RADIATION-PROTECTION CALCULATIONS TO SUPPORT SNS ACCELERATOR COMMISSIONING

I.Popova and F.Gallmeier

ORNL/SNS PO Box 2008, MS6475, Oak Ridge, TN 37831-6471, popovai@ornl.gov

A wide range of neutronisc and shielding analyses were performed for each SNS accelerator facility commissioning stage to provide safe commissioning from radiation protection point of view. Analyses cover prompt radiation levels including localized temporary shielding development; residual radiation levels after beam termination and commissioning beam characteristics limitations in order to restrict equipment activation; water and air activations near points of beam termination; monitoring dose rates by sets of TLD and real time measuring instruments.

I. INTRODUCTION

Commissioning of Spallation Neutron Source (SNS)[1] accelerator facility, which is a transition period between construction and operation, was one important period, when all accelerator structures were tuned and tested for the very first time. Commissioning was performed in steps according to the Commissioning Program Plan[2] from summer 2003 until spring 2006 exposing increasingly larger sections of the accelerator complex to the beam.

The beam power deposited locally in the tunnel during the commissioning phases greatly exceeded the typical operational line losses that are of the order of 1W/meter with the consequence of very high level expected radiation fields. During this period construction work inside the unexposed section of the accelerator tunnel was continued.

For each step radiation protection analyses were performed, covering following areas:

- prompt radiation levels including localized temporary shielding development:
  - during normal operation
  - hypothetical and intentional beam accident (fault studies);
- residual radiation levels after beam termination;
- commissioning beam characteristics limitations in order to restrict equipment activation; water and air activation near points of beam termination;
- monitoring dose rates by sets of TLD and real time measuring instruments.

On the base of analyses, proper temporary shielding was installed in local areas near beam termination points (beam stops and beam collectors) and some critical locations, such as penetrations, in order to minimize dose rates in generally occupied areas.

II. COMMISSIONING STEPS

II.A. General SNS layout

The SNS (Fig. 1) consists of accelerator, target and conventional facilities. The accelerator is powered by H^- beam produced in the front-end ion source and systems. The beam is accelerated in the linear accelerator (LINAC) from 2.5 MeV up to 1 GeV. The LINAC consists of: a drift tube LINAC (DTL) section housing six drift tube tanks; a coupled cavities LINAC section, housing four coupled cavity modules, each has 12 segments; a super conducting LINAC (SCL) section housing 23 superconducting cryo-modules, medium and high beta, and including 22 warm spacers; and a spare section for the future power upgrade.

H^- beam accelerated up to 1 GeV is passed through the high-energy-beam-transfer line (HEBT) into the accumulator ring as it is converted to a proton beam by having its electrons stripped away. In the accumulator ring, the proton beam is compressed from 1 millisecond to 1 microsecond long pulses through nominally one thousand turns and is extracted. Through the ring-to-target- beam-transfer line (RTBT), the beam is delivered to the target station nominally at 1 GeV energy, 1.4 mA current, 60 Hz repetition rate, and 1 μs pulse width. The proton beam intercepts the liquid mercury target and produces neutrons that are moderated to thermal and sub-thermal energies and guided through 24 beam lines to scattering instruments primarily for conducting material studies.

There are three permanents beam stops. Two, the LINAC and extraction beam stops, are passively cooled and designed to accept 7.5 kW beam power. The third one is injection beam stop, which is actively cooled and designed to accept up to 100 kW.

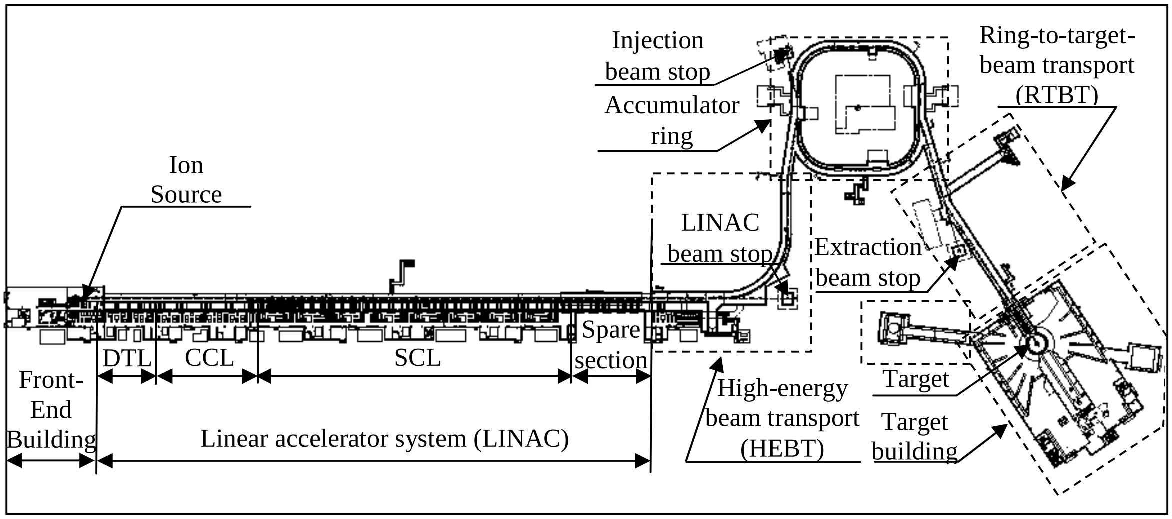

Fig. 1. Layout of the SNS facility

II.B. Commissioning steps

Commissioning refers to activities, which take place after installation and integrated testing, and require use of beam to determine operational parameters, tune and verify equipment performance. Commissioning of SNS accelerator was performed incrementally under DOE Accelerator Safety Order, DOE O 420.2 A. During each step beam was safely terminated in temporary beam stops located after commissioned structures or in the permanent beam stops.

After the ion source and front-end structure commissioning, the first accelerator structures commissioned was DTL tank 1 generating beam energy up to 7.5 MeV with beam termination into a temporary beamstop at the end of DTL tank 1. On the second step were added DTL tanks 2 and 3, delivering beam energies up to 39.5 MeV with beam termination again into a temporary beamstop at the end of DTL Tank 3. On the third step were added DTL tanks 4 to 6 and CCL modules 1 to 3, generating beam energies up to 156 MeV with termination at the end CCL module 4 into a temporary structure. Beams were usually aimed at the temporary beamstops, but for diagnostic and fault studies also intercepted by beam collectors located at the end of the DTL tanks arriving at beam energies of 22.3, 39.8, 56.6, 72.5, and 86.8 MeV for tanks 2 to 6, respectively. On the forth step beginning from the last CCL module (module 4), and continuing throughout the SCL cryogenic modules, beam was commissioned into two locations: beam stop at the end of CCL module 4 and at the permanent LINAC beam dump. On the fifth step HEBT, RING and RTBT were added and beam was commissioned to the injection beam stop to tune HEBT and once beam was extracted from the ring it was directed to the extraction beam stop. In the final commissioning step the beam was sent through the RTBT to the mercury target. Table I presents commissioning parameters.

TABLE I. Commissioning steps parameters

<table>
<tr><th rowspan="2">Parameters</th><th rowspan="2">Stage</th><th colspan="6">DTL tanks</th><th colspan="4">CCL modules</th><th rowspan="2">SCL</th><th rowspan="2">HEBT/Ring/RTBT up to extraction dump</th><th rowspan="2">RTBT to Target</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td rowspan="7">Beam stop material</td><td>1</td><td>Nickel</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="5"></td><td></td></tr>
<tr><td>2</td><td colspan="3">Copper</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td colspan="9">Copper</td><td></td><td></td><td></td></tr>
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<tr><td colspan="11">Copper</td><td></td></tr>
<tr><td>5</td><td colspan="12">Copper</td><td></td></tr>
<tr><td>6</td><td colspan="13">Mercury</td></tr>
<tr><td colspan="2">Beam energy MeV</td><td>7.5</td><td>22</td><td>40</td><td>57</td><td>73</td><td>87</td><td>107</td><td>132</td><td>157</td><td>157</td><td>1000</td><td>1000</td><td>1000</td></tr>
<tr><td colspan="2">Beam power, W</td><td>$1.6\cdot10^3$</td><td>160</td><td>160</td><td>160</td><td>160</td><td>160</td><td>250</td><td>250</td><td>250</td><td>250</td><td>250</td><td>7500</td><td>100000</td></tr>
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III. RADIATION PROTECTION ANALYSES

Development of the radiation protection plan during of each step includes shielding for commissioning enclosures, for temporary beam stops and for accelerator tunnel penetrations.

Shielding enclosure for each commissioning step includes permanent front end shielding (around DTL tank 1, which is outside accelerator tunnel), accelerator tunnels wall with surrounding earth berm, and temporary shielding walls protecting the work areas of yet to be commissioned structures in the accelerator tunnels. These walls were usually designed to form a labyrinth in order to provide access inside the enclosure. Shielding design criteria is 0.25mrem/h in generally occupied area, which was the tunnel outside enclosure as well, where construction workers were continuing installation.

After defining enclosure and beam stop material, neutronics calculations were performed to define shielding around beam stop and temporary labyrinth to the enclosure from the commissioning beam parameters. Material choice for shielding was made on the basis of effectiveness, expected levels of activation, and availability. Ordinary concrete was used for the temporary labyrinths. For the beam stop shielding borated Polyethylene was used for first commissioning step and ordinary concrete for following steps. Steel was avoided due to affinity to high and long-living activation.

For usually conservatively long estimation of the commissioning duration, predictions of residual dose rates were calculated, which induced mostly sources from the beam stops, it's shielding and accelerator structures located close to the beam termination points. Another issue was air activation near points of beam termination and water activation of temporary beam stop coolants.

An understanding of potential fault conditions is essential to ensure adequate protection of the accelerator beamline components for high beam-power facilities. During each commissioning step, fault studies were planned and performed with the beam spill at various energies deliberately steered into the beam tube at locations according to the fault studies plan. Dose rate were predicted for this conditions and were used setting the maximum allowed beam power for the respective commissioning campaigns.

During the commissioning runs dose rate were monitored inside and outside the shielding envelope in key location by sets of TLDs and real time measuring instruments. Measured dose rates were compared to predicted dose rates and generally were in a good agreement.

III.A. Calculation tools and methods

Full three-dimensional Monte Carlo calculations with detailed modeling of accelerator tunnel, penetrations and etc. were performed applying the MCNPX[3] code version 2.4.0. 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 gammas and neutrons) and their transport. Dose equivalent rates were tallied by folding neutron and gamma fluxes with flux-to-dose conversion coefficients, which were taken from the HILO2K neutron/gamma multi cross section library[4].

Source terms were described as a pencil beam incident on the beam stop with certain energy and intensity corresponding to each commissioning stage. For the beam accident and fault studies the lost beam along the beam tube was described with an aperture given by a Gaussian distribution.

Dose rates were analyzed for each commissioning step with according to the respective beam parameters, first without shielding, then with an estimated amount of proper shielding. The analyses were repeated and if necessary shielding was revised in further iterative fashion until dose rates below 0.25 mrem/h were achieved in generally occupied areas.

For residual analyses, the isotope production rates that resulted from the MCNPX calculations were fed into the Activation Analysis System[7] (AAS), which includes the ORIHET95[8] 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 for subsequent residual dose analyses. The radioactive isotope inventory was evaluated for the estimation of water and air activation.

The 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.

IV. RESULTS FROM COMPARISON MEASURMENTS VS CALCULATIONS

The measured radiation fields were analyzed and compared to the results from the transport simulations during commissioning stage. The most extensive comparison was performed during LINAC commissioning. Results are listed below.

Radiation monitoring was performed using the real time radiation measurement devices listed below and TLDs to measure absorbed dose and dose equivalent rates:

- Chipmunk: Fermilab-designed neutron and gamma sensitive PPS detector;
- Far West: Chipmunk equivalent unit;
- RO20: gamma sensitive;
- REM500 survey meter: neutron sensitive;
- RemBall, neutron sensitive;

- Albatross: activation-style neutron counter;
- Snoopy: neutron sensitive;
- MicroRem: gamma sensitive;
- Far West HPI 1030 survey meter for pulsed fields: gamma and neutron sensitive.

IV.A. First step – DTL tank 1

DTL tank 1 was commissioned at full 16-kW beam power with 7.5-MeV energy into a beam stop. Results are presenting in Table 2. In some locations there is a large discrepancy between measurements and calculations, which is due to some complication during beam operation. For example an emittance slit was accidentally being moved into the beam at the downstream end of the DTL tank, and some beam scraped at a bellows located between the DTL tank and the temporary beam stop, creating secondary radiation sources upstream of the shielding not accounted for in the source modeling. TLD measured gamma dose rates compared well to the measured dose rates of real time instruments.

For Tables II to VI, M means measurements, C means calculations, and M/C indicates the ratio between measurements and calculations.

TABLE II. Measurements (M) vs. calculations (C), DTL tank 1 commissioning

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
Above shielding/TLD	neutron gamma	92 564	5 1100	18.4 0.51
Backscattering cone/TLD	neutron gamma	464 88	55 25	8.4 3.7
Detector cluster/RO-7	gamma	7	6	1.12
Detector cluster/chipmunk	neutron+ gamma	6.8	9.5	0.72
Detector cluster/ Far West	neutron+ gamma	6.8	9.5	0.72

IV.B. Second step – DTL tank 1 to 3

During DTL tank 1 to 3 commissioning only TLDs were placed inside the accelerator tunnel to measure radiation fields. Table III shows the results. The maximum deviation between TLD measurements and calculations is about a factor of 1.8, which we regard as a satisfying agreement taking into account the complicated geometry model, and shielding thickness around source and the beam stop (about 0.8 m around the beam stop).

TABLE III. Measurements (M) vs. calculations (C), DTL tank 1 to 3 commissioning

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
Back-streaming cone	Neutron	1.020	0.924	1.1
	Gamma	0.248	0.180	1.4
Top of beam stop shielding	Neutron	0.832	0.650	1.28
	Gamma	0.186	0.100	1.8
Tunnel wall at beam stop level	Neutron	0.182	0.100	1.8
	Gamma	0.054	0.075	0.72

IV.C. Second step – DTL tank 1 to 6 and CCL modules 1 to 3

Specific to this commissioning stage was the fact that straight conduits (klystron wave guide ducts) penetrate the tunnel shielding near the DTL beam collectors going from the tunnel to the klystron gallery. As a result of radiation studies, shielding was installed inside the accelerator tunnel closing the penetrations. Additionally, access to the klystron gallery was controlled.

Table IV summarizes commissioning results for DTL tanks 1 to 6 and CCL module 1 to 3 commissioning to the temporary beam stop located downstream of CCL module 4. The maximum deviation between TLD (Far West) measurements and calculations is about factor of 2.6.

TABLE IV. Measurements (M) vs. calculations (C), DTL tank 1 to 6, CCL module 1 to 3commissioning to the temporary beam stop

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
On the North side of the beam stop shielding monolith, against the block wall	Neutron	88,000	98,000	0.90
	Gamma	5000	6000	0.83
On the tunnel wall directly opposite the beam stop shield monolith	Neutron	32,000	16,000	2.0
	Gamma	1000	900	1.1
Along the tunnel north wall, 20' upstream of the beam stop	Neutron	7000	3500	2.0
	Gamma	180	130	1.4
Near the tunnel wall, next to the real time instruments	Neutron TLD	2300	900	2.2
	Neutron Far West	2000	900	2.6
	Gamma	61	31	2

Table V summarizes results for commissioning DTL tanks 1 to 5 onto a beam collector, located downstream of tank 5. The M/C ratio for gamma dose rates are higher than unity due to dark current effects originating from the microwaves powering the DTL tanks that were not considered in the calculations. There is larger inconsistency between calculations and the readings from

TLDs located on the penetration side of the shielding inside the tunnel. Other numbers agree within a factor of 2.

TABLE V. Measurements (M) vs. calculations (C), DTL tank 1 to 5, commissioning to the beam collector

Location/ Detector	**Particle type**	**Dose rate (mrem/hr)**		
		M	C	M/C
On the collector side of penetration shielding	Neutron	320,000	257,000	1.3
	Gamma	11000	2420	4.6
On the penetration side of shielding	Neutron	215,000	42,000	5.1
	Gamma	5000	1082	4.6
On the North wall of the tunnel, directly opposite to the collector	Neutron	140,000	110,000	1.3
	Gamma	3200	1040	3.1
At the top of the penetration, in the center opening (RemBall)	Neutron TLD	5	11	0.5

IV.D. Third step – DTL tank 1 to 6 and CCL modules 1 to 4 and SCL

During final LINAC commissioning step, the beam was accelerated to the nominal energy of 1 GeV. The maximum commissioning accident – full beam loss in the SCL section close to klystron penetrations - was simulated as part of the fault studies among other measurements not elaborated here.

Table VI shows measurements of a variety of radiation instruments compared with calculations during a simulated beam accident at 387MeV near penetrations 91, 94 and 95 in the klystron gallery. For these studies the penetrations were unshielded.

TABLE VI. Measurements (M) vs. calculations (C) during last LINAC commissioning stage, beam accident near penetrations

Detector type	**Units, particles**	**Penetration 91**		**Penetration 94**		**Penetration 95**	
		M	M/C	M	M/C	M	M/C
Albatross	(mrad/h)	1.00	0.42	4.0	0.20	15.0	0.75
Remball	(mrem/h)	2.70	0.18	19.0	0.16	15.0	0.13
Snoopy	(mrem/h)	0.40	0.03	0.70	0.01	1.7	0.01
Rem500	(mrem/h)	4.70	0.31	101.0	0.85	169.0	1.44
RO20	(mrem/h)	0.60	1.20	3.7	1.32	11.0	3.67
MicroRem	(μrem/h)	95.00	0.19	150.0	0.05	165.0	0.06
Calcula-tions	(mrem/h) Neutrons	15.00		119.0		117.0	
	(mrad/h) Neutrons	2.40		20.0		20.0	
	(mrem/h) Gammas	0.50		2.8		3.0	

According to the Table VI there is a large discrepancy between different instrument readings. Snoopy measurements fall short compared to other instruments. The Albatrossn, Remball and Rem500 readings are generally lower than the calculations.

V. CONCLUSIONS

Neutronics simulations were an integral part of commissioning planning. Detailed predictions for radiation fields, created inside and outside of the accelerator tunnel, were performed for each of the SNS accelerator commissioning stages, throughout the entire LINAC, HEBT, ring and RTBT for nominal commissioning parameters, fault studies and induced dose rated after each commissioning step. Proper shielding solutions were developed and installed around temporary beam stops, commissioning enclosure and near penetrations into the tunnel. Radiation fields created during commissioning were measured and compared with simulations and generally were in a good agreement, which shows applicability of used calculational tools and methods.

Analyses for the air activation have shown that during SNS commissioning air activation is not an issue. Predicted water activation was one of the limiting factors for commissioning parameters.

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