is a calculation of the radiation field in a maze with a very complex source term.

A. Shielding at the Start of the DTL Linac

The SNS linac is defined to start with the drift tube linac that is fed by a 2.5 MeV H^- ion beam chopped to 60 Hz pulses generated by the front-end including the ion source. The DTL linac accelerates the H^- ions to 87-MeV energy in about 36-meters length. The first 10 meters of the DTL linac are housed in the front-end building. A considerable neutron and gamma radiation field is expected in this first DTL section, firstly from beam losses that are specifically high in the very first DTL section although the beam energy only rises moderately to 20 MeV, and secondly due to backscattering contributions from beam losses in the higher energy sections of the linac tunnel. Also an x-ray field, which is generated from bremsstrahlung due to electrons produced by the RF-fields between the drift tubes, will be present, but is not considered here. The shield configuration around the DTL in the front-end building is sketched in Fig.1.

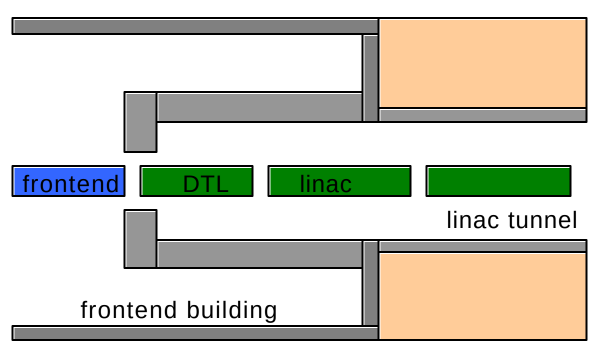


Fig. 1: Sketch of the front-end building and linac

tunnel. Concrete structures are colored in grey, soil in light brown.

Coupled MC and DO analyses were performed to determine the concrete thickness required around the DTL in the front end building, and also to evaluate the radiation streaming through the opening in the back shield wall where the front-end and the first DTL tank are connected. The first task was performed by applying neutron and gamma leakages in one-meter-long sections from the DTL linac structures generated by an MCNPX calculation to one-dimensional DO calculations with the coupling tool MTA and ANISN. All analyses were performed in cylindrical symmetry with the HILO multigroup neutron/photon cross-section library.

The MC part of the analysis modeled in detail the space, angle and energy dependent beam loss characteristics. Using the shell source option in ANISN conserved the angle and energy dependence of the neutron and gamma leakages at 60 cm radius from the beam axis. Dose equivalent rates were obtained by folding the multigroup flux information with flux-to-dose conversion coefficients provides by the HILO library.

R-Z dose contours are presented in Fig. 2. The dose requirement is met by 0.1 mrem/hr, marked in the plot with the yellow line. The plot shows that the required concrete thickness varies from 70 cm at the start of the DTL to 120 cm at about 10 m downstream because of the increased beam energy.

A material study was performed using borated concrete, and 20 cm borated polyethylene followed by ordinary concrete, just by rerunning the quick ANISN runs with different material identifiers. Both material options allow reducing the shield thickness about 25% as shown in Fig. 3.

The issue of backstreaming of radiation into the front-end building was tackled by coupling the MC surface source term generated with MCNPX at the inner surface of the concrete wall into DO calculations. Evaluation of the MC surface source with the MTA code and a subsequent ANISN calculation determined the required thickness of the concrete wall to 70-80 cm.

Radiation streaming through the holes cannot be modeled with one-dimensional transport analyses.

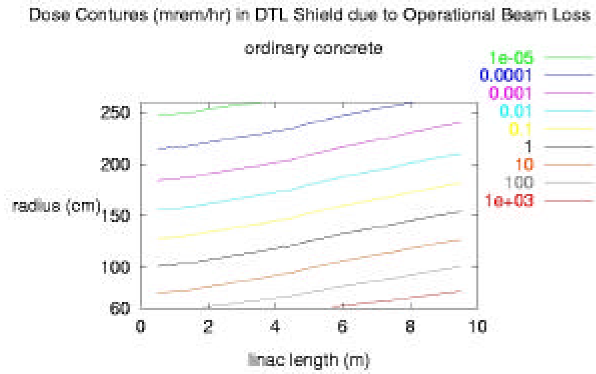


Fig. 2: Dose equivalent rate contours in a cylindrical concrete shield around the first 10 meters of the DTL extending radially from 60 cm outward.

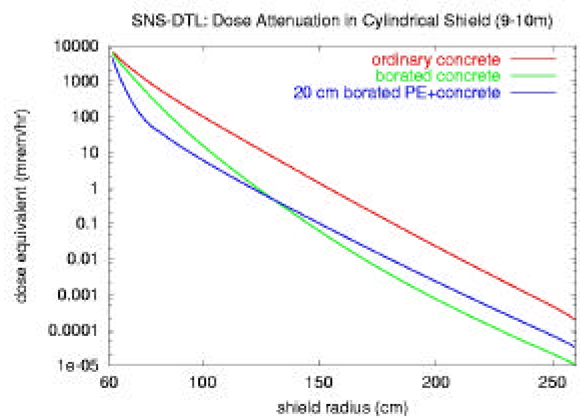


Fig. 3: Material study for the DTL shield.

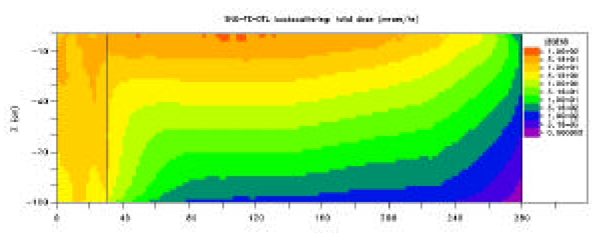


Fig. 4: R-Z contours of dose equivalent rates in the penetration of the linac tunnel end wall.

For this reason the two-dimensional DO code DORT was used to evaluate the backstreaming of radiation through the 60 cm diameter penetration through the end wall of the extended tunnel. The linac structures in the penetration were not considered. The same MC surface source was analyzed with the MTD code to prepare a boundary source definition for the cylindrically symmetric DORT calculation.

The total dose equivalent rates in the penetration (R<30 cm) and the shield wall are presented in Fig. 4. The calculation confirms the required concrete thickness of 70 –80 cm. It also shows that dose levels of about 10 mrem/hr will be expected near the penetration.

B. Radiation Propagation through an Oxygen Deficiency Duct

An oxygen deficiency/helium (ODH) vent is installed at the beginning and at the end of the superconducting part of the linac (SCL) to be able to release an accidental helium spill into the environment and to ensure oxygen supply for the maintenance personnel. The ODH vent penetrates the earthberm surrounding the accelerator tunnel. A source term of a continuous proton loss of 1W/m was assumed for the whole length of the linac. The objective was to evaluate the present design for equivalent dose rates at the exits of the duct, in the presented case for the ODH vent at the end of the SCL with proton beam energies of about 1 GeV.

The ODH vent extends from the linac tunnel through about 5 meters of soil to the top of the earthberm. It consists of four straight legs that are connected, with a 45-degree bend, a 90-degree bend and another 45-degree bend, to build a kind of spiral in order not to line up the first and fourth leg. A sketch is presented in Fig. 5.

A combination of a three-dimensional Monte Carlo analysis with the MCNPX code and two-dimensional discrete ordinate analyses with the DORT code has been applied that makes extensive use of the coupling tools MTD and DTD.
An initial MCNPX calculation tracks the modeled proton losses in the accelerator tunnel, generates the secondary radiation from the proton interactions with the accelerator structure and transports this radiation throughout the accelerator tunnel. Besides calculating flux and dose values in the air zones of the tunnel, the code also writes a file of boundary crossing events at a user defined cylindrical surface. Because of the large volume air zones of the accelerator tunnels that leads to long travel distances of radiation and because of the extended sources, large MCNPX models, which cover from 50 to 100 meters of accelerator structure and tunnel, are involved in the first part of the calculation.

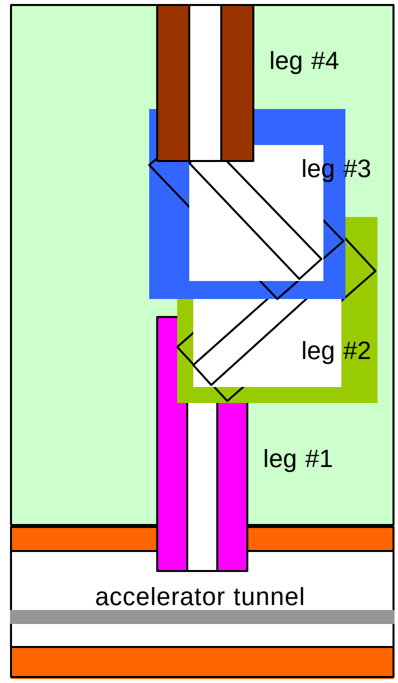


Fig. 5: Sketch of the ODH vent penetrating the SNS linac earthberm.

The coupling code MTD processes a boundary source file for the discrete ordinates transport code DORT from the file of boundary crossing events. The DORT code performs the neutron and photon transport calculation through part of the tunnel air, the concrete walls and several meters into the earth berm in a cylindrical model. Therefore, for this analysis, the rectangular tunnel was converted into an idealized cylinder model conserving the absolute area of the tunnel cross section.

The coupled neutron/photon HILO cross section library was applied for all the DORT calculations. Applying a gray absorber blends the area in the center of the tunnel that describes the accelerator structure out. Using periodic boundary conditions allowed for the reduction of the DORT model to a 2.3-meters-long tunnel section.

A second cylindrical model describes the first leg, the air zone, the concrete wall and some earth berm. The DTD coupling code was used to generate a boundary source for the second DORT model from the angular flux matrix of the first DORT run. The second DORT calculation employs the boundary source obtained in the first DORT calculation, and performs the radiation transport in the first leg. A forward biased angular quadrature

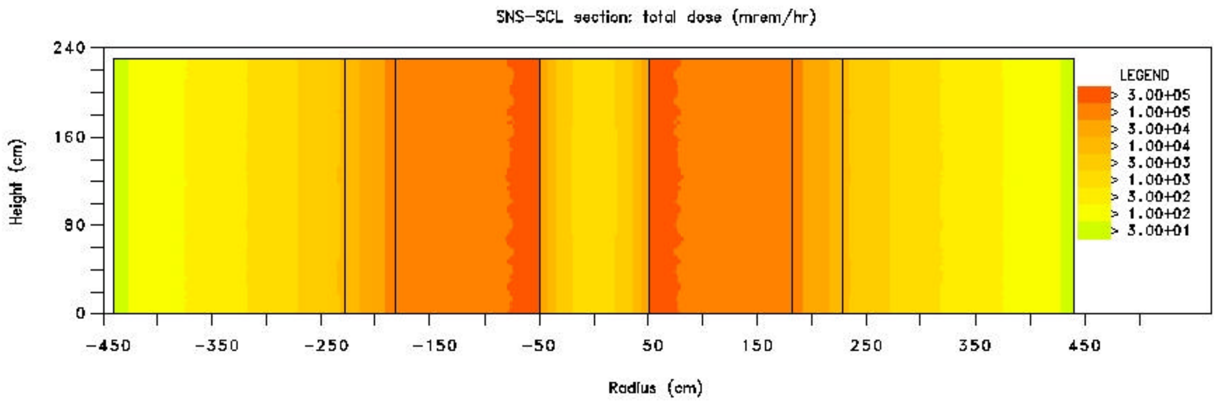
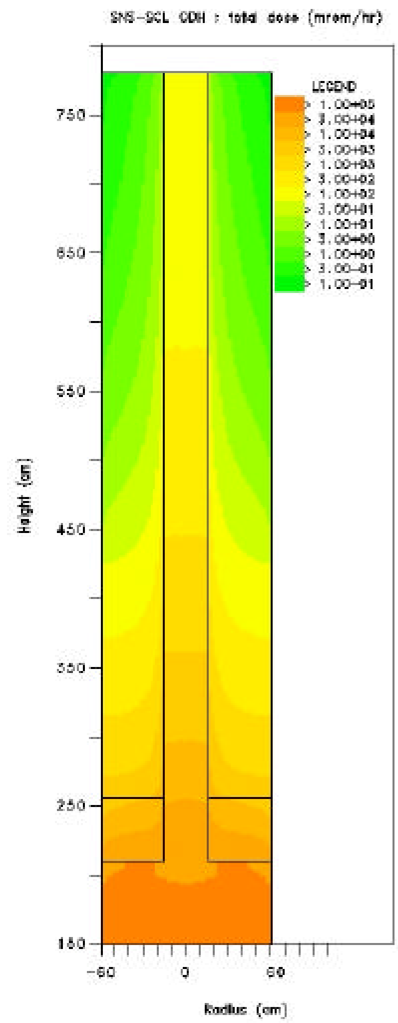


Fig. 6: Contours of dose equivalent in the accelerator tunnel leg due to a 1 W/m proton beam loss in the SNS linac.



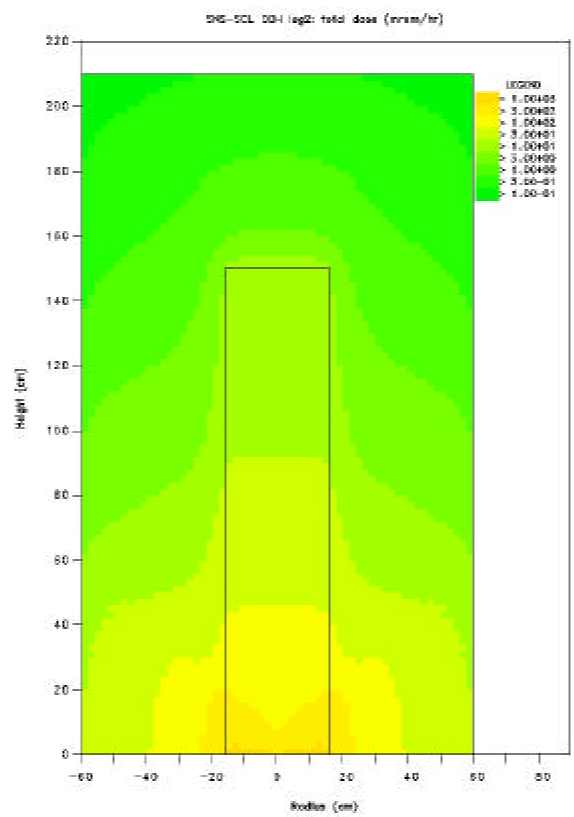


Fig. 7: Contours of dose equivalent in the first leg of the ODH vent due to a 1 W/m proton beam loss in the SNS linac.

Fig. 8: Contours of dose equivalent in the second leg of the ODH vent due to a 1 W/m proton beam loss in the SNS linac.

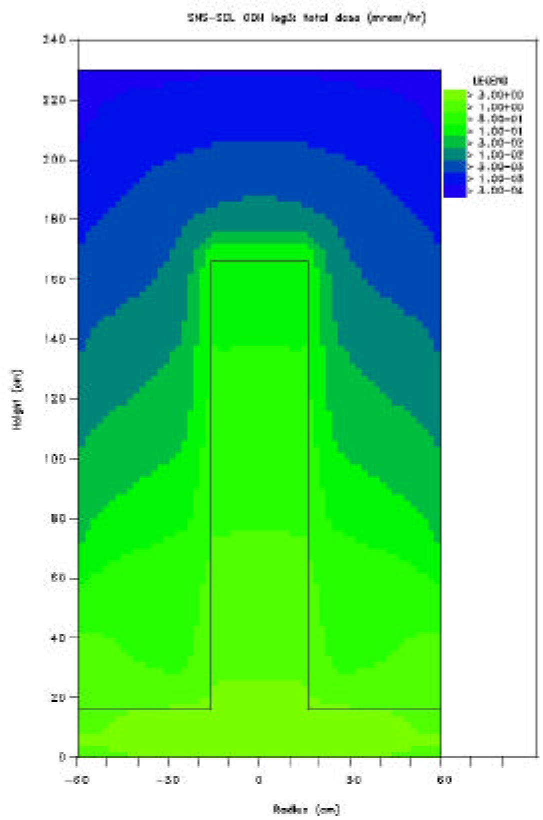


Fig. 9: Contours of dose equivalent in the third leg of the ODH vent due to a 1 W/m proton beam loss in the SNS linac.

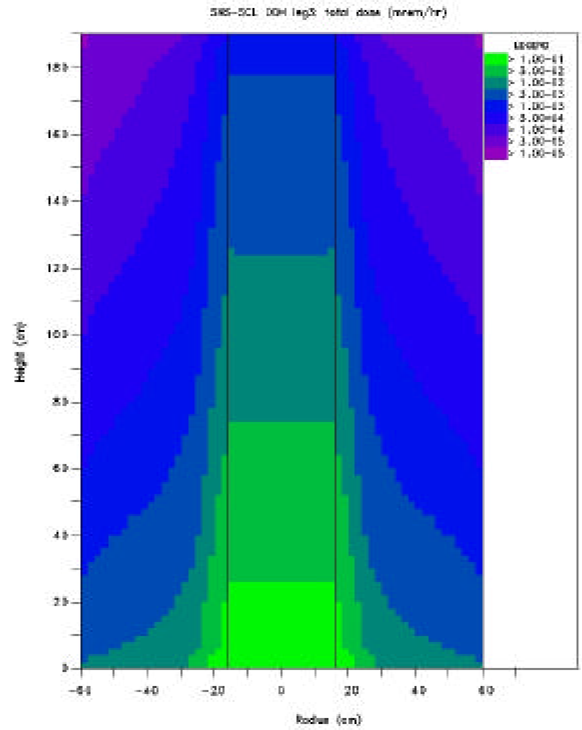


Fig. 10: Contours of dose equivalent in the fourth leg of the ODH vent due to a 1 W/m proton beam loss in the SNS linac.

set was used in order to give a refined description of the propagation of the radiation into the duct. Three more sequences of DTD and DORT transport calculations follow for the legs #2 to #4.

Doing a large fraction of the radiation transport with coupled 2D cylindrical calculations azimuthally smears out flux modulations that might occur around a circumference. These flux modulations are regarded to not be significant, because they are suppressed in the multi-bend configuration of the vent.

Neutron and gamma fluxes are folded with the flux-to-dose conversion factors distributed with the HILO cross-section library to obtain the equivalent dose rates presented in Figs. 6-10. The contribution to the dose equivalent rate at the ODH vent exit on top of the earthberm due to streaming through the vent pipes was calculated to be 0.001 mrem/hr. Hence, the dose equivalent rate is dominated by the radiation penetrating the bulk shield that was calculated to be 0.2 mrem/hr.

C. Evaluation of the HEBT Maze

During the tuning of the SNS linac[4], the accumulator ring is going to be accessible for maintenance. A traverse shield wall will be located at the end of the High Energy Beam Transport (HEBT) tunnel to mitigate the radiation generated by operational and accidental beam losses transported from the linac tunnel through the HEBT arc to the ring (see Fig. 11). The maze, by definition, provides a walkway for personnel, but also a straight penetration for the feed-through of the beam transport line. As a worst-case scenario, the full tuning beam with 1 GeV beam energy and 7.5 kW beam power is assumed to impinge on the front face of the first HEBT dipole.

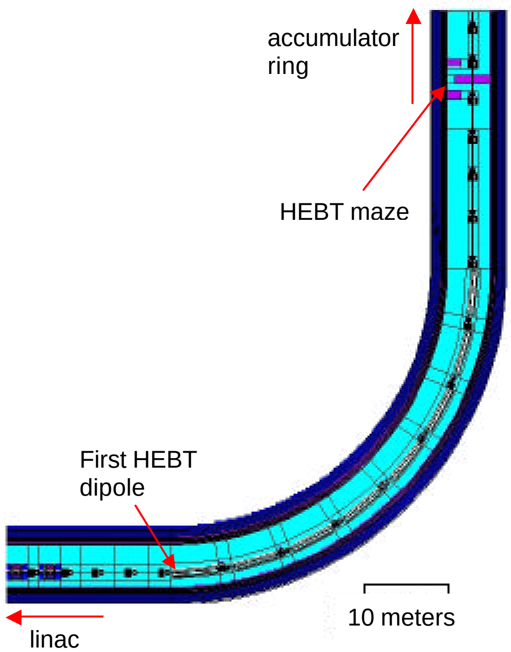


Fig. 11: The MCNPX model of the high energy beam transfer (HEBT) line from the linac to the accumulator ring including a shield maze at its exit.

The first part of the calculation, the primary beam interaction with the first HEBT dipole magnet and the transport of the secondary radiation to the shielding labyrinth including secondary interactions with the accelerator equipment and the tunnel walls was performed with the Monte Carlo code MCNPX. In the MCNPX calculation the boundary crossing events of neutrons and photons through an interface surface about 3-4 meters before the maze were written to a file.

DXTRAN spheres in combination with the LA150[19] neutron cross section library were applied to boost the particle population in the shielding maze area. This procedure cuts off possible neutron contributions above 150 MeV because DXTRAN spheres work only in the tabular data regime of the neutron transport.

As only contributions scattering from the concrete walls of the tunnel were expected to make it to the maze, this fact was not thought to seriously limit the calculation. Although a significant amount of

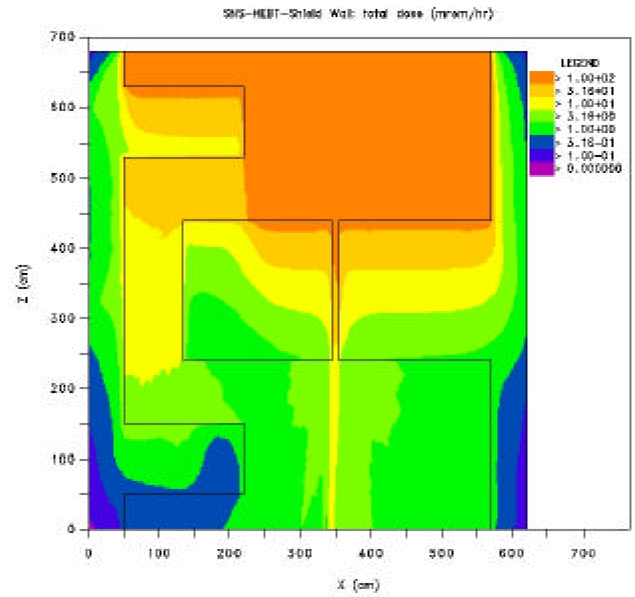


Fig. 12: Dose equivalent contour lines in the HEBT shield maze. The concrete wall contours are overlaid.

cpu time was spent for the MCNPX run, the boundary crossing file contained only about 280,000 particle tracks.

As the radiation transport through a maze is a complex problem in itself, it was performed in a separate task. A good balance of the attenuation through the shield walls, and the attenuation of the radiation streaming through the walkways had to be found, so that the deep penetration and streaming effects were equal important to the doses at the exit of the maze. For such environments using discrete ordinates methods for the second part was thought to be superior to Monte Carlo techniques, although it involves some assumptions simplifying the geometry.

The shield labyrinths consisting of three overlapping transverse walls at different sections of the tunnel were modeled in two-dimensional X-Y DORT calculations assuming an infinite tunnel height. This assumption represents a conservative approach, and is valid especially for forward peaked sources as found in this problem. In the radiation transport of the maze the reflection terms from the concrete ceiling and the concrete floor are slightly overcompensated by inscattering from the infinite columns above and below.

Hence, in the second part of the calculation a boundary source for two-dimensional X-Y discrete ordinates calculations needed to be created. The boundary crossing events from MCNPX were evaluated for the neutron and photon energy and angular distribution on a per unit area basis averaged over the tunnel cross sectional area. Because of the limited number of boundary crossing events on the MCNPX boundary crossing file, the coupling tool MTD was applied using only one spatial mesh to obtain a good angular representation of the boundary source. A small user-written program generated the boundary source for the X-Y DORT cases by applying the one-mesh boundary source uniformly to all tunnel air meshes at the entrance of the tunnel section. The DORT analyses were performed for a 210 angle downward biased quadrature set, applying the 75 neutron group/22 gamma group HILO2k cross section library with upper neutron and photon energies of 1000 MeV and 20 MeV, respectively.

The dose equivalent rates of about 200 mrem/hr are attenuated by the shield maze with two lined up 1-meter-thick concrete walls and one 2-meter-thick central wall, as shown in Fig. 12. The penetration in the central wall will allow collimated radiation leaking through the maze, raising the dose in the beam line area after the maze to 10-30 mrem/hr.

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REFERENCES

1. A.H. Sullivan, *"A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerator,"* *Nuclear Technology*, Ashford, England (1992).

2. H. Dinter, D. Dworak, K. Tesch, "Attenuation of the Neutron Dose Equivalent in Labyrinths trough an Accelerator Shield," *Nucl. Inst. Meth.* A333, 507-512 (1993).

3. National Spallation Neutron Source Conceptual Design Report, Oak Ridge National Laboratory, NSNS/CDR-2/VI (1997).

4. R. L. Kustom, "An overview of the Spallation Neutron Source Project," *Proceedings of the XX International Linac Conference*, Monterey (2000).

5. H. G. Hughes et. al., "MCNPX for Neutron-Proton Transport," *International Conference on Mathematics & Computation, Reactor Physics & Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 27-30, 1999, *American Nuclear Society* (1999).

6. DOORS3.2, One-, two-, and three-dimensional discrete ordinates Neutron/photon transport code system, *RSIC Computer Code Collection*, CCC-650, (1998).

7. R. G. Alsmiller Jr., J. M. Barnes, and J. D. Drischler, "Neutron-photon multigroup cross sections for neutron energies less than or equal 400 MeV (Revision 1)," Oak Ridge National Laboratory, ORNL-TM 9801 (1986).

8. R. A. Lillie and F.X. Gallmeier, "HILO2k: A coupled Neutron-Photon Transport Cross-section Library for Neutron Energies up to 2000 MeV," *Fourth International Topical Meeting on Nuclear Applications of Accelerator Technology, American Nuclear Society*, Washington D.C. (2000).

9. W. W. Engle Jr., "A users manual for ANISN: A one-dimensional discrete ordinates transport code with anisotropic scattering," K-1693, Oak Ridge Gaseous Diffusion Plant, Union Carbide Corp. (1967).

10. W. A. Rhoades and R. L. Childs, "The DORT Two-Dimensional Discrete Ordinates Transport Code," *Nucl. Sci. & Engr*. 99, 1, pp. 88-89 (1988).

11. W.A. Rhodes and D.B. Simpson, "The TORT three-dimensional discrete ordinates neutron/ photon transport code (TORT version 3)," ORNL/TM-13221, Oak Ridge National Laboratory, Oak Ridge, TN (1997).

12. F. X. Gallmeier and R. E. Pevey, "Creation of a set of interface utilities to allow coupled Monte Carlo/discrete ordinates shielding analysis," *Third International Topical Meeting on Nuclear Applications of Accelerator Technology*, Long Beach, California, November 14-18, 1999, p 404, American Nuclear Society (1999).

13. J.F. Briesmeister, "MCNP-A general Monte Carlo n-particle transport code, Version 4B", Los Alamos National Laboratory, LA-12625-M version 4B (1997).

14. N.V Mokhov, "MARS Code Developments, Benchmarking and Applications," Fermilab-Conf-00-066 (2000).

15. R. A. Lillie, "DTD: A Coupling Code for Two-Dimensional R-Z Cylindrical Geometries," *Trans. Am. Nucl. Soc.* 61, 381 (1990).

16. F. X. Gallmeier, "Shielding the SNS Klystron Building from the Linac," *Fourth International Topical Meeting on Nuclear Applications of Accelerator Technology*, Washington D.C., November 12-15, 2000, p. 234, *American Nuclear Society* (2000).

17. J. A. Bucholz, F. X. Gallmeier, I. Popova, "Egress Shielding Studies for the SNS Accelerator System," *Fifth International Topical Meeting on Nuclear Applications of Accelerator Technology*, Reno, Nevada. November 11-15, 2001, *American Nuclear Society* (2001) in print.

18. T. M. Miller, R. E. Pevey, R. A. Lillie, and J. O. Johnson, "Radiation Transport Analyses in Support of the SNS Target Station Neutron Beamline Shutters Title I Design." *Proceedings of the Topical Meeting on Radiation Protection for our National Priorities: Medicine, the Environment, and the Legacy*, Spokane, Washington, September 17-21, 2001, p.141-147, *American Nuclear Society* (2001).

19. M. B. Chadwick, P. G. Young, S. Chiba, S. C. Frankle, G. M. Hale, H. G. Hughes, A. J. Koning, R. C. Little, R. E. MacFarlane, R. E. Prael, and L. S. Waters, "Cross Section Evaluations to 150 MeV for Accelerator-Driven Systems and Implementation in MCNPX," *Nuclear Science and Engineering* 131, No. 3, p 293 (1999).