SNS shielding analyses overview

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Abstract

This paper gives an overview of on-going shielding analyses for Spallation Neutron Source. Currently, most of the shielding work is concentrated on the beam lines and instrument enclosures to prepare for commissioning, save operation and adequate radiation background in the future. There is on-going work for the accelerator facility. This includes radiation-protection analyses for radiation monitors placement, designing shielding for additional facilities to test accelerator structures, redesigning some parts of the facility, and designing test facilities to the main accelerator structure for component testing. Neutronics analyses are required as well to support spent structure management, including waste characterisation analyses, choice of proper transport/storage package and shielding enhancement for the package if required.

Introduction

The Spallation Neutron Source (SNS)[1] currently operates at 1.2-Megawatt (MW) proton beam power incident on a mercury target, with a proton beam energy of 1 GeV and a repetition rate of 60 Hz. The facility is still ramping up the power to reach the design goal of 1.4MW on target. SNS consists of accelerator system, target system, and a world-class suite of neutron scattering instruments to benefit material, life-science and fundamental physics research.

The SNS accelerator is powered by an H- beam, which transfers after acceleration into proton beam and consists of the linear accelerator (linac), the high-energy-beam-transfer line (HEBT), the accumulator ring and the ring-to-target-beam-transfer line (RTBT). The high-energy neutrons resulting from the proton initiated spallation reactions in the mercury target are converted to thermal and cold neutrons by one ambient water and three supercritical hydrogen moderators placed above and below the target. The thermalised neutrons are directed to the neutron scattering instruments through neutron beam lines. There are 18 beam lines, 6 of which serve two instruments each, so the facility is able to accommodate 24 instruments. Currently, 17 instruments are operating, two additional instruments are in or near the commissioning stage.

Although the facility is completed and in operation, there is still a wide range of demands for shielding analyses. During accelerator operation, some parts of the facility are redesigned and improved, and neutronics optimisations are an important part of the process. Linac access way redesign is on-going work. Additional facilities for test purposes for accelerator structures are being built and require shielding. Recently, a linac cryomodule RF test facility and an RFQ test stand were constructed. A conceptual study for standalone electronics irradiation station for single-event effects in avionic and ground based systems is in preparation to scope out the feasibility and cost. Shielding requirements are a huge factor in the construction cost. The neutron scattering instruments USANS and Corelli will be commissioned soon, which require extensive work on beam line and instrument enclosure shielding. The neutron imaging instrument VENUS is currently being designed; also their shielding is an integral part of the instrument and a large cost factor. Another large area of neutronics/shielding work is the prediction of isotope composition for spent structures from accelerator and target facilities in order to do waste characterisation analyses and to develop proper transport and storage containers such as spent proton beam window and target modules, neutron beam line shutters and neutron beam collimators and spent accelerator components.

Methods and codes

Radiation transport calculations for shielding design and radiation protection analyses are performed mainly with the Monte Carlo code MCNPX version 2.6.0 [1] with realistic three-dimensional geometric description for all facility components and support structures. The MCNPX code simulates the particle transport of hadrons, continuous energy loss of charged particles in matter, elastic and nonelastic hadron interactions, secondary particle generation (here mainly gamma ray and neutrons) and their transport. Geometry splitting is applied to force particles towards the outside of the shielding for deep penetration calculations. MCNPX calculations are usually run on multiprocessor computers in the parallel mode. For beam line analyses applications, an in-house version is used with a neutron mirror guide option, permitting the thermal and cold neutron transport in the neutron guides to be adequately modelled.

Effective dose rates are obtained by folding neutron and gamma ray fluxes with flux-to-dose conversion coefficients, which are taken from standardised SNS neutron and gamma ray flux-to-dose conversion factors libraries [2]. For scoring the neutron and gammas dose rates, two types of tallies are generally used – surface and mesh tallies.

Analyses are performed in three steps for residual dose calculations for the parts of facility, and for developing storage/transport containers for extracted irradiated structures. In the first step, reaction rates in the requested structures were calculated using MCNPX. In the second step, isotope production rates are fed into the Activation Script [3]. This script provides the interface between MCNPX and the transmutation codes CINDER’90 [4], ORIHET3 and SP-FISPACT. CINDER’90 is usually applied to obtain the time dependence of the isotope build-up and decay for given locations according to the provided operational scenario. From the transmutation code outputs, gamma ray decay spectra and gammas ray power are extracted. In the third step, the extracted gamma spectra are formatted into source descriptions for MCNPX to perform decay gamma ray transport calculations.

For the radionuclide inventory analyses, steps one and two are applied, and then isotope concentrations are extracted from the transmutation code outputs for structural accelerator materials, water and soil.

Beam line shielding

Most of the shielding work is concentrated on the neutron beam lines. Neutron beams are contaminated by a large fraction of fast neutrons with energies up to the driving proton energy. The fast neutrons can be attenuated by choppers making use of the pulsed beam structure, the discrimination of fast and thermal neutrons by time of flight, and by curved neutron guides. In either way the neutron flight paths have to be packed into heavy thick shielding that needs to be custom tailored to each specific instrument including the neutron guides, choppers, sample environments, detectors and beam stops. Each beam line requires elaborative work to design shielding because of differences in the viewing moderator (which means different sources), the size of neutron beam pipe, neutron optics, distance between sample position and moderator, and differences in the nominal conditions of operation. Guidelines for the SNS neutron beam line shielding calculations [2] provide standards for the beam line and instrument enclosure analyses. Beam line shielding analyses are logically divided into two sets:

- analysis of the incident beam line;
- analysis of the instrument cave or enclosure, including the neutron beam stop.

Beam line and instrument shielding analyses are performed using source terms describing the neutron in scattering into the beam lines starting at about one metre distance from the moderator faces.

Beam line specific neutron and gamma source terms [5] were generated for beam lines depending on which moderator beam line faces. The source terms were built by taking into account the neutron in-leakage into the core vessel insert opening.

Incident beam line shielding

Neutron beam lines at SNS can be straight (allowing passage of fast and high-energy neutrons) or curved (relying on neutron optics to transport slow neutrons). All beam lines have primary shutters within the shielding monolith. Many beam lines also have secondary shutters, either to allow multiple instruments to use a single primary shutter or to permit more rapid personnel access to the instrument sample area.

Beam line shielding should limit dose rates to 0.25 mrem/h at 30 cm distance from accessible shielding surfaces for at least the following conditions:

- white beam (all choppers open or removed);
- any single chopper, slit, secondary shutter, or other beam obstruction expected to affect shielding closed or in place;
- dual beam lines (e.g., POWGEN and MANDI) must consider both source terms, or if one beam line is not built out, it must be shown to be adequately blocked.

The secondary shutter must be designed for dual beam lines in order to provide independent work of the beam lines as a safety feature. The criterion for the design is to assure that a total dose rate at the sample position and/or the end of the neutron guide of less than 2 mrem/hour when the primary shutter is open, secondary shutter closed, and all choppers are open or removed.

Figure 1 gives an example for the straight beam line shielding design, beam line 17, the SEQOUIA instrument shielding. The beam guide is tapered towards the sample position from 9.567 x 11.43 cm to 5.042 x 5.455 cm at sample position, which is 20 m from the moderator face. Numbers on the bottom show distance from the moderator to components of the beam line. Figure 2 shows the dose rates along the flight path for beam line 17, the SEQOUIA instrument, when T0 chopper is open and when T0 shopper is parked in a closed position. This beam line is straight and its sample is positioned 20 m from the moderator. Black lines represent the beam line geometry on all the figures. Dotted lines represent cavities for the choppers. The beam line model starts at 100 cm from the moderator and extends to 1709 cm from moderator. Lines after 1709 cm from the moderator represent the front portion of the instrument enclosure shielding. Shielding around the beam line guide is 15 cm of steel followed by high-density concrete with varying height depending on the distance from the moderator.

Figure 1. SEQOUIA beam line layout

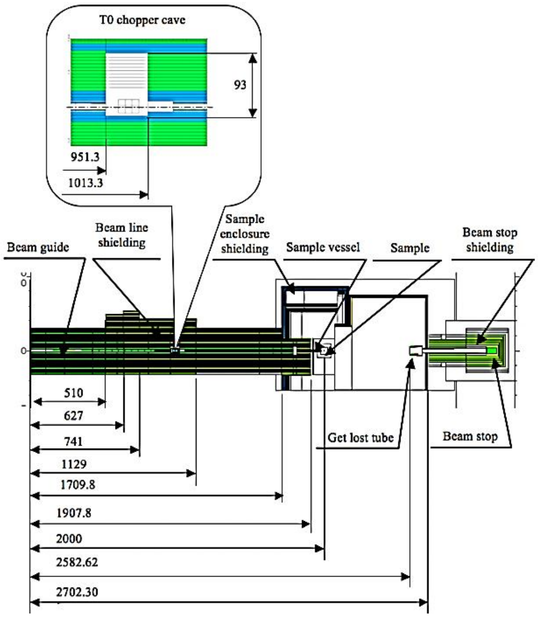
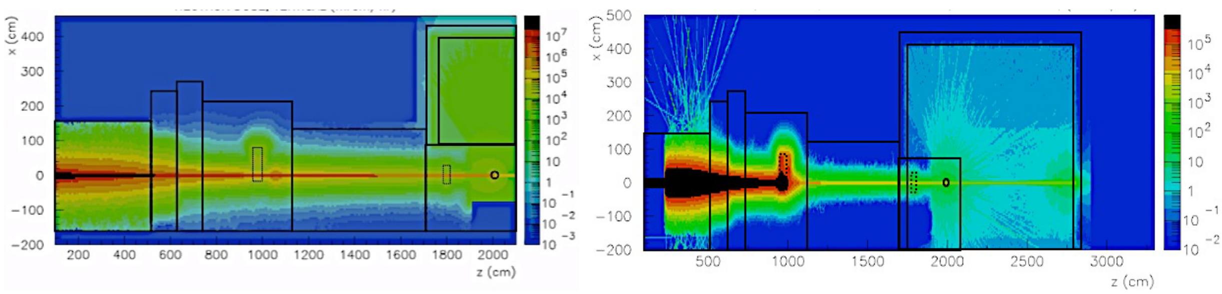


Figure 2. Dose rate map in elevation view of SEQOUIA beam line, T0 chopper is open and T0 chopper is closed, mrem/h (dimensions in cm)



Shielding analyses for the curved beam lines are more challenging, especially when beam pipe aperture is small. Figure 3 gives an example for the curved beam line shielding design, beam line 11b, the MANDI instrument. Red numbers show height of the shielding from the beam centreline and numbers on the bottom show distance from the moderator. Beam guide opening at position 28.5 m from the moderator is 1.214 cm by 1.531 cm. The beam line model starts at 100 cm from the moderator and extends to 2620 cm from moderator. Lines after 2620 cm from the moderator represent the front portion of the instrument enclosure shielding. Beam line curvature radius is 1200 m, and line of sight is lost at about 1550 cm from the moderator. Material for the beam line shielding changes along the beam line. From the target monolith to the 1020 cm position from the moderator, the shielding material is high density concrete. There is a slab of steel shielding inside the high-density concrete above the first/second chopper cavity, which is 55 cm high and goes through the whole shielding in width. From a 1020 cm position from the moderator to a 2620 cm position from the moderator beam line shielding is regular concrete. Figure 4 shows the dose rates along the flight path for beam 11b, MANDI instrument in elevation and horizontal view. Because MANDI instrument is a dual beam line, a second shutter is required as a safety measure. A secondary shutter from borated carbon neutron absorber followed by 2 cm of the steel was designed. The secondary radiation field is well mitigated by the beam line shielding, when the shutter is in a closed position. Also the in-beam dose rate predicted in the instrument enclosure with the secondary shutter closed meets the dose rate design criterion for all analysed cases.

Figure 3. MANDI beam line layout (dimensions in cm)

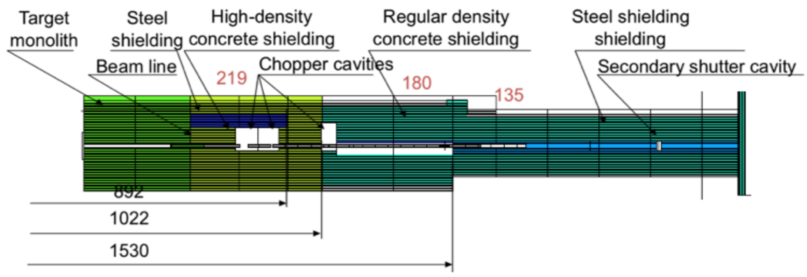
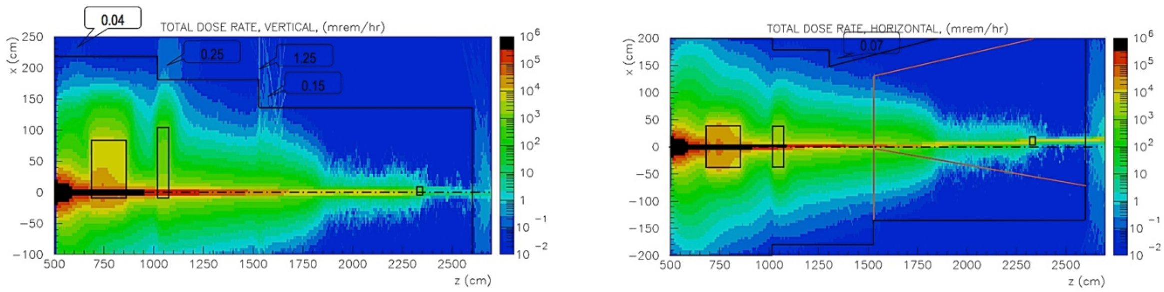


Figure 4. Dose rate map in elevation and horizontal view of MANDI beam line, mrem/h



Instrument cave/enclosure shielding

The instrument enclosure shielding analyses will include two separate analyses: the beam stop and the enclosure shielding design. Enclosure shielding is designed for the "normal operation" beam conditions (beam with limited energy bandwidth) in case an area monitor activates the closing of the shutter in case of elevated dose rates. Otherwise accident-case beam conditions are considered such as a white unobstructed beam running into the piece of equipment or the worst case samples. Both polyethylene and steel samples are used for those analyses. The beam stop shielding must be designed for the white unobstructed beam with no sample inserted.

Figure 5. VENUS enclosure layout in elevation and horizontal view

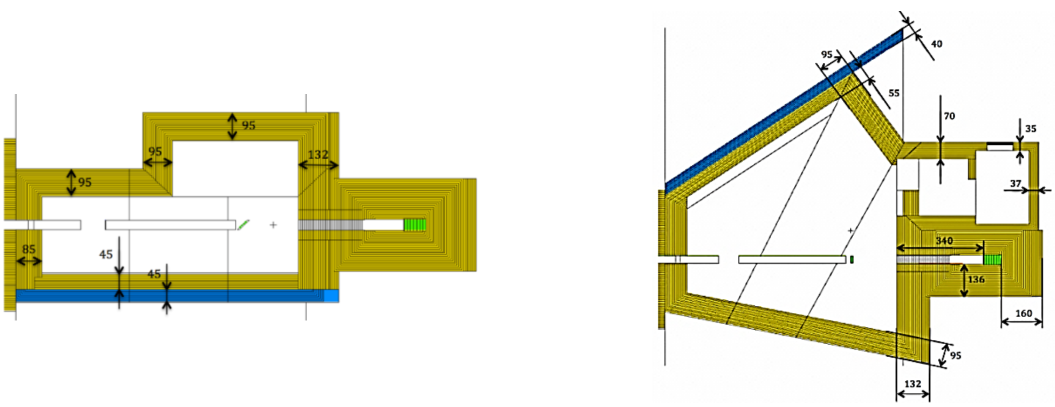
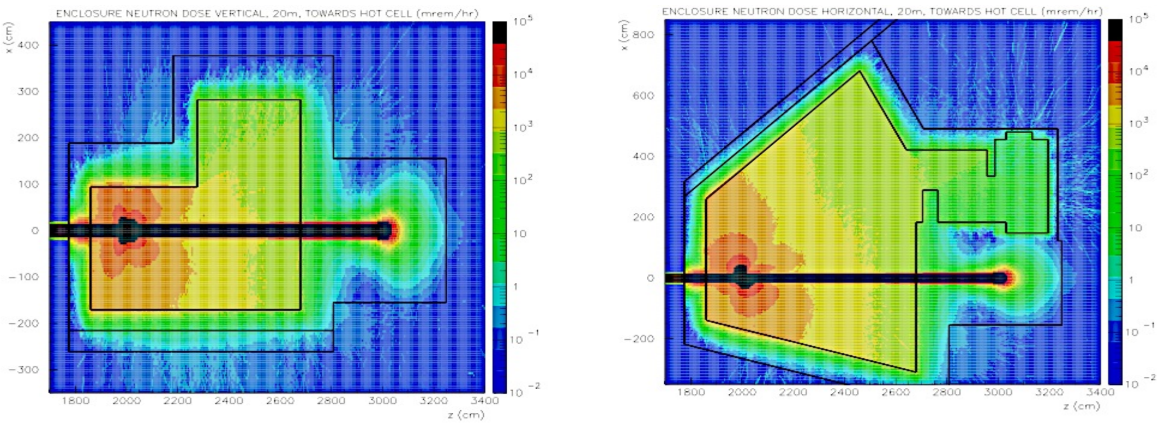


Figure 5 gives an example of shielding design for enclosure for beam line 12, VENUS instrument in elevation and horizontal view. This instrument set-up requires the thickest instrument enclosure compared to all the other SNS instruments because of large beam opening at the sample position – about 21 cm in diameter near the sample position at 2000 cm from the moderator. The suggested thickness of the enclosure is 95 cm of high density concrete. This work is still on-going. Figure 6 shows the dose rate map of VENUS instrument enclosure in elevation and horizontal view.

Figure 6. Dose rate map in elevation and horizontal view of VENUS instrument enclosure, mrem/h



Accelerator facility shielding aspects

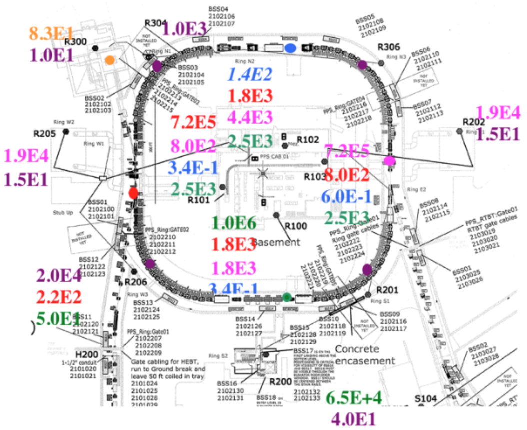
The accelerator facility has been in operation since 2006, however, it is still necessary to perform neutronics work. The scope of work to support accelerator facility includes:

- radiation-protection analyses for radiation monitor placement;
- shielding for additional facilities to test accelerator structures (linac cryo-module RF and RFQ test stands, Integrated test stand facility for accelerator front-end);
- neutronics optimisation for redesign and improved components (Linac access way redesign, HEBT momentum dump redesign).

Radiation protection analyses

Extensive work has been completed to summarise the response of the area radiation monitors ("chipmunks") to the maximum possible accidental beam spill around the accelerator facility and to evaluate whether any beam-spill accidents would be detected by at least two chipmunks. Analyses for the dose rates at the chipmunks were performed based on the maximum possible accident of a full beam spill for each considered accelerator section. The location of the accident was considered to be in the closest possible position to the chipmunk. As an example, Figure 7 summarises chipmunk readings in case of a possible maximum beam spill in the ring section of the accelerator. The coloured dot shows the location of the beam spill at a thick target or the centre of the beam spill on the beam pipe assuming a Gaussian distribution. The coloured dot shows the location of the beam spill; the coloured numbers near each chipmunk show the dose rate measured at the chipmunk in mrem/h. The colour of the number refers to the dose rate measured by the chipmunk when the spill appears in the place marked with the same colour. Chipmunk locations are marked by the letter R. Analyses show that the existing chipmunk locations are satisfactory to measure any elevated dose rate from accident conditions in the accelerator and that there is overlapping response - if one detector fails other detector will identify beam loss. Maximum dose rates in occupied areas are calculated to be approximately 110 rem/h in the ring section.

Figure 7. Dose rate at chipmunks at the ring section of accelerator, mrem/h



Linac test stands

Test pit for RF cryo-module cavities is an example of linac test stands shielding design. This facility is an underground construction with concrete lining with varying thickness inside the pit. In order to ensure safe operation from radiation protection point of view, a cover, which will be placed over the pit, needed to be designed as radiation shield of varying RF conditions. Figure 8 shows configuration of test pit facility modelled in MCNPX geometry language. Source for shielding analyses to design pit cover is an electron beam, which hits the end plate of cryo-module and generates gamma emission. Analyses were performed for the most conservative possible source – an electron energy of upcoming beam is 20MeV, and electron current is 200nA.

Figure 8. Layout of the pit with the cover in elevation views (dimensions in cm)

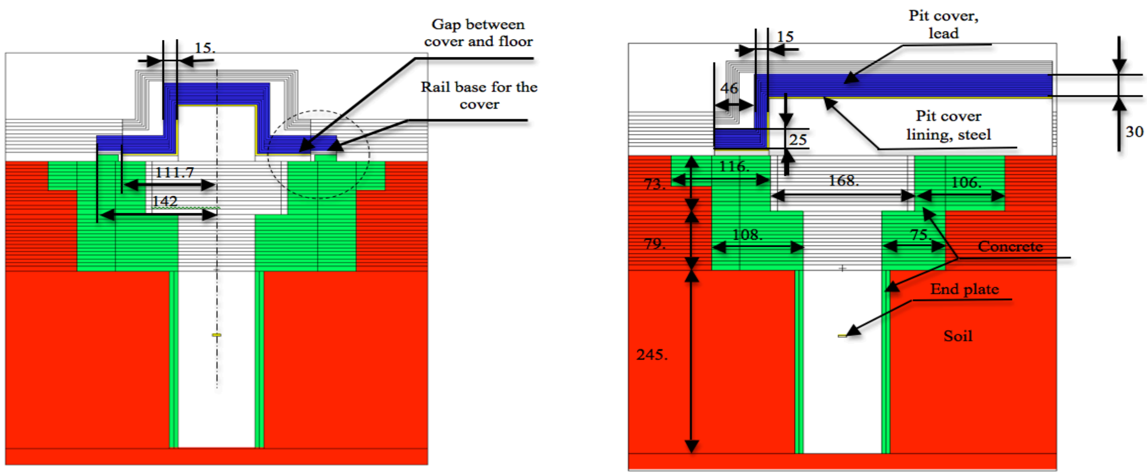
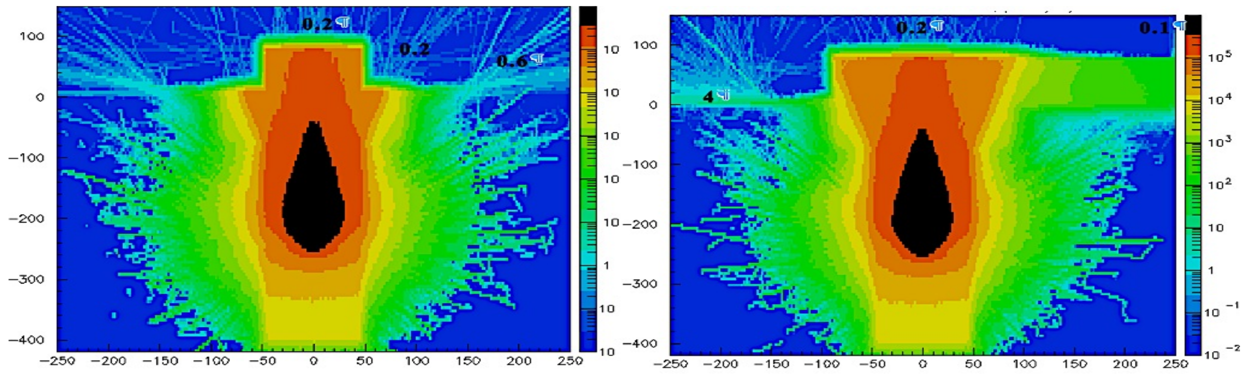


Figure 9 shows the dose rate map in the vicinity of the test pit facility in 2 elevation views. Analyses show that with the present configuration (Figure 8) there are some areas with slightly elevated dose rates. It has been suggested that elevated dose rates should be mitigated by putting lead bricks in locations of elevated dose rates.

Figure 9. Dose rate map in elevation views for test pit facility, mrem/h



Neutronics optimisations for redesigned and improved components

Some of the existing accelerator structures are replaced for various reasons such as facilitating access to the tunnel or replacing old components with newer and better performing ones. Extensive work has been performed to redesign the momentum beam stop in Linac-to-Ring transfer line and the accelerator tunnel front-end door.

The accelerator tunnel starts in the front-end building. The front wall of the accelerator tunnel contains an access for moving Linac equipment and supplies in and out of the tunnel. This access is closed by the so-called plug door, which provides with 90 cm thick concrete, the same shielding as the surrounding tunnel walls. The plug door is very heavy and difficult to handle. In order to make it more manageable a door with lighter weight was designed.

A full-scale model of the front-end of the accelerator and first accelerating sections was built for these simulations. First, source terms near the front end inside the tunnel were calculated based on measured beam losses during normal operations. Then scaling calculations were performed to figure out the proper amount of materials for the door, which were resulted in 2.5 cm of steel followed by 10 cm of 5% borated polyethylene followed by 2.5 cm of steel. The area in the front of the accelerator tunnel is a radiation controlled area, the door was designed so that the dose rate outside the front accelerator wall would not exceed 5 mrem/h.

Neutronics analyses for waste management

Components are replaced when they reach their end-of-life due to radiation-induced material damage or burn-up, or because of mechanical failure. During operation, these components, especially those in proximity to the target, are exposed to a radiation environment and build up significant activity during their service lifetime. All these components must be safely removed, placed in a container/package for storage, and ultimately transported off-site for disposal.

Target system facility

Target vessel, proton beam window (PBW), inner reflector plug (IRP) and core vessel insert (CVI) plugs are routinely scheduled to be replaced in maintenance periods following the facility operation periods about twice a year. Target and proton beam window are replaced to avoid material embrittlement. Estimated allowable peak damage of the steel and inconel structures is 10 dpa.

IRP is expected to be replaced in 2016. The process for the determination of right box/package has started. CVI plugs are temporary constructs and are replaced, when a beam line is opened up, a full beam line shutter and actual optics components are installed. At present, we have two CVI plugs being prepared to be transported off-site.

The most time consuming analyses are required for target vessel disposal. The SNS target vessel contains the liquid mercury target in the in-beam area of the target station. The target vessel is exposed to a severe radiation environment and builds up significant activity during its service lifetime. The target vessel is routinely replaced as it approaches its estimated life-time, or if it prematurely fails. Based on the estimated radionuclide inventory for full beam power (2MW) for 5000 h operations, as well as the size and weight of the target vessel, it was decided to use the TN-RAM cask or equivalent for off-site transport to a waste disposal facility. Figure 10 shows the MCNPX model of target station for target vessel for transport calculations. Figure 11 shows the MCNPX model for typical configuration of spent target inserted in liner and TN-RAM cask. The radionuclide inventory for the target vessel includes three components: the target vessel, 200 g of activated mercury dispersed in the target, and 10% of the mercury radionuclide inventory (other than mercury, gold and noble gas isotopes) deposited on mercury exposed steel piping.

In order to simplify analyses and avoid errors arising from manual preparation of calculations, the Perl script TARGET_DISPOSAL was created to run these analyses. This script uses reaction rates in the target vessel and in the mercury calculated by MCNPX, and stored in the output and runs ACTIVATION_SCRIPT, for transmutation analyses to produce the radionuclide inventory and gamma source terms. Then, the script prepares the decay gamma source definition for MCNPX photon transport calculations for the target vessel inside a liner and also for the target vessel inside the liner inside the transport cask. For analyses of residual dose rates, next-event point and ring detectors are applied, as well as dose rate mesh tallies, to allow for dose rate contours in and around liner and cask geometries. After completion of the transport analyses, the script automatically generates a final report. As an example, Figure 11 shows a typical configuration for spent target inserted in the liner and TN-RAM cask modelled in MCNPX geometry language and dose rate contours in and around the TN-RAM cask loaded with the liner and the SNS spent target #8 after 202 days decay. Target #8 module had a service lifetime of approximately 0.97 years in which it accumulated slightly more than 3744 MWh proton beam energy at 1GeV proton energy.

Figure 10. MCNPX model for target vessel and proton beam window transport calculations

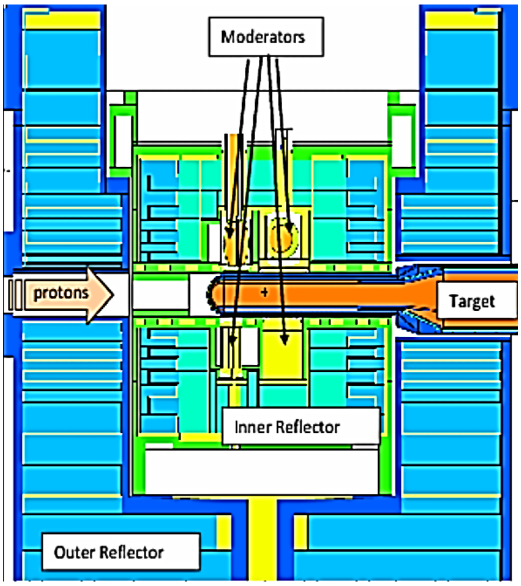
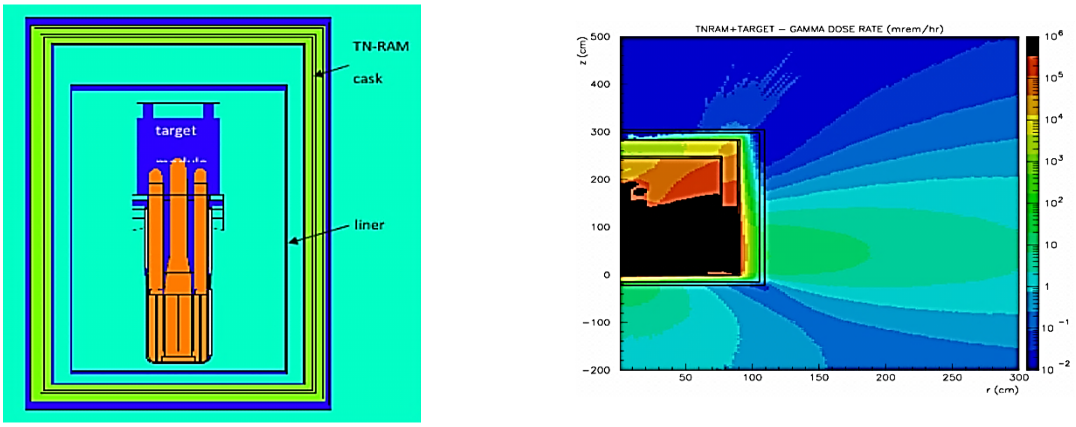


Figure 11. MCNPX model for typical configuration of spent target inserted in the liner inside TN-RAM cask and dose rates map around this configuration, mrem/h

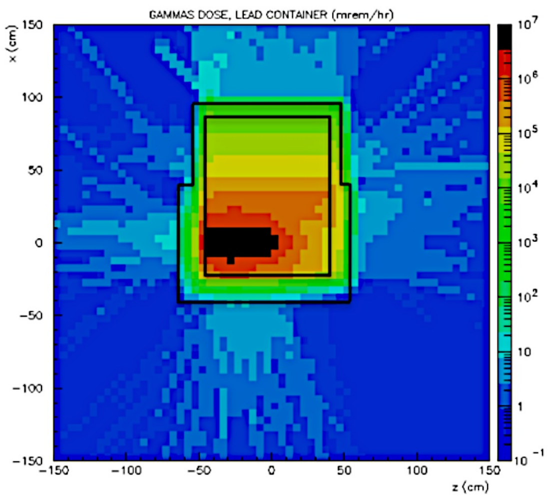


Accelerator system facility

Temporary storage casks for accelerator spent structures are designed under the criterion, that the dose rate outside the container will not exceed 5 mrem/h at 30 cm distance from the container surface and are already designed for: HEBT momentum beam stop, RTBT harp and ring injection dump (RID).

According to the accelerator operations plan, the beam stop core and window assemblies of the existing RID will be removed when they have reached their end-of-life. Both parts are expected to be highly activated because the RID receives the highest losses in the accelerator facility, 5% of the accelerator beam power (100kW). Shielding above these two assemblies has to be removed to allow access, and will be placed into temporary storage containers while the beam stop core and window assemblies are removed and reinstalled. Two container configurations for each assembly were suggested. The first configuration assumes use of a lead container whereas the second configuration assumes use of a steel container, but reinforced with lead. Figure 12 shows dose rate distribution for beam stop assembly lead container as an example. The container has variable thickness around the RID assembly.

Figure 12. Dose rates map inside and outside the beam stop assembly lead container, mrem/h



Conclusions

Neutronics work is in full swing for the SNS facility, meeting demands on shielding work for neutron beam line in preparation for their commissioning and to ensure their safe operation; providing support for accelerator components to help redesign parts and system and to do shielding design for test stands; providing support for radiations protection analyses for radiation monitors placement and performance; and providing analyses to support waste management of spent components.

Acknowledgements

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