Soil Activation Surrounding the Electron Accelerator Enclosures

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Abstract

The radiation generated at modern electron accelerator facilities is of sufficiently high energy to permit activation of the soil surrounding the concrete shielding of the enclosures. Bremsstrahlung is generated inside the accelerator vessel by the radiative interaction of the electron beam with the residual gas or with the internal accelerator components. This radiation further interacts with the surrounding air, soil and cooling water to produce radioactive isotopes by emission of neutrons. These interactions could be either direct photo-spallation reactions as in the case of air and water activation, or could be secondary interactions of the high energy neutrons generated by photo-neutron production. The high energy neutrons produced by the photonuclear interactions will penetrate the concrete shield and produce radioisotopes in the surrounding soil by (n,n), (n,2n) etc. reactions. The activation of soil surrounding the concrete shielding is usually limited at the electron accelerator facilities. However there exists a potential for the high energy neutron component to penetrate through the transverse concrete shield and produce radioisotopes like ^{3}H and ^{22}Na in the soil. These isotopes can be leached from the soil by rain water and migrate to the ground water systems. This risk is assessed using analytical methodology and verified by FLUKA calculations at the NSLS-II accelerator complex.

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1. Introduction

The radiation generated at modern electron accelerator facilities is of sufficiently high energy to permit activation of the soil surrounding the concrete shielding of the enclosures. Bremsstrahlung is generated inside the accelerator vessel by the radiative interaction of the electron beam with the residual gas or internal accelerator components. This radiation further interacts with the surrounding air, soil and cooling water to produce radioactive isotopes by emission of neutrons. These interactions could be either direct photo-spallation reactions as in the case of air and water activation, or could be secondary interactions of the high energy neutrons generated by photo-neutron production. The high energy neutrons produced by the photonuclear interactions will penetrate the concrete shield and produce radioisotopes in the surrounding soil by (n,n), (n,2n) etc. reactions.

2. Soil Activation

The potential for soil activation is usually limited at the electron accelerators in the transverse directions, since the main radiation component due to accelerator beam losses, bremsstrahlung, is peaked in the forward direction[1] of the beam. The soil berm is generally at right angles to the direction of the beam (floor or lateral berm). However there exists a potential for the high energy neutron component to penetrate through the transverse concrete shield and produce radioisotopes in the soil[2] surrounding the lateral and floor shield. Some of these isotopes can be leached from the soil by rain water and migrate to the ground water systems. It is important to assess this risk for electron accelerators to determine the potential harmful consequences to the environment due to accelerator operations.

3.1 Methodology to Estimate Soil Activation

The mechanism of formation of radionuclides in the soil is due to the interaction of high energy neutrons with the elements in the soil. In the present analysis only the high energy neutron component needs to be considered, because only these neutrons have the penetrating power to escape the concrete shielding. As required by the BNL subject area Accelerator Safety, analysis has been done to estimate the rate of formation of two radioactive isotopes ^{3}H and ^{22}Na in the soil during the routine operation of NSLS-II. Table 1 gives the summary parameters used for this analysis. The cross section values are obtained from the literature[3,4] and the soil composition for the Long Island soil has been provided by the BNL Environmental and Waste Management Services Division[5]. The soil density at the Long Island is taken as 1.6 gm/cm^3. Table 1 gives the soil compositions and the high energy neutron activation cross sections used for the analysis.

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Table 1 Soil Composition and Cross Sections used for Activation Analysis
Cross Sections for High Energy (>50 MeV) Neutrons

Parent Nucleus	Weight (%) In soil	^{3}H Production Threshold (MeV)	^{3}H Production Cross section (mb)	^{22}NaProduction Threshold (MeV)	^{22}NaProduction Cross section (mb)
^{16}O	51.3	15.0	3.07		
^{23}Na	0.0196	20.0	6.81	15.0	36.6
^{24}Mg	0.21	25.0	6.48	25.0	28.2
^{27}Al	1.65	25.0	8.23	50.0	14.5
^{28}Si	45.1	50.0	3.54	50.0	14.5
^{39}K	0.063	50.0	3.56		
^{40}Ca	0.058	50.0	3.0		
^{55}Mn	0.012	50.0	2.0		
^{56}Fe	1.44	50.0	1.65		

From Table 1 the following average parameters can be derived.

Weighted average cross section for ^{3}H production 3.35 mbarns
Weighted average cross section for ^{22}Na production 14.56 mbarns
Weighted average of soil atomic mass number 22.17
Atomic Number density of soil 4.35×10^{22} atoms/cm^3
Number density of ^{3}H producers (100%) 4.35×10^{22} atoms/cm^3
Number density of ^{22}Na producers (47%) 2.04×10^{22} atoms/cm^3

When the electron beam interacts with the storage ring components or beam stops an electromagnetic shower will be generated within the material due to successive bremsstrahlung and pair production interactions. The ultimate product of these interactions is a large number of low energy gammas, electrons, positrons and a few neutrons. Almost 80% of the neutrons emitted are with a median energy of 2.1 MeV and are effectively attenuated by the concrete shielding. However, the high energy component of the neutrons can penetrate the concrete shielding and cause interactions in the surrounding soil.

The high energy neutron (HEN) component in the transverse direction of the beam loss location on a thick target is provided by Fasso[6] et al. as;

1.3×10^{-3} HEN/ GeV/ electron/ steradian

The neutron flux at the external surface of the concrete shield wall of thickness 'r' cm at a distance of 'R' cm from the source in the transverse direction, without assuming any self shielding for the neutrons in the target can be estimated as;

$$\Phi(0) = \frac{1.3\times10^{-3}}{R^2} N_e \times E \times e^{-r/\lambda} \text{ neutrons/cm}^2\text{.s} \qquad (1)$$

Where N_e = Number of electrons interacting with the target material / sec

E = Energy of the electron in GeV

R = Distance of the flux point from the source in cm

r = Thickness of the concrete shield in g/cm^2

λ = Attenuation length of HEN in concrete in g/cm^2 (115 g/cm^2)

As high energy neutrons traverse through the soil a large fraction of neutrons are removed from the soil by the elastic and non-radiative capture reactions. These neutrons do not take part in the activation reactions. The neutron removal cross section for the soil is given in the literature[7] as 0.016 cm^{-1} for the soil density of 1.6 gm/cm^3. The high energy neutron flux in the soil as a function of soil thickness (x) can be written as;

$$\Phi(x) = \Phi(0)\, e^{-\Sigma x} \qquad (2)$$

Where Σ is the neutron removal cross section of the soil and $\Phi(0)$ and $\Phi(x)$ are neutron flux values at a soil thickness of 0 and x cm correspondingly. The neutron flux declines in an exponential manner with the mean path ($1/\Sigma$) of neutrons in the soil. In approximately 4.8 mean free paths (300 cm) 99 % of the neutrons will be removed from the soil by the removal reactions. The average flux of neutrons, Φ_{av}, for activation reactions in the soil can be written as;

$$\Phi_{av} = \frac{\int \Phi(x)dx}{\int dx} = \frac{\int \Phi(0)e^{-\Sigma x}dx}{\int dx} \qquad (3)$$

Where $\Phi(0)$ is the flux at the external surface of the concrete shield and the integration is carried out for 300 cm of the soil thickness. Integrating equation (3) for 300 cm of soil and substituting for Σ of the soil, It can be shown that;

$$\Phi_{av}\,(\text{soil}) = 0.2066\, \Phi(0)$$

In general beam dumps in the accelerator enclosures have the highest beam losses during lattice optimization studies. In a year, 500 hours of linac and 500 hours of booster study period (15 nC/s fill and dump) is assumed. Table 2 summarizes the electron energy dissipation at linac and booster beam dumps under consideration and the resulting average neutron fluxes Φ_{av} in the soil, exterior to the concrete shielding for 15 nC/s beam loss.

Table 2 Electron Energy dissipation at Linac and Booster Beam Dumbs

Soil Location	Electron Loss (e/s)(15 nC/s)	Neutron Flux Φ_{av} (n/cm^2.s)	^{3}H (pCi/cm^3)	^{22}Na (pCi/cm^3)
Linac Dump 200 MeV	9.36E10	3.0E2	0.014	0.52
Booster Dump 3 GeV	9.36E10	3.9E3	0.130	0.46

Average flux in the soil has been used to calculate the neutron reaction rate in the soil to produce radioactive ^{3}H and ^{22}Na.

Rate of radioactive atom production in soil = $\Phi_{av} N \sigma$ (4)
Where Φ_{av} = Average high energy neutron flux in the soil (n/cm^2.s)
N = Number density of element in the soil producing the radioactive isotope
σ = Neutron cross section of the element for activation (cm^2)

The number of atoms of the radionuclide of interest (n) per unit volume is governed by the following differential equation during the period of irradiation:

$$\frac{dn}{dt} = - \lambda_R n + \Phi_{av} N \sigma$$

The equation has the following solution applying the boundary condition when n = 0, t=0;

$$n(t) = \frac{\Phi_{av} N \sigma}{\lambda_R} (1 - e^{-\lambda R\, t}) \qquad (5)$$

where
λ_R = Decay constant of the radioactive isotope
t = Irradiation time (for NSLS-II operations, a conservative annual irradiation time of 500 hours for the dump is considered).
Thus the specific activity (Bq/cm^3) induced in the soil as a function of time by this nuclide of interest;

$$A(t) = \Phi_{av} N \sigma (1 - e^{-\lambda R\, t}) \quad Bq/cm^3 \qquad (6)$$

The activity of the radioactive nuclide of interest in the soil is calculated using equation (6) and available cross sections from Table 1.

3.2 Results of Soil Activation Calculations for NSLS-II

Table 2 also gives the activity in the soil at two beam loss locations created due to ^{3}H and ^{22}Na. The beam loss locations are linac and booster dumps at the rate of 15 nC/s. Five hundred hours (roughly 10% of annual NSLS II operation. Using the methodology established in the Accelerator Safety Subject Area of BNL, the leachable concentration created in the soil has also been

estimated. Leachability of 100 % and 7.5 % are assumed for ^{3}H and ^{22}Na correspondingly. A water concentration factor of 1.1 is taken due to the annual rain fall of 55 cm at BNL site, according to reference [7]. It can be mentioned that the soil underneath the concrete floor is not exposed to rain fall and the potential leachability of radioactive isotopes from the soil to the water table at these locations will be minimal.

3.3 Comparison with FLUKA Simulation

FLUKA Monte Carlo calculations have been performed to validate and benchmark the analytical results. Identical input parameters have been used for FLUKA calculations as in the case of analytical methodology. The additional FLUKA capability of irradiation and cooling profiles has been adopted. Five hundred hours of total annual irradiation time has been distributed as three-months period of irradiation with cooling time of one month each in between. 15 nC/s fill and dump is assumed during the irradiation period. ^{3}H and ^{22}Na has been scored around the booster and the linac dumps in a 1 m radius and 3 m deep soil column. The results of FLUKA calculation and the comparison with the previous analytical results have been provided in table 3.

Table 3 Comparison of FLUKA Results with the Analytical Estimations

Soil Location	^{3}H (pCi/cm^3)		^{22}Na (pCi/cm^3)	
	Analytical	FLUKA	Analytical	FLUKA
Linac Dump 200 MeV	0.014	0.020	0.520	0.250
Booster Dump 3 GeV	0.130	0.700	0.460	1.050

4. Summary Conclusions

The FLUKA results compare reasonably well with the approximate analytical results, considering the approximations involved in the analytical methodology. In the comparison presented in table 3, FLUKA predicts in general higher activity values in the soil, except for ^{22}Na near linac dump. FLUKA also utilizes more accurate multi-group cross section values for the interactions, compared to flux averaged one group cross sections used in the analytical calculations. However, this methodology will be a valuable tool to make quick and easy estimations of soil activation around the electron accelerator enclosures.

5. References

1. Bathow, G., et.al., Measurements on 6.3 GeV Electromagnetic Cascades and Cascade Produced Neutrons , Nucl. Phys., B2 (1967).
2. Radiation Protection for Particle Accelerator Facilities, NCRP Report 144 (2003).
3. Alexandrov, A.A., et.al., Induced Activity in Soil, Atomaya Energia, 34-3 (1973).

4. Gabriel, T.A., Calculation of Long Lived Induced Activity in Soil, ORNL-TM-2848 (1970).
5. Private communication with D. Paquette, a BNL hydrogeologist
6. Fasso, A.,et.al., Radiation Problems in the Design of LEP Collider, CERN-84-02 (1984).
7. Borak, T.B.,et.al., The Underground Migration of Radionuclides Produced in Soil, Health Physics, 23 (1972).