Prediction of the Radiation Fields for Commissioning of the SNS Linac

Irina I. Popova and Franz X. Gallmeier

Oak Ridge National Laboratory
P.O. Box 2008, MS-6474
Oak Ridge, TN 37830, USA
Email:popovai@ornl.gov

Abstract – *For the commissioning phase the prompt and residual dose rates in the vicinity of the SNS linac (DTL and CCL sections) were investigated for the scenarios of running proton beam into the beam collectors located at the downstream end of the DTL tanks and CCL modules. For the CCL module 3 commissioning, which produces the highest dose rates in the accelerator tunnel, the dose rates on the top of the earth-berm were calculated as well. On the base of the same source terms the shielding forming commissioning envelope was designed. MCNPX and Activation Analyses System were used as tools for the analyses.*

I. INTRODUCTION

The Spallation Neutron Source[1] (SNS) is powered by a high intensity 2mA, 1GeV proton beam. The beam starts as negatively charged hydrogen ions (H^-), which are generated in an ion source and accelerated from 2.5 MeV up to 1-GeV in a linac system (255 meters long) consisting of a drift tube linac (DTL), a coupled cavity linac (CCL) and a superconducting linac (SCL). Then the beam is transported through the 170-meters-long high energy beam transport (HEBT) line and injected into an accumulator ring (248 meters long) converting the beam to the proton beam by stripping away the electrons. In the accumulator ring the proton beam is accumulated through nominally one thousand turns, and then extracted from the ring and transported by the ring to target beam transport (RTBT) line (150 meters long) to the mercury target.

Commissioning of the accelerator system is a critical step in the transition from the fabrication and installation phase to the operational phase. The proton beam power deposited in the linac tunnel during commissioning greatly exceeds the typical operational line losses that are of the order of 1W/meter with the consequence of very high level expected radiation fields. Therefore, analyses to predict prompt and residual radiation levels inside the accelerator tunnel and on the top of earth berm were performed. Wherever it was necessary, localized shielding solutions were investigated to mitigate the dose and activation of system components.

According to the SNS Commissioning Program Plan[2], the linac sections will be commissioned in steps, starting with the DTL tank 1, adding DTL tanks 2-6, and CCL modules 1-4. Up through CCL module 3 the commissioning beam will be terminated in beam collectors positioned at the end of the respective linac structure. Beginning from the last CCL module 4 throughout the SCL cryogenic modules, the linac will be commissioned into the permanent linac beam dump.

Shielding analyses for commissioning DTL tank 1 running under one shielding envelope, and for the commissioning DTL tanks 2 to 6 and CCL modules 1 to 3 running under another shielding envelope are the objects for this paper.

II. COMMISSIONING PARAMETRS

Fig. 1 shows the general facility layout up to start of SCL section. Red points show the beam collectors positions. The DTL and CCL commissioning will run under two shielding envelopes.

The first shielding envelope is for DTL tank 1 commissioning, which is formed by the shielding in the front-end building and an additional shielding wall downstream of a commissioning beam stop 3 meters downstream of the tank. The second shielding envelope will be established for DTL tanks 2 to 6 and CCL modules 1 to 3 commissioning. This envelope is formed by the linac tunnel and a labyrinth downstream of the SCL at the start of the HEBT section (Fig. 2).

The DTL tank 1 will be commissioned at full 16 kW beam power with 7.5 MeV energy into a beam stop. The calculations were performed for 16 kW beam power for this case. The DTL tanks 2 to 6 will be commissioned by running a 160 W proton beam into the beam collectors located at the downstream end of the tanks with beam energy 22.3, 39.8, 56.6 72.5 and 86.8 MeV for tanks 2 to 6, respectively. Because the CCL module 1 to 3 are commissioned into one beam collector downstream the

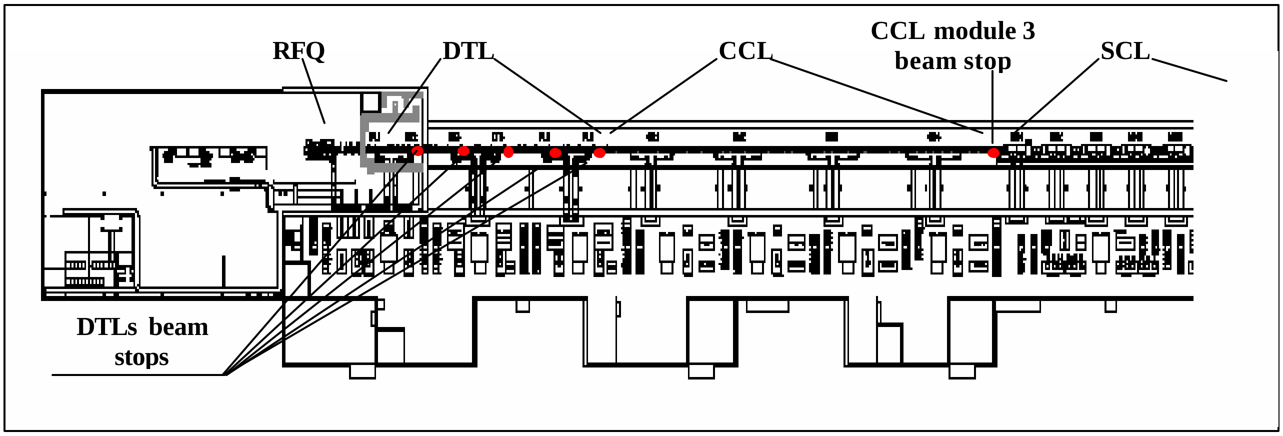

Figure 1. Facility layout up to beginning of SCL section

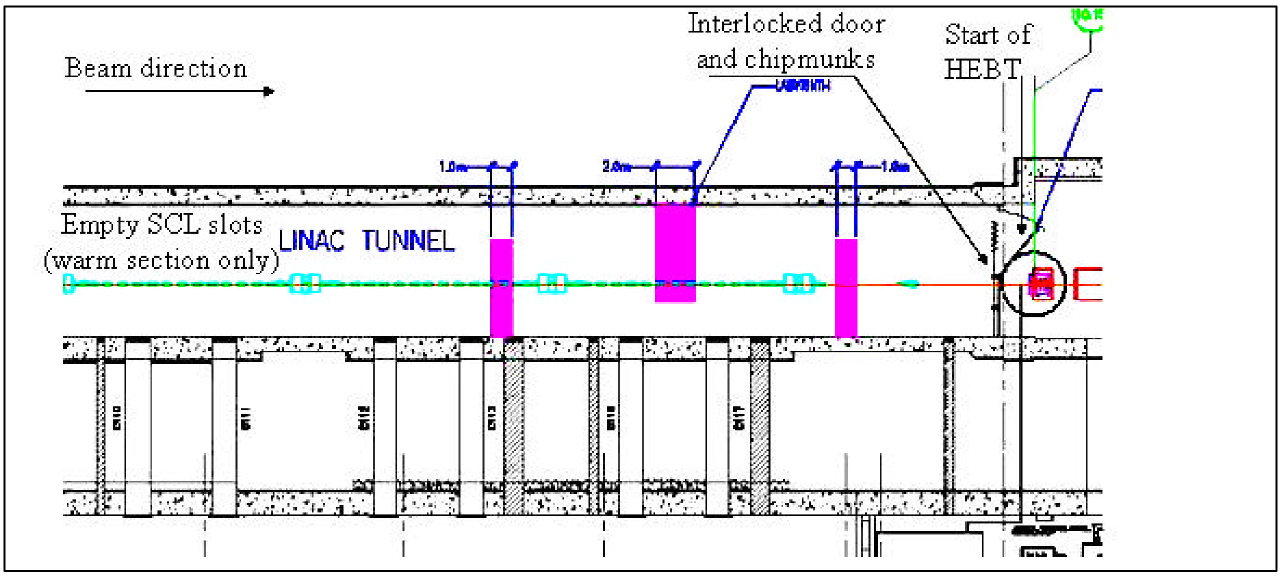

Figure 2. Facility shielding envelope in the linac end and HEBT beginning. Magenta color identifies labyrinth walls.

CCL module 4, only one case with the highest beam energy 157 MeV for CCL module 3 was analyzed with a 250W proton beam. The same unshielded case was used to design the labyrinth and estimate dose rates on the top of earth-berm.

For the residual dose rates calculations, activation scenarios of 1 days of continuous operation DTL tank 1 at 16 kW, 10 days of continuous operation at DTL tanks 2 to 6 at 160 W, and 70 days of continuous operation the CCL module 3 at 250 W, with a decay time of 1 hour after the beam terminating were considered. 70 days of CCL module 3 operation take into account commissioning of modules 1 and 2, which have slightly lower beam energy parameters.

III. CALCULATIONAL MODELS

The calculations were performed separately for DTL and CCL sections. The geometry models for both sections in the MCNPX[3] input language were developed for earlier studies[4], where the beam line structures were described rigorously. Only the beam collectors in the end of DTL and CCL structures were added. Both CCL and DTL sections models include the 0.61-m-thick tunnel walls surrounded by 5 meter thick layer of the soil. The tunnel is 3.04 m high and 4.26 m wide. The center of the proton beam line is located 1.83 cm from the closest sidewalls and 1.25 m from the floor.

The DTL section model consists of six DTL tanks located in the accelerator tunnel including the drift spaces

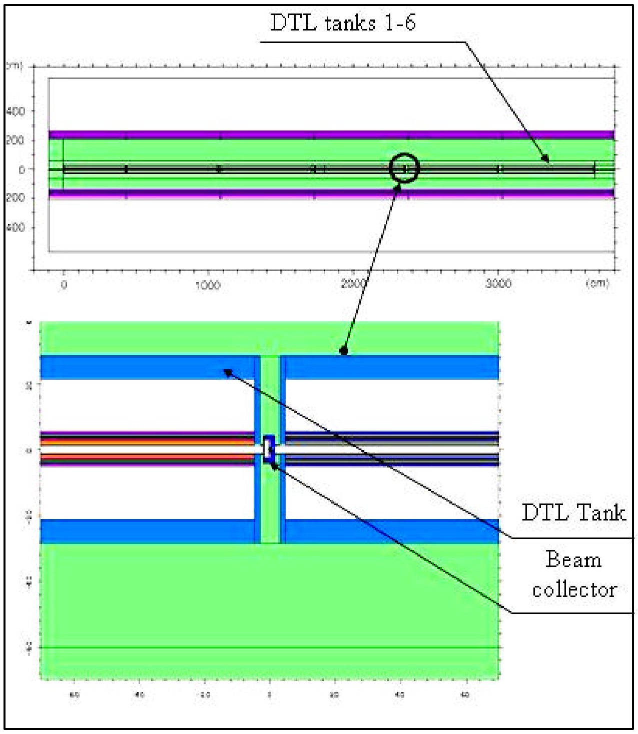

Figure 3. DTL model.

and beam collectors located between them (Fig. 3). The DTL tank 1 beam collector was modeled as a water-cooled nickel cone mounted at the end of a diagnostic plate and optionally surrounded by a borated polyethylene enclosure (Fig. 4). The DTL tanks 2 to 6 beam collectors were modeled as 8 cm diameter sandwich of discs with an energy-adjusted absorber layer of graphite or copper, followed by a collector layer of 6-mm-thick copper in a water-cooled copper housing. Table 1 lists the absorber thicknesses of all beam stops/collectors. The beam stop/collector thicknesses were designed to completely range out the incident protons.

Table 1. Absorber thickness and materials of the DTL beam collectors.

Collector No.	Proton energy (MeV)	Absorber thickness, mm	Absorber material
1	7.5	2.0	nickel
2	22.3	3.036	graphite
3	39.8	8.299	graphite
4	56.6	4.197	copper
5	72.5	6.546	copper
6	86.8	9.139	copper

The section of the CCL section model includes four CCL modules; each module contains 12 segments. The last module is followed by a beam collector and SCL medium beta cryomodules (Fig. 5). The beam collector is a vertical copper cylinder with 5.5 cm diameter, which is mounted on the tunnel floor.

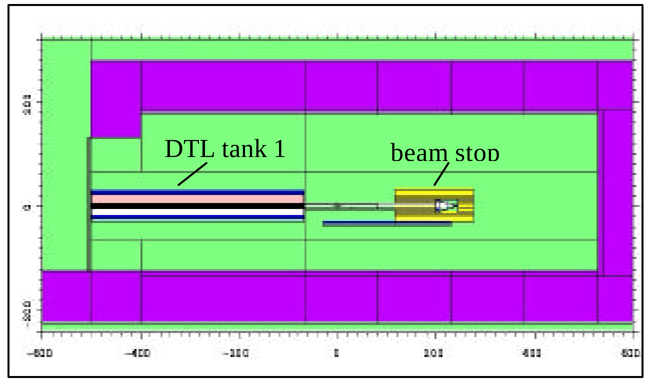

Fig. 4: Vertical cut through the MCNPX model for DTL tank 1 commissioning.

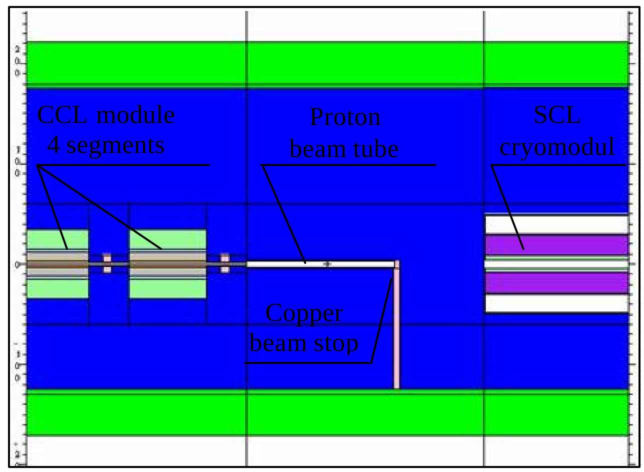

Figure 5. Part of SCL model including end of CCL, beam stop and start of SCL section.

The same geometry was used for both the prompt and the residual calculations.

VI. METHODS

The prompt dose rate levels in the accelerator tunnel were calculated applying the MCNPX Monte Carlo multi-particle transport code, which simulates the generation of secondary radiation fields due to the impact of proton beams on the beam collectors. The proton sources were defined as a pencil beam incident to the beam collectors using standard MCNPX source input cards with location, energy and source strength adjusted for each commissioning step. Beam losses along the proton line were not considered, as they were believed to be negligible compared to the 16 kW, 160W or 250W beam power deposited into the beam collectors. Each commissioning step was simulated in a separate calculation.

For the DTL tank 1 case, evaluated proton cross sections for proton transport for energies below 150 MeV were used in MCNPX since these were believed to give much more accurate results especially for very low proton energies. The neutron production probability was found to be 1.4e-5 per proton with an average energy of about 1 MeV. Detailed neutron and gamma production characteristics were generated with a simple model of a 7.5 MeV proton beam impinging on a 2-mm-thick disc, and used as a source for subsequent calculations. This circumvented long running times needed for simulating the proton interactions in MCNPX. The proton induced isotope production in the nickel beam stop was calculated using the physics model approach in MCNPX. We were surprised to find that this crude approach gave neutron production values that were within 20% of the tabulated data approach with only a slightly softer spectrum. All other isotope production origins in neutron activation and is extracted from an analyses with the detailed neutron source in the beam stop (see below).

Surface flux tallies and track length tallies were applied to obtain neutron and gamma fluxes. The surface tallies were defined at a cylindrical envelope with 60-cm radius around the linac structures and averaged over 50-100 cm long segments. Dose results were obtained from the flux results applying flux-to-dose conversion coefficients taken from the HILO multi-group cross section library[5]. For cases, when we were looking for more detailed spatial distribution, mesh tallies were applied.

For residual dose rate calculations the isotope production rates, which were resulting from the MCNPX calculations, were fed into the Activation Analysis System[8] (AAS) which includes the ORIHET95[9] isotope production and depletion module. The time dependence of the isotope buildup and decay was obtained for the given commissioning scenarios, and gamma decay spectra were extracted for all material cells in the problem. These gamma decay spectra were used as sources for subsequent MCNPX transport analyses to calculate the residual gamma dose distributions in the vicinity of the beam collectors.

The estimation of dose rates on the top of the earth-berm, which is 5 meters thick, was performed in two steps. The first step has been to obtain the rigorous boundary source terms as events of neutron and gamma leakages through a cylindrical surface inside the accelerator tunnel. The second step, neutron and gamma transport through the tunnel concrete ceiling and the soil, has been solved in two ways: (a) by direct application of MCNPX using geometry splitting, and (b) by using discrete-ordinates transport calculations applying the DORT[6] code and the HILO cross section library. The coupling tool MTD[7] was used to bin the MCNPX boundary source into the multi-group structure of the HILO cross section library and angle-wise into a symmetric S64 angular quadrature set applicable for the discrete ordinate DORT code.

VI. RESULTS

The studies performed for DTL tank 1 commissioning showed that the neutron field causes significant activation not only of the components of the diagnostic plate, but also of the DTL tank 1. Enclosing the beam stop and the flight tube into a layer of 0.3 meters of borated polyethylene was found to confine the neutrons to the beam-stop area and was thought to be highly beneficial.

Calculations were performed with and without borated polyethylene enclosure. The resulting prompt dose rate profiles at 60 cm radius form the beam line presented in Fig. 6 indicate that the peak dose rates of 500 rem/hr can be reduced about at least a factor of 10 using borated polyethylene; even more, the neutron component of the dose is suppressed by more, than a factor of 500.

Residual dose rates near the tank1 beam stop of about 100 mrem/hr are expected as demonstrated by Fig. 7. The decay gamma source strength of the beam stop is expected to drop about a factor of 10 within one day, but not much further within one week.

At the time the article was written, it was not clear to which extent space constraints permit to mount shielding at the start of the DTL. At the downstream end of the shielding envelope, was estimated a concrete wall of 1.5 meters would be needed for the case without borated polyethylene around the beam stop, and about 1.3 m for the case with borated polyethylene envelope.

Prompt and residual dose rate profiles are presented in the Figs. 8 and 9 for DTL tanks 2 to 6 commissioning, and in the Figs. 10 and 11 for CCL module 3 commissioning. The prompt dose rate levels consist of both neutron and gamma contributions (the neutron contributions are generally dominating) whereas for the residual doses only the decay gamma contribution is present.

As expected the dose profiles peak near the positions of the beam collectors, starting out with prompt peak dose levels of about 20 rem/hr for DTL tank 2 commissioning, ramping up to 200 rem/hr and 2000 rem/hr for tanks 3 and 4, respectively. The reason for this sharp increase is seen in the increase of the neutron production rates for the increased final energies of the different commissioning steps. For tanks 5 and 6 the dose levels increase only slightly to 3000 rem/hr indicating that the increase of the neutron production rates due to the increased final beam energies is more or less compensated by the reduction of the beam current by having the beam power fixed to 160 W. The prompt peak dose level is about 9000 rem/hr

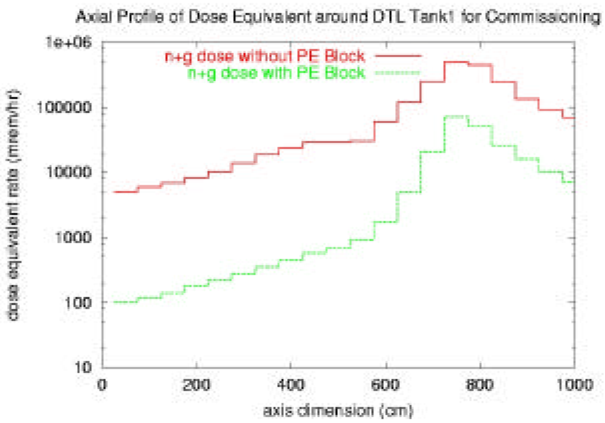

Figure 6: Axial profile of neutron/gamma dose rates at 0.6 meter radius from the beam axis during full beam operation into the beam stop for DTL tank 1 commissioning.

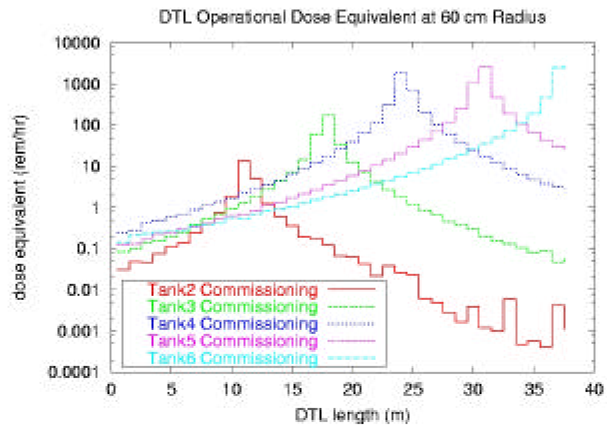

Figure 8. Total prompt dose rate equivalent profiles in the accelerator tunnel at 30 cm distance from the DTL structure.

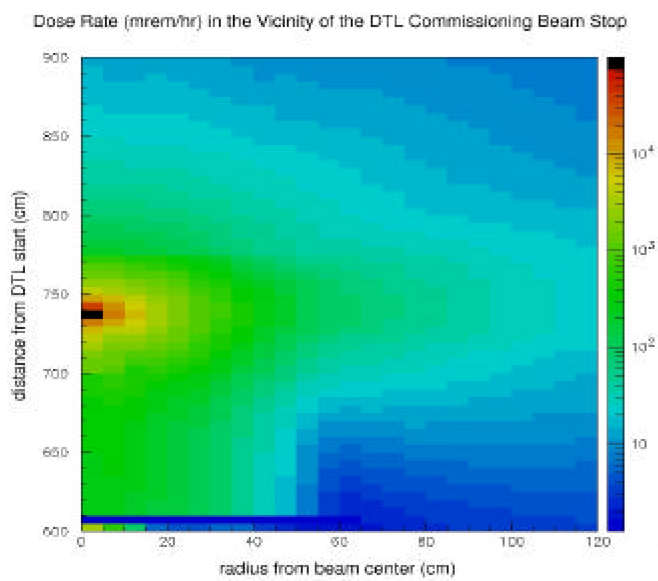

Figure 7: Contour plot of the residual dose rate commissioned at 2.1mA proton beam current for 10 days, and a 1 hour decay period after beam termination. The origin of the axis dimension is defined by the start of the DTL.

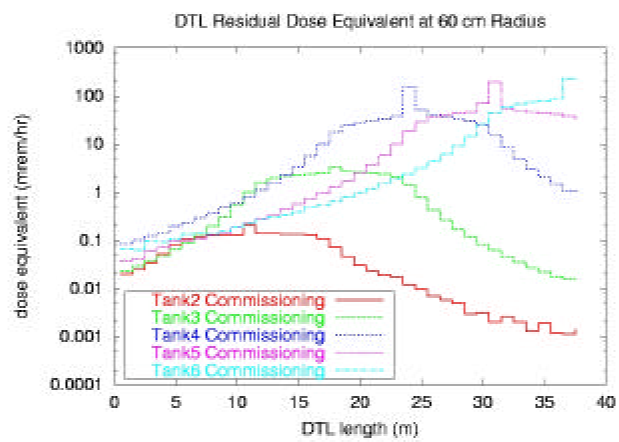

Figure 9. Residual dose rate profiles in the accelerator tunnel at 30 cm distance from the DTL structure commissioned for 10 days, and a 1 hour decay period after beam termination.

unshielded for the CCL module 3, which is somewhat higher compared to DTL cases.

The residual dose rate profiles for DTL tanks commissioning after 1 hour decay are reduced by a factor of 10,000 compared to the prompt radiation levels for the tanks 4 to 6 resulting in peak doses of 200-300 mrem/hr near the beam collimators. The residual dose levels at tanks 3 and 2 are suppressed to peak at levels of 5 and 0.2 mrem/hr respectively, indicating reduction factors even higher than 10,000 compared to the prompt dose levels.

The residual dose rate profile for CCL module 3 are reduced by a factor of 4,500 with peak doses of 2 rem/hr near the beam collector, which is one order of magnitude higher than the worst DTL commissioning case, because the beam energy and power are higher and the irradiation time is 7 times longer. Figure 7 shows the residual dose rates due to CCL modules, beam stop and tunnel walls. The dominant source of residual radiation is the copper beam stop within 5 meters radii and the concrete tunnel walls elsewhere.

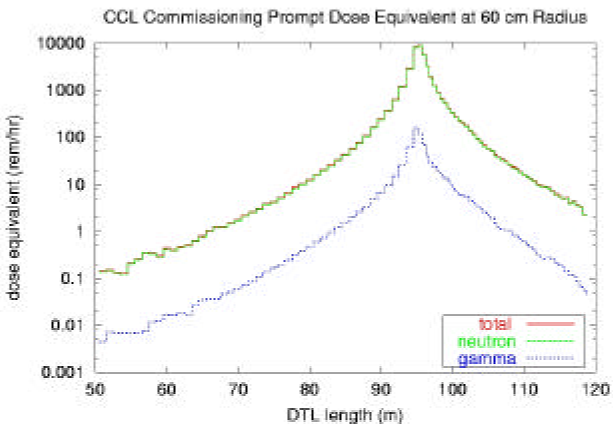

Figure 10. Total prompt dose rate equivalent profiles in the accelerator tunnel at 30 cm distance from the CCL structure.

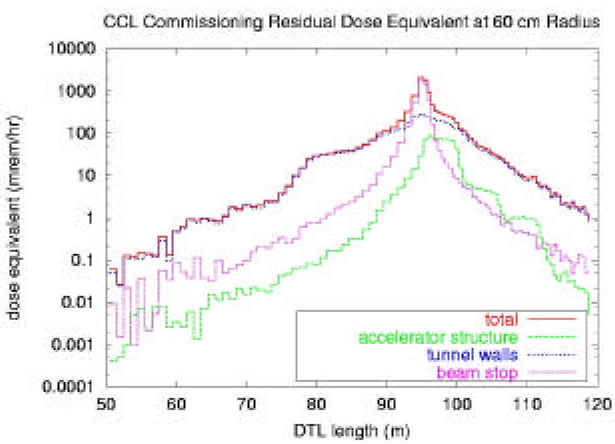

Figure 11. Residual dose rate profiles in the accelerator tunnel due to structures and walls at 30 cm distance from the CCL structure commissioned for 70 days, and a 1 hour decay period after beam termination.

The time behavior of the gamma power of the beam collimators including the nearby DTL tank walls is presented in Figures 12, 13 and 14 for the commissioning steps of DTL tank 3 and 5 and CCL module 3 respectively. The dose levels around the beam collimator following DTL tank 3 will not fall significantly within weeks. The dominating radioactive nuclide is Be-7 in the graphite absorber layer that has a half-life of 53 days. With a drop of the gamma activity of a factor of 50 within a day, the time characteristic of the gamma activity and hence of the residual dose is completely different for the beam collimator following DTL tank 5, as the absorber layer of the beam collimator is fabricated of copper. Thus this decay characteristic, which will result in acceptable dose rate levels after one day of decay time, is also representative for commissioning of DTL tanks 4 and 6.

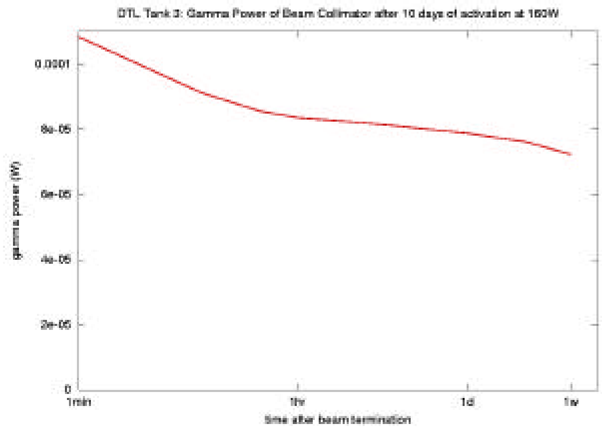

Figure 12. Gamma decay power of the beam collector between DTL tanks 3 and 4 for 10 hour irradiation at 160 W beam power at a beam energy of 39.8 MeV

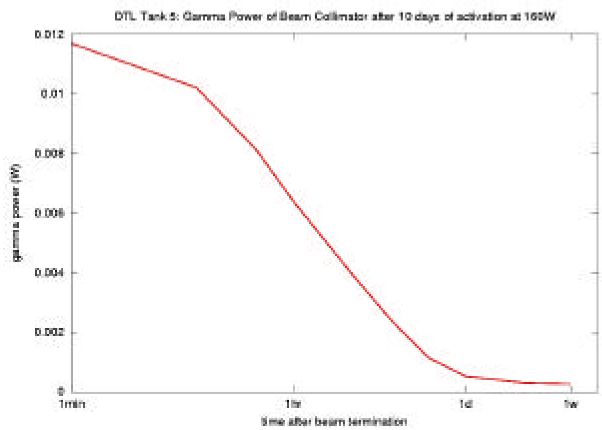

Figure 13. Gamma decay power of the beam collector between DTL tanks 5 and 6 for 10 hour irradiation at 160 W beam power at a beam energy of 72.5 MeV

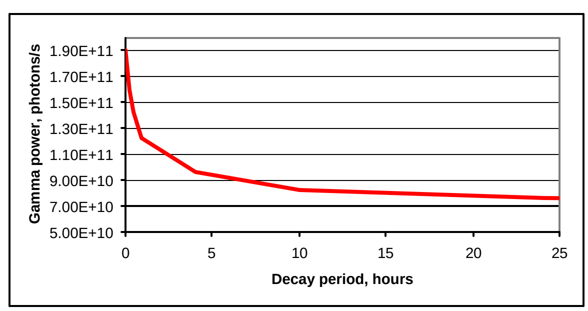

Figure 10. Gamma decay power of the beam collector for CCL module 3 for 70 hour irradiation.

The gamma power decrease with time from the CCL module 3 copper beam collector is significant in the first 10 hours. After one day decay, the gamma power drops about factor of two and even then the resulting residual radiation is still high for the unshielded access. So, shielding around the beam stop during and after commissioning is desirable and needs optimization, which is in progress.

Mesh tally neutron and gamma dose rate evaluations were done simultaneously with the regular tallies for the vicinity of the beam collectors to get dose contours with finer spatial (5 cm radial and 5 cm axial) resolution and more accurate peak dose values, for all commissioning steps. Prompt radiation fields show very distinct dose distributions that peak radially extending from the beam collectors (Figures 11 and 12). The contour maps confirm the dose rate levels obtained by the regular tallies and show that the DTL tank and CCL modules structures act very well as radiation shields.

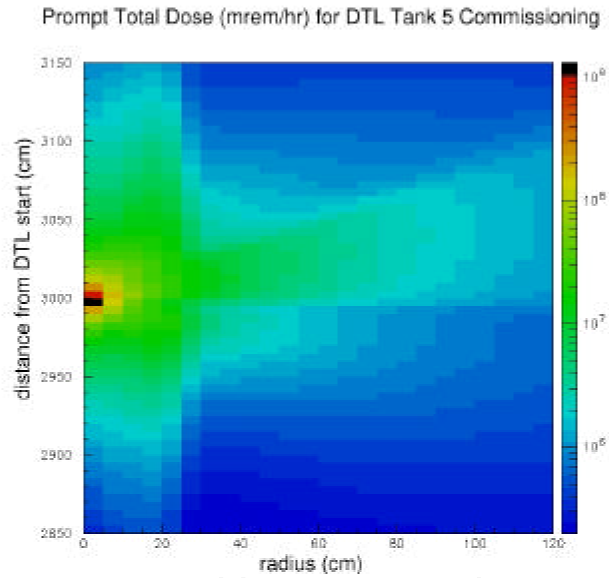

Figure 11: Total dose rate contours in the vicinity of the beam collector for DTL tank 5 commissioning.

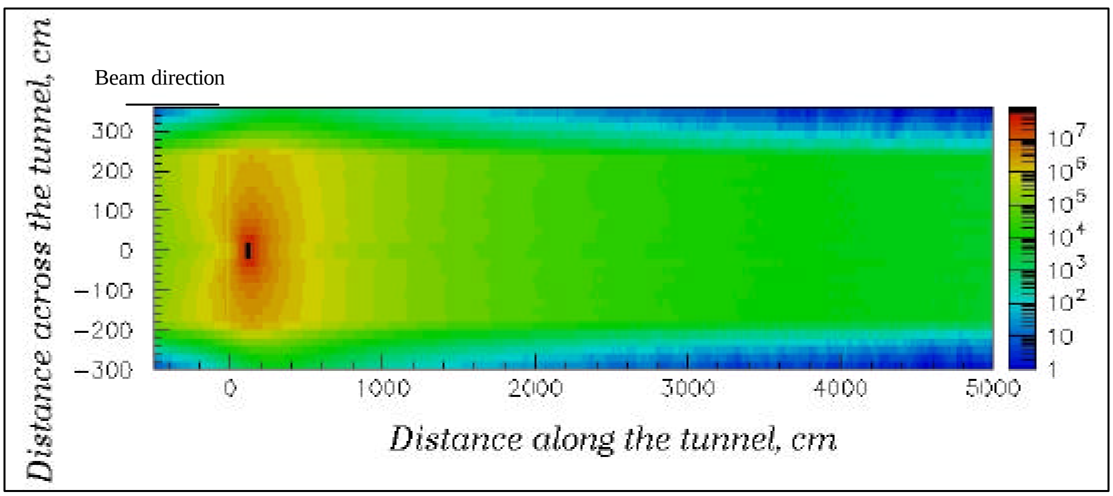

Figure 12: Total dose rate contours in the vicinity of the beam collector for CCL module 3 commissioning

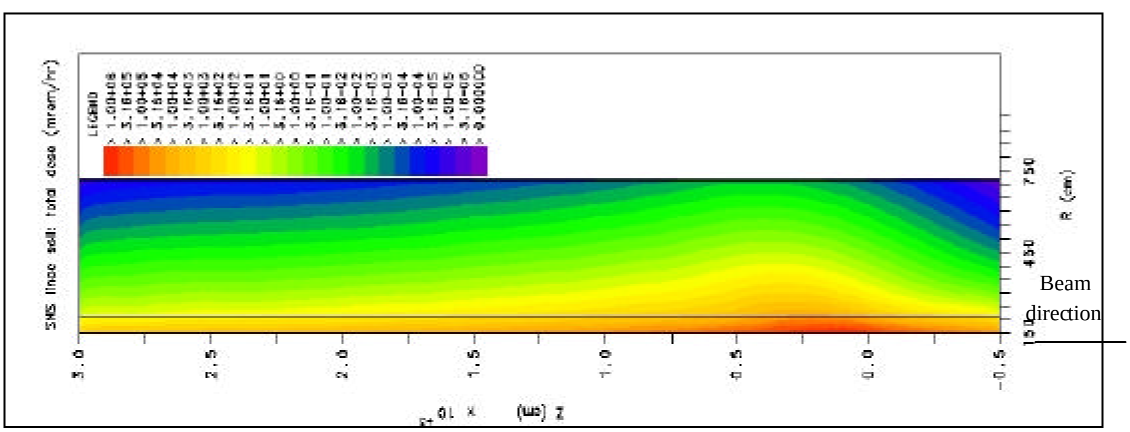

Figure 13. Total dose rate at the top of the soil above linac tunnel during CCL module 3 commissioning.

According to the performed analyses, the CCL module 3 commissioning is the configuration with the highest dose rates in the accelerator tunnel. For this case the calculation of radiation through the soil on the linac tunnel was performed. The estimated peak of neutron/gamma dose rates on the top of the earth berm is about 0.01mrem/h (Figure 13) and shifted about 4 meters downstream beam collector. The difference in the estimation of the dose rate between both methods is 20% for the total (neutron/gamma) dose rate, which is consider a perfect agreement.

The labyrinth was developed to close the shielding envelope DTL tanks 2 to 6, CCL modules 1 to3 commissioning to allow unlimited access to the HEBT during the linac commissioning. The source terms are based on the CCL module 3 commissioning. The distance from the beam collector to the first labyrinth wall is 210 meters. The distance between the walls forming the labyrinth is required to be 7 meters. To simplify the calculation, the conservative assumption that there are no SCL structures between the beam stop and the labyrinth was made. Figure 2 shows the design of three walls labyrinth, which mitigates dose rate of 62 mrem/h upstream the labyrinth entrance.

V. CONCLUSIONS

Operational and residual dose rates were calculated at 30-cm distance from the beam line linac components for DTL tank 1 to 6, and CCL modules 1 to 3 commissioning, which will take place under two shielding envelops. The calculated peak prompt dose rate levels range from 20 rem/hr for DTL tank 2 to 9000 rem/hr for CCL module 3. The residual dose rate levels after linac commissioning are a factor of 4,500-10,000 lower than the operational dose rates with peak values from 0.2 to 2000 mrem/h 1 hour after beam termination. After one day decay, the doses decrease to acceptable levels for maintenance personal to access the tunnel except for CCL module 3. For this case the shielding around the beam collector will be designed.

The transport through the soil above the accelerator tunnel for the case with the highest radiation levels - CCL module 3 - was calculated using both Monte Carlo and discrete ordinate methods. The analyses show that the results from both methods are consistent and way below the limit of 0.25 mrem/h.

The wall and labyrinth for both DTL tank 1, and the DTL tanks 2 to 6, CCL modules 1 to 3 commissioning shielding envelopes, respectively, were designed.

REFERENCES

1. "*National Spallation Neutron Source Conceptual Design Report*, Oak Ridge National Laboratory, NSNS/CDR-2/VI, 1997.
2. "Spallation Neutron Source Commissioning Program Plan" Oak Ridge National Laboratory, SNS 100000000P-PN0004-R00, July 2002.
3. L.S. Waters, ed., "MCNPX User's Manual – Version 2.1.5", Los Alamos National Laboratory, NM, TPO-E83-G-UG-X-00001, Nov. 1999.
4. Franz X. Gallmeier, "Calculations of Operational and Residual Doses for the SNS Linac", Proc. AccApp'01 - Applications of Accelerator Technology, ANS, Reno, Nevada, USA, November 11-15 2001
5. 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 (February 1986).
6. M.B.Emmet, W.A. Roades, R.L. Childs, and J.O.Johnson, the DORT section of "A User's Manual for MASH 1.0 – A Monte Carlo Adjoint Shielding Code System", ORNL/TM-11778 (March 1 992)
7. F. X. Gallmeier and P. 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, American Nuclear Society, Long Beach California, (1999).
8. N. Odano et al., "Development of the Activation Analysis Calculational Methodology for the Spallation Neutron Source (SNS)," 1998 ANS radiation Protection and Shielding Division Topical Conference, American Nuclear Society, Nashville, Tennessee, April 19-23, 1998; and Greg McNeilly, "AAS-Activation Analysis System", SNS-101040200-TR0003R00, UT-Battelle (1999).
9. F. Atchison, "*OriHet95 for the VAX*", ORNL, internal documentation, 1984.