INITIAL ESTIMATION OF THE RADIONUCLIDES IN THE SOIL AROUND THE 100 MEV PROTON ACCELERATOR FACILITY OF PEFP

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The Proton Engineering Frontier Project (PEFP) has designed and developed a proton linear accelerator facility operating at 100 MeV – 20 mA. The radiological effects of such a nuclear facility on the environment are important in terms of radiation safety. This study estimated the production rates of radionuclides in the soil around the accelerator facility using MCNPX. The groundwater migration of the radioisotopes was also calculated using the Concentration Model. Several spallation reactions have occurred due to leaked neutrons, leading to the release of various radionuclides into the soil. The total activity of the induced radionuclides is approximately 2.98×10^{-4} Bq/cm^3 at the point of saturation. ^{45}Ca had the highest production rate with a specific activity of 1.78×10^{-4} Bq/cm^3 over the course of one year. ^{3}H and ^{22}Na are usually considered the most important radioisotopes at nuclear facilities. However, only a small amount of tritium was produced around this facility, as the energy of most neutrons is below the threshold of the predominant reactions for producing tritium: ^{16}O(n,X)^{3}H and ^{28}Si(n,X)^{3}H (approximately 20 MeV). The dose level of drinking water from ^{22}Na was 1.48×10^{-5} pCi/ml/yr, which was less than the annual intake limit in the regulations.

KEYWORDS : Proton Accelerator, MCNPX, Soil Activation, Groundwater Migration, Concentration Model

1. INTRODUCTION

While many papers have been published regarding the radiological environmental effects of a high energy charged particle accelerator in other countries [1 - 4], few studies in this area have been reported in Korea. For this reason, a 100 MeV proton linear accelerator located in Korea is considered a worthwhile facility to investigate, as it will be the first mA-grade proton accelerator in Korea.

This facility is divided into three areas: the beam accelerator tunnel area, the beam utilizing area, and the office area, as shown in Fig. 1. The beam accelerator line is equipped with an injector, LEBT (Low Energy Beam Transport), a RFQ (Radio Frequency Quadrupole), a 20 MeV DTL (Drift Tube Linac) tank assembly with four tanks, MEBT (Medium Energy Beam Transport), and a 100 MeV DTL tank assembly with 16 tanks. The beam accelerator line is divided into two parts as the protons that are accelerated from the injector to the 20 MeV DTL tank are supplied into the 20 MeV beam utilizing area, and the protons that are accelerated from the MEBT to the 100 MeV DTL tank are supplied to the 100 MeV beam utilizing area. The beam utilizing area is divided into 20 and 100 MeV beam utilizing areas that each have five targets (Cu, Si, Be) and a beam dump. There are 30 offices located in the office area. Each area is sufficiently shielded with a 2 m-thick concrete wall.

Reactions between a beam loss and beam line components produce neutrons that create spallation reactions with soil components. Due to these reactions, several radioisotopes are produced in the soil. These radioisotopes may leach out to groundwater then expose the public general to radiation.

The National Council on Radiation Protection and Measurements (NCRP) recommends that a radiological environmental effect should be estimated quantitatively when accelerators of charged particles with energies from 0.1 to 100 MeV are under construction [5]. The radiological environmental effect estimation is a criterion to receive a permit for constructing in Korea. This estimation would also determine adequate shielding levels in terms of radiation safety and cost. Additionally, this particular accelerator facility may be increased to 1 GeV in the future. While carrying out these objectives, this study

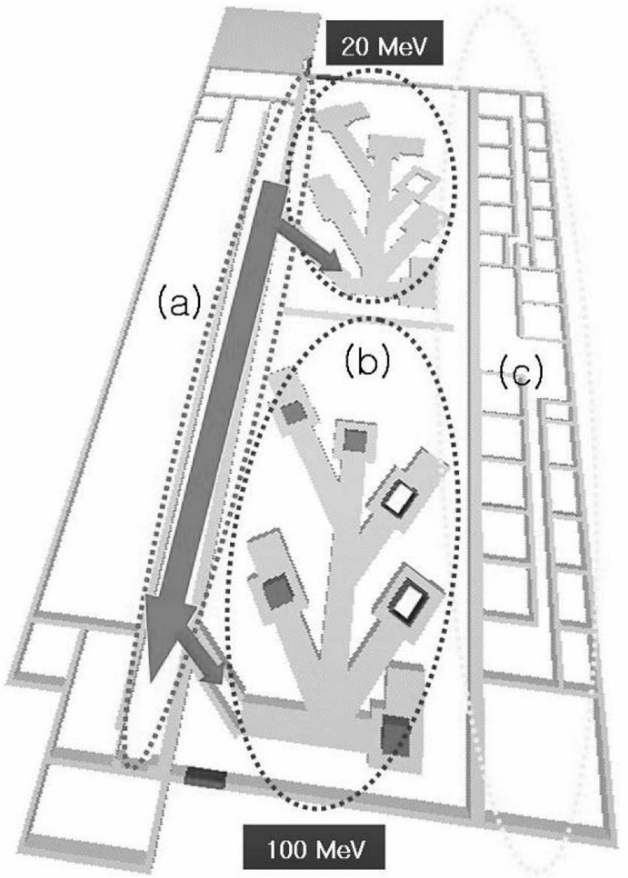


Fig. 1. Geometry of a 100 MeV Proton Accelerator Facility Drawn Using Sabrina™ (a) The Beam Accelerator Tunnel Area, (b) the Beam Utilizing Area, and (c) the Office Space

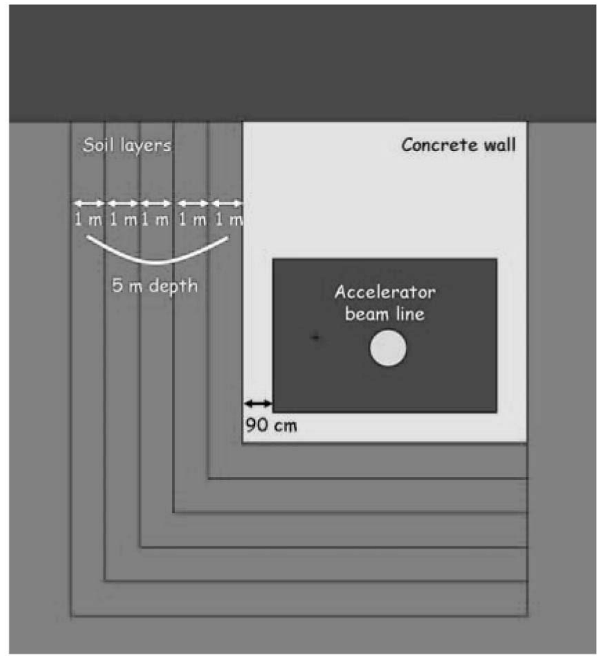


Fig. 2. Geometrical Model for the MCNPX Simulation

estimated the radiological environmental effect through a calculation of the level of soil activation using the MCNPX Monte Carlo particle transport simulation code and it estimated the level of groundwater migration using the aforementioned Concentration Model.

2. METHODS

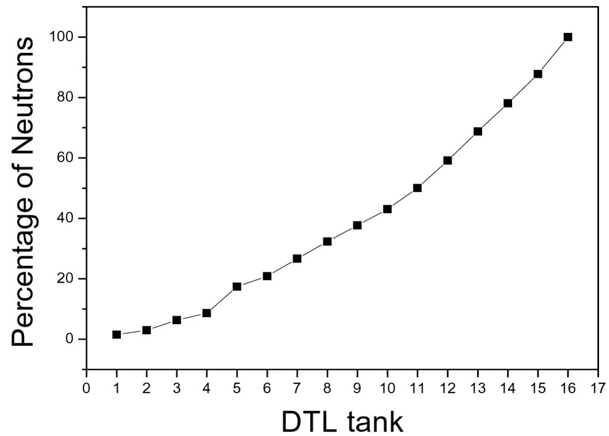
In this study, the MCNPX Monte Carlo simulation code was used. This code is the most widely used code for a radiation shielding calculation. DTL tanks 7 - 16 for the 20 - 100 MeV beam accelerator line, the 90 cm-thick concrete shielding wall, and the soil layer around the facility were modeled for geometry, as shown in Fig. 2. The length and radius of the beam line are 10 m and 35 cm, respectively. The characteristic (silty gray), density (1.5 g/cm^3), and depth (5 m from facility) of the soil were determined from a geometrical research report [6]. The soil was comprised of O (54.6 %), Si (30.7 %), Al (4.2 %), K (2.5 %), Fe (1.8 %), Mg (1.7 %), H (1.6 %), Na (1.3 %), Ca (1.2 %), and Mn (0.003 %).

The beam loss of the beam line was assumed to be 1 W/m, which is the criterion for the design. Thus, the percentage of induced neutrons with energy above the threshold of a spallation reaction (approximately 20 MeV) was determined, as shown in Fig. 3 (a). As shown in this graph, less than 20 % of the total neutrons are generated in DTL tanks 1 - 6. Therefore, only DTL tanks 7 - 16 are used for the neutron source, as shown in Fig. 3 (b). While JENDL nuclear data set was used for important radionuclides, a physics model was used when such nuclear data did not exist. The FT8 RES option and FM card of the MCNPX were used to determine the production rates of the radioisotopes [7]. The simulation was performed on 3.2 GHz and 2.8 GHz PENTIUM 4 Xeon processors using LINUX.

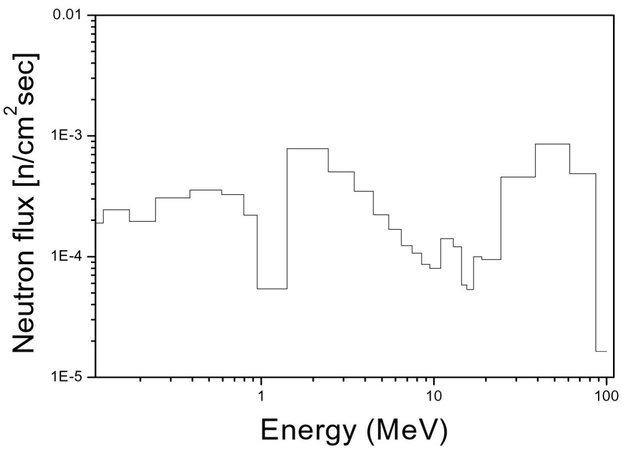
3. RESULTS

3.1 Estimation of the Production Rates of the Radionuclides in the Soil

The production rates were calculated in the soil around the 100 MeV proton accelerator facility. This facility will



(a)



(b)

Fig. 3. (a) Percentage of Neutrons with Energy Above 20 MeV
(b) The Neutron Spectrum in the 100 MeV Accelerator Tunnel

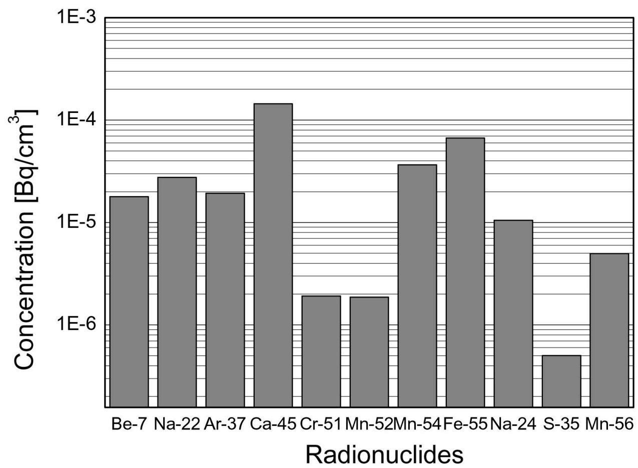


Fig. 4. The Production Rates of Radionuclides in the Soil

be was constructed over a 5 m-deep soil layer; thus, the soil layer was determined assumed to be 5 m around the beam accelerator tunnel building in this study. The types of radionuclides and production rates were evaluated by the MCNPX with the FT8 RES option and FM card. The neutrons from the accelerator tunnel induce over one hundred types of radionuclides in the soil, but this study calculated only the production rates of the radionuclides considered important from a radiation safety aspect (10 h $< T_{1/2} <$ 100 y). Fig. 4 shows the production rates of the radionuclides when the accelerator was operated for 1 year. Fig. 4 shows that ^{45}Ca has the highest production rate (= 1.78×10^{-4} Bq/cm^3). While ^{3}H and ^{22}Na are typically considered as the most important radionuclides in high energy accelerator facilities, few ^{3}H were produced in the soil around the accelerator facility in this study, as the energies of the protons are not sufficiently high to induce the necessary spallation reactions for producing ^{3}H. The production rates of radionuclides in the soil have also been calculated in other studies. SLAC estimated the production rates of radioisotopes and the soil activation level for a 500 GeV Next Linear Collider (NLC) electron/positron accelerator using FLUKA. In addition, Spallation Neutron Source (SNS) performed a similar study for a 1 GeV proton accelerator [1, 3]. A comparison of these results for different facilities is presented in Table 1.

3.2 Estimation of the Soil Activation by Induced Radionuclides

Radioisotopes produced by spallation reactions between high energy neutrons and soil components lead to the soil activation. It is necessary to estimate the soil activation continuously during the operation and after the shut-down of an accelerator. The level of soil activation was estimated in a 5 m-deep region for the radionuclides with relatively long half-lives and high production rates. It was assumed that the accelerator operated for 6,000 hours and stopped for 2,760 hours per 1 year. The saturation point was reached after the accelerator had been operated for 10 years. Table 2 shows that ^{37}Ar, ^{45}Ca, ^{54}Mn, and ^{55}Fe contribute considerably to the total activity during the operation of the reactor. While ^{55}Fe and ^{22}Na are predominant in the total activity up to 30 years after the shut-down, ^{37}Ar, ^{45}Ca, and ^{54}Mn do not contribute to the total activity due to their short half-lives. 30 years after a

Table 1. Comparison of Production Rates of Radionuclides for Different Facilities

Radionuclide	SLAC (500 GeV, electron/positron)	SNS (1 GeV, proton)	PEFP (100 MeV, proton)
^{3}H	8 %	-	-
^{7}Be	19 %	-	9.4 %
^{14}C	-	0.66 %	-
^{22}Na	6 %	1.4 %	2.7 %
^{37}Ar	-	-	10.5 %
^{42}K	-	-	-
^{45}Ca	13 %	-	51.8 %
^{51}Cr	-	-	1.0 %
^{52}Mn	-	-	1.0 %
^{54}Mn	22 %	3.3 %	8.5 %
^{55}Fe	-	94 %	6.3 %
^{56}Fe	22 %	-	-

Table 2. The Activity from Various Radionuclides in the Soil around the Accelerator Tunnel

Radionuclide (Half life)	Concentration [Bq/cm^3]				
	Saturation	1-yr after shut-down	10-yr after shut-down	20-yr after shut-down	30-yr after shut-down
^{3}H (12.33 y)	1.39E-16	1.31E-16	7.91E-17	4.51E-17	2.57E-17
^{22}Na (2.6 y)	2.76E-5	2.11E-5	1.92E-6	1.34E-7	9.34E-9
^{37}Ar (35.0 d)	1.93E-5	1.42E-8	-	-	-
^{45}Ca (162.6 d)	1.45E-4	3.06E-5	2.54E-11	4.47E-18	-
^{51}Cr (27.7 d)	1.92E-6	2.07E-10	-	-	-
^{54}Mn (312.3 d)	3.67E-5	1.63E-5	1.12E-8	3..39E-12	1.03E-15
^{55}Fe (2.7 y)	6.72E-5	5.21E-5	5.30E-6	4.19E-7	3.31E-8
^{35}S (87.32 d)	5.02E-7	2.77E-8	1.32E-19	-	-
Total activity	**2.98E-4**	**1.20E-4**	**7.24E-6**	**5.53E-7**	**4.24E-8**

shut-down, the total activity is reduced to 0.01 % in comparison with the point of saturation.

3.3 Estimation of the Migration of the Radionuclides in the Soil

Most radioisotopes produced in the soil undergo beta decay. In particular, ^{3}H and ^{22}Na are leached out of the soil and are readily dissolved in the surrounding water. ^{7}Be, ^{45}Ca and ^{54}Mn are also produced in the soil, but these radioisotopes rarely move into the groundwater. As the other radioisotopes have short half-lives or immobilities, ^{3}H and ^{22}Na are the major radioisotopes of interest in this research area. Only a small amount of tritium was produced around the tested facility; hence, only the migration of ^{22}Na was estimated. The velocities of the radionuclides through the soil were estimated using the following equation [8]:

$$\frac{v_i}{v_w} = \frac{1}{1 + K\,(\rho/P\,)} \tag{1}$$

By considering the characteristics of the soil around the facility (K: 0.2 mL/g, P: 0.45, ρ: 1.5 g/cm^3), ^{22}Na moves at a 60 % velocity of that of water in the soil. However, it was not possible to use the groundwater around the accelerator facility as a public water-supply. Therefore, this method is not feasible for estimating the irradiation level. For this reason, this study estimated the migration of the radioisotopes using the Concentration Model. After the Concentration Model was proposed by the Fermi Laboratory in 1993, many studies have used this method [9]. This model uses the concentrations directly by removing the discussion concerning how much water is used daily by a typical resident drinking from a single well. Instead, the new model considers the concentrations of radionuclides (pCi/cm^3) in unprotected soil. By applying leaching measurements, pCi/cm^3 in the soil can then be changed into pCi/ml in the water. The specific volume activity for ^{22}Na was given as 1.34×10^{-4} pCi/cm^3/yr. Assuming that the weight fraction of water in the soil is 20 %, 4.15 % of ^{22}Na is leached out from this empirical equation.

$$L\,(\,^{22}Na\,) = L_2(\,1. - e^{-4.5w}\,) \tag{2}$$

Here,

w = the weight of water as a fraction of soil weight
L_2 = 7 %, the leachability factor for sand and gravel

Combining the radioactivity and the leaching fraction, the initial concentration C_0 of ^{22}Na per year is calculated as 1.48×10^{-5} pCi/ml/yr.

$$C_0(pCi/ml/yr) = \frac{A_i(pCi/cm^3/yr)\times V_s(cm^3)\times L_i}{V_w(ml)} \tag{3}$$

where

A_i = the concentration of the radionuclide per year
V_s = volume of the soil
L_i =the leachability factor for the radionuclide
V_w = volume of the water

There are no limits for ^{22}Na in drinking water in Korea; thus, the regulation of the Department of Energy of the USA (40 CFR 141) was applied. From the result, the dose from ^{22}Na is considerably less than the annual intake limit of 0.1 pCi/ml.

4. CONCLUSION

This study estimated the production rates of radionuclides and the level of soil activation in the soil around a 100 MeV beam accelerator tunnel. Dose estimation for the general public was also estimated. From the results, ^{55}Fe, ^{54}Mn, ^{45}Ca, and ^{42}K are mainly produced in the soil. These radionuclides induced a soil activation rate of approximately 2.98×10^{-4} Bq/cm^3 at the point of saturation. 30 years after a shut-down, only ^{55}Fe and ^{22}Na contribute to the soil activation. The total activity at this time is reduced to 0.01 % in a comparison with the point of saturation. Consequently, soil activation will not be a problem 30 years after a shut-down. The dose from ^{22}Na was 1.48×10^{-5} pCi/ml/yr in drinking water, which was found to satisfy the limit of the regulation. These results provide fundamental information regarding an estimation of the environmental radioactivity from a 100 MeV proton accelerator facility. Further study will be performed for a more comprehensive estimation of the radiological environmental effect.

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