Activation Studies and Radiation Safety for the n_TOF Experiment

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Abstract

The Neutron Time Of Flight (n_TOF) facility, whose installation is about to be completed at CERN, will use a high intensity proton beam \((7 \times 10^{12} \text{ protons per bunch, 1 or 4 bunches allowed per 14.4 s at 20 GeV/c})\), which through the spallation process onto a solid lead target \((80 \times 80 \times 60 \text{ cm}^3)\), produces a high flux of neutrons, charged particles, and photons. Intensive simulation studies with the FLUKA Monte Carlo code were undertaken to calculate the radioactivity induced in the target and in the surrounding structures as well as in the cooling water. Shielding calculations were also performed for the various critical locations along the 200 m long tunnel which houses the proton beam line, the target and the TOF tube. In particular, extensive simulations were required to define the shielding of the target area and the dimensions of the access labyrinths.

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Introduction

The n_TOF (neutron Time-Of-Flight) is a high flux spallation neutron source followed by a 200 m time of flight basis. The aim of the n_TOF facility at CERN is to measure the cross-sections needed for the design of innovative ADS applications like the incineration of nuclear waste [1], energy production [2], radio-isotope production for medical applications [3] and many other basic science subjects in particular astrophysics [4]. As a result of the studies reported in a first paper [5] and an addendum [6], the neutron time of flight facility has been proposed at the CERN PS [4] delivering a maximum intensity of $2.8 \times 10^{13}$ protons within a 14.4 s supercycle at a momentum of 20 GeV/c. This allows one to study systematically and with excellent resolution, neutron cross-sections of almost any elements using targets of very modest mass, necessary for unstable or otherwise expensive materials, in the interval from 1 eV to 250 MeV.

The n_TOF facility uses a high intensity proton beam which, through the spallation process, produces a high neutron flux as well as charged particles and photons [7]. The radiation protection aspects of such a facility are clearly a major concern. Therefore, intensive simulation studies were undertaken to calculate the activity and the dose equivalent rates at different locations of the facility. These simulations cover different topics, such as the activation of the lead target, the cooling water, the dose rates around the target area and near the charged particles sweeping magnet. The neutrons streaming in a service tunnel linking the n_TOF tunnel (TT2A) to a laboratory located in the basement of an adjacent building as well as the dose rate in this tunnel have been estimated and will also be discussed below.

Simulation studies on activation

Activation of the lead target

The target is made with pure lead blocks and its shape is $80 \times 80 \times 60$ cm$^3$, except for the spallation area where a volume of $30 \times 55 \times 20$ cm$^3$ was removed to have the nominal design dimension [8] (Figure 1a). The exit plane is at an angle of -0.676° with respect to the vertical. The target is mounted on a steel support and is submerged in water contained in an aluminium alloy vessel. The water layer surrounding the lead block is 3 cm thick except at the exit face of the target where it is 5 cm thick. The walls of the aluminium container are 0.5 cm thick, except the exit wall that consists of a thin single metallic window [8]. This aluminum window mounted onto the water tank is 1.6 mm in thickness and 80 mm in diameter.

In order to calculate the activity of the target the residual nuclei produced by inelastic hadronic interactions in the lead volume were scored. The intensity of the beam was assumed to be $7 \times 10^{12}$ protons per bunch. Two cases were considered, the first with a bunch every 14.4 s (supercycle duration), the second with 4 bunches every 14.4 s. Two representative irradiation periods were considered, one lasting one month and the other nine months. The beam intensity is supposed to be constant and equal to the average value (i.e. $4.9 \times 10^{11}$ and $1.94 \times 10^{12}$ protons per second for 1 and 4 bunches per supercycle, respectively). At the end of the irradiation the activity of the lead target is about 800 Ci for the one bunch scenario (Figure 1b). After one year of decay, the total activity is about 1 Ci for one month’s irradiation, and about 7 Ci for nine month’s irradiation. For 4 bunches the values are obviously four times larger.
The dose equivalent rate after an irradiation of one month and one day of cooling, is estimated to be at maximum 25 Sv/h on the exit face of the lead target. This result is obtained by using the $\omega$ factor [9] which converts star density to dose rate in contact with an extended target. The star density rate (hadron inelastic interaction per cm$^3$/s) is calculated by Monte-Carlo (the FLUKA code [10] in our case). The dose rates obtained after different irradiation and cooling periods, for a beam intensity of $1.94 \times 10^{12}$ protons/s (4 bunches scenario) are given in table 1.

<table>
<thead>
<tr>
<th>I = $1.94 \times 10^{12}$ p/s</th>
<th>$T_{irr} = 1$ month</th>
<th>$T_{irr} = 1$ year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c = 1$ day</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>$T_c = 10$ days</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>$T_c = 30$ days</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 1:** Maximum dose equivalent rates on the exit face of the lead target expressed in Sv/h, for different irradiation and cooling times.

**Activation of the cooling water**

The activation of the cooling water was calculated under the same conditions described previously for the target activation. The total volume of water used in the cooling system is about 700 l; the aluminum container contains 20% of this volume. At the end of the irradiation, the activity is about 2.7 Ci for the one bunch scenario. After one year of decay, the total activity is around 5 mCi for one month’s irradiation and about 20 mCi for nine month’s irradiation. For 4 bunches, the values are four times larger. The activity decreases rapidly after one day because of the short half-life of most of the produced radionuclides (Figure 2).

We can reasonably assume that the specific activity of the whole water volume is five times lower than the specific activity in the water inside the container, as this water permanently circulates in the cooling system. The radionuclides dominating the activity are given in table 2 (one month’s irradiation). After one day of decay, the activity is mainly due to $^7$Be and tritium, with 53.3 d and 12.33 y half-lives respectively.
Figure 2: Activity of the cooling water versus cooling time after 1 month’s and 9 month’s irradiation with 1 or 4 bunches per PS supercycle, $7\times10^{12}$ protons per bunch.

<table>
<thead>
<tr>
<th>Tcooling</th>
<th>Residual Nuclei</th>
<th>Becquerel</th>
<th>A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>$^7$Be (ec mode, $T_{1/2}=53.3$ d)</td>
<td>$1.3\times10^7$</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td>$^3$H ($\beta^-$ mode, $T_{1/2}=12.33$ y)</td>
<td>$5.3\times10^7$</td>
<td>3.9</td>
</tr>
<tr>
<td>Month</td>
<td>$^7$Be</td>
<td>$9.1\times10^4$</td>
<td>94.5</td>
</tr>
<tr>
<td></td>
<td>$^3$H</td>
<td>$5.3\times10^7$</td>
<td>5.5</td>
</tr>
<tr>
<td>Year</td>
<td>$^7$Be</td>
<td>$1.2\times10^7$</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>$^3$H</td>
<td>$5.0\times10^7$</td>
<td>80.2</td>
</tr>
</tbody>
</table>

Table 2. Radionuclides dominating the total activity of the cooling water irradiated for a period of one month.

Radiation safety

Target shielding

The lead target is situated at a depth of 9 m under the ISR tunnel, which is a supervised area. The dose rate allowed in this region must be less than 2.5 $\mu$Sv/h; the design value for the shielding was taken at 1 $\mu$Sv/h. FLUKA [10] simulations were performed to determine the shielding requirements.

The TOF target will be removed from the TT2A tunnel via a shaft set in concrete and linking a service tunnel located in-between TT2A and the ISR, which will serve as a storage area for the target. The concrete’s thickness between TT2A and this service tunnel is 5.5 m. FLUKA simulations were performed to estimate the dose in the ISR during the TOF operation. Only neutrons have been transported without any energy cut-off.

Simulations were performed of the neutrons transmitted through the shielded shaft. For this purpose the 130 cm diameter shaft was assumed to be filled with 4.55 m of concrete, divided into 10 slices and 12 regions for simulation purposes (Figure 3) [8]. The density of the concrete is 2.35 g/cm$^3$. An average quality factor of 5 was applied to convert absorbed dose in Gray to dose equivalent in Sievert. We have considered 1 bunch and 4 bunches every 14.4 s with an intensity of $7\times10^{12}$ protons per bunch.
In region No. 1, 1.3 m above the target and before any shielding, the dose equivalent rate is about 80 Sv/h for the one bunch scenario. In region No. 12, the dose equivalent rate is around 3 mSv/h. For the 4 bunches scenario the values are obviously 4 times higher. The dose equivalent rate in the ISR with the shaft ‘plugged’ with 4.55 m of concrete is clearly far too high. To reduce it to the design value, additional shielding has to be installed on top of the target. Additional calculations have shown that a shielding consisting of 80 cm iron plus 2.4 m concrete placed in the service tunnel in-between the shaft and the ISR will reduce the dose equivalent rate to below 1 µSv/h.

**Shielding of the basement of building 287**

*Initial dose rate estimation*

A laboratory routinely occupied by personnel is located at the same level of the TOF TT2A tunnel. This room, located in the basement of building 287 (Figure 4), is linked to TT2A by a 12 m long tunnel, which serves as an emergency exit and therefore cannot be completely blocked off. The way to reduce neutron streaming from TT2A into building 287 is to install a properly designed labyrinth. As building 287 is a supervised area, the ambient dose equivalent rate in the laboratory must not exceed 2.5 µSv/h.

A collimator and the TOF sweeping magnet are located near to the tunnel aperture, about 140 m from the TOF target. The integral neutron background fluence in the tunnel (outside the neutron tube) versus the flight distance has been estimated at around $10^5$ n/cm$^2$/3×$10^{13}$ protons. The neutron spectrum at the entrance of the service tunnel is shown in figure 5a. This neutron fluence has then been folded with the neutron fluence to ambient dose equivalent conversion factors (Figure 5b) given by [12]. The total dose equivalent for 4 bunches is $1.3\times10^7$ pSv, or a rate of 3.25 mSv/h for 4 bunches every 14.4 s.
**Figure 4**: TT2A and service tunnel linking to the basement of building 287.

**Figure 5**:  
(a) background neutron flux in the TOF tunnel, at 140 m from the lead target  
(b) neutron fluence to dose equivalent conversion factor  
(c) neutron ambient dose equivalent per isolethargic bin for 4 bunches.

Simple estimate

A first estimate of the attenuation provided by a labyrinth made of concrete and consisting of two legs each of 5.60 m long, 0.9 m wide and about 2.5 m high (cross sectional area $A = 2.30 \text{ m}^2$) was carried out using the attenuation curves given in [13]. The resulting dose equivalent rate is estimated to be less than 1 $\mu$Sv/h. The attenuation factors and results are given in table 3.

<table>
<thead>
<tr>
<th>leg dimensions: $l = 5.60 \text{ m}; A = 2.3 \text{ m}^2$</th>
<th>attenuation factor</th>
<th>initial dose rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st leg</td>
<td>0.022</td>
<td>71.5 $\mu$Sv/h</td>
</tr>
<tr>
<td>2nd leg</td>
<td>0.009</td>
<td>0.6 $\mu$Sv/h</td>
</tr>
</tbody>
</table>

Table 3. Estimate of the dose rate in the labyrinth, in the case of $3 \times 10^{13}$ protons/14.4 s

Monte-Carlo simulation

Due to the complexity of the problem, a Monte Carlo simulation was performed to estimate the neutron streaming in this tunnel, with the two concrete blocks of the labyrinth defined above (Figure 6).

At the tunnel entrance, 139 m after the lead target, the ‘background’ neutron fluence is about $10^5$ n/cm$^2$/3$\times$10$^{13}$ protons (4 bunches per PS supercycle); these neutrons are mainly fast; the dose equivalent rate is about 7.5 mSv/h using the ambient dose equivalent conversion factor given by [12] for fast neutrons (300 pSv cm$^2$). At the entrance of the small experimental room, the neutrons are mainly thermal, the fluence is reduced by 6 orders of magnitude, and the dose rate estimated with the conversion factor for thermal neutrons is reduced to 0.2 nSv/h.
The dose equivalent rate obtained by the simple calculation is a priori 3 orders of magnitude higher than the rate obtained by simulation. The first estimate was done just by considering a 12 m long straight tunnel with two concrete legs, and taking an initial dose equivalent rate of 3.25 mSv/h at the entrance situated 142 m upstream from the target. The geometry of this area is in reality more complex (as shown in figure 4), and the previous rate is obtained at 139 m, before the collimator wall (Figure 6). By considering the fast neutron fluence of $10^3 \text{n/cm}^2/3 \times 10^{13}$ protons, the dose equivalent rate at 142 m is 0.22 mSv/h. This rate is reduced to 44 nSv/h after the two concrete legs, and should be reduced even more by the perpendicular shape of the passage leading to the laboratory. The results given by the calculation and simulation are consistent.

**Dose rate estimate at the measuring station**

The measuring station is located at 187.5 m from the lead target. After the proton beam is stopped, the background in the experimental area will be dominated by $\gamma$-rays emitted by the lead target and propagating through the TOF tube. The diameter of this tube will be 1.8 cm for the capture cross-section measurements, and 15 cm for the fission cross-section measurements. Calculations were performed to determine the dose rate in this area and to design the lead shutter to be inserted at the end of the TOF tube.

Considering the dose equivalent rate of 25 Sv/h on the exit face of the target, an estimate of the rate at 187 m gives 0.5 $\mu$Sv/h by considering the solid angle subtended by a surface of 10 cm in diameter. This simple calculation does not take into account the effects of the reductions and collimators at different places on the neutron TOF tube (Figure 7). A more detailed calculation was done by means of a Monte-Carlo simulation including the complex geometry of the n_TOF line.

After an irradiation period of 1 month, the activity of the lead target saturates around 800 Ci, emitting $2.5 \times 10^{13}$ $\gamma$/s. The photon energy distribution from the whole lead block was obtained using the activity of the residual nuclei from FLUKA and the intensity of the $\gamma$-rays corresponding to each nucleus, taken from the ENSDF database of nuclei decay modes [11]. These source photons were then transported with FLUKA from the lead target to the measuring station, taking into account the whole and detailed geometry of the 200 m long TOF tunnel. The calculated dose equivalent rate is about 1 nSv/h; this simulation was done with the photons isotropically distributed into the target and not transported from their creation point (coordinates of the residual nucleus).
The actual dose rate will most likely be in-between the two values obtained by these extreme approaches. Further developments of the FLUKA Monte-Carlo code should include the residual nuclei decay modes.

Figure 7: TOF tube sections from the lead target up to the end of the TT2A tunnel.

Conclusion

The n_TOF facility at CERN offers unique features to study neutron cross-sections. The CERN PS will deliver a maximum intensity of $2.8 \times 10^{13}$ protons within a 14.4 s supercycle at a momentum of 20 GeV/c. The spallation process in the 4 ton pure lead target will produce high flux of neutrons, charged particles and photons. Intensive simulation studies with the FLUKA Monte-Carlo code were undertaken to estimate the radioactivity induced in the target. The induced activity should reach 800 Ci after 1 month’s running time with $7 \times 10^{12}$ protons per supercycle (1 bunch scenario); the dose equivalent rate on the exit face has been evaluated to 25 Sv/h, using $\omega$ factor. The activity of the cooling water was estimated at about 2.7 Ci for the same irradiation conditions. The nuclei dominating the activity after one year of cooling down are $^7$Be and $^3$H.

Shielding calculations were also performed for the various critical locations around the lead target and along the 200 m neutron line. During the running period, the dose equivalent rate above the target due to neutrons was estimated at about 80 Sv/h, for one PS bunch per supercycle. A massive shielding is required to keep the ISR tunnel safe situated 9 m above the target. Results from FLUKA simulations show that the dose equivalent rate is decreased to 3 mSv/h with 4.55 m of concrete in the shaft above the target. This shaft is needed to allow the removal of the lead target for maintenance purposes. To reduce the dose rate to the design value of 1 $\mu$Sv/h, additional shielding consisting of 80 cm of iron and 2.4 m of concrete was installed on top of the target.

Another critical location is the laboratory located in the basement of building 287 and linked to the TOF tunnel by a 12 m long emergency exit tunnel. The ambient dose equivalent rate in this room must not exceed 2.5 $\mu$Sv/h. Simplified calculations and FLUKA simulations have shown that a labyrinth of two legs of 5.6 m in length and with a cross-section of 2.3 m$^2$, will reduce efficiently the neutrons streaming from the TOF tunnel to the laboratory. The dose equivalent rate of 3.25 mSv/h at the entrance of the 12 m long tunnel, situated at 140 m from the lead target, will be reduced to less than 1 $\mu$Sv/h in the laboratory.

After the beam is stopped, $\gamma$-rays are emitted by all the activated materials mainly by the lead target. A fraction of these gammas will propagate through the n_TOF tube to the measuring station situated 187 m downstream from the target. A lead shutter of 5 to 10 cm in thickness will be needed to shield this residual photon flux.

The commissioning of the n_TOF experiment should start during the summer of 2000. A radiation monitoring system [8] was installed to measure the induced activity and the dose equivalent rates at the critical locations. The results of the measurements provided by the various monitors will be compared to the predictions of the present simulations.
References


