

## Shielding design for the LBNE decay pipe

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### Abstract

The Long Baseline Neutrino Experiment (LBNE) is being designed to deliver a high intensity neutrino beam from Fermilab to a detector 1300 km away in South Dakota. The neutrino beam will be produced from the decays of pions and kaons generated from a 120 GeV proton beam incident on a 95 cm long graphite target. The pions and kaons will decay in flight in the 200 m decay pipe downstream of the two magnetic focusing horns. The operation of this proposed beamline will generate radionuclides in the soil surrounding the beamline complex which may leach into the groundwater resources. Sufficient shielding will therefore be required to maintain the concentration of the radionuclides in the ground water resources, over the lifetime of the facility, below the environmental regulatory limits. This paper presents an estimate of the minimum decay pipe shielding required to maintain the radionuclide concentrations in the ground water below the regulator limits. A 30-year operation period of the LBNE beamline at a 2.3 MW beam power is assumed.

### Introduction

The proposed LBNE project [1] is planned to deliver a beam of neutrinos to a detector located 1300 km away in South Dakota. The operation of this beamline has the potential to activate the soil and water in its vicinity. As the beamline is angled 102 mrad downward with respect to the plane of the accelerator, this will result in the hadron absorber being located at the soil rock interface, which, in turn, will increase the potential of contaminating the ground water with radionuclides. The focus of this document is on the soil and water activation in the vicinity of the 200 m long decay pipe. Detailed within are the calculations used to estimate the amount of decay pipe shielding required to maintain the concentration of radionuclides that can be leached into the aquifers to be below the Federal and State regulatory standards for drinking water.

### Regulatory standards

The Federal Ground Water Regulatory standards [2-4] require that the radionuclide concentrations in water meet the following requirement:

$$\sum_i \frac{C_i}{C_{\max,i}} \leq 1 \quad (1)$$

where  $C_i$  is the concentration of the  $i^{\text{th}}$  radionuclide and  $C_{\max,i}$  is the derived concentration standard, the maximum concentration allowed for a single radionuclide. The purpose of this regulatory standard is to limit the dose the general public receives from drinking water to be under 4 mrem per year [2].

Of particular concern are the  $^3\text{H}$  and  $^{22}\text{Na}$  radionuclides given their long half-lives and copious production in earth shielding used at accelerator facilities [5]. For ground water, the Federal derived concentration standards for  $^3\text{H}$  and  $^{22}\text{Na}$  are 20 pCi/mL [2,3] and 0.4 pCi/mL [4], respectively. All other radionuclides are either too short-lived or are produced in such insignificant quantities that they will be effectively undetectable when appropriate shielding is applied for  $^3\text{H}$  and  $^{22}\text{Na}$ .

The State of Illinois regulations requires [6] that no degradation of the waters of the State resources should occur. To satisfy this requirement, the LBNE Project aims to have sufficient shielding in place so that the concentrations of radionuclides that do leach into the ground water are below the levels defined as detectable by Federal standards. Having enough shielding to just satisfy the Federal regulatory standards will not be sufficient and could be interpreted as a violation of the State of Illinois standard. The limits of detectability for  $^3\text{H}$  and  $^{22}\text{Na}$  are 1 pCi/mL and 0.04 pCi/mL, respectively. At the limit of detectability, the sum of the concentration ratios becomes:

$$\frac{C_{^3\text{H}}}{C_{\max, ^3\text{H}}} + \frac{C_{^{22}\text{Na}}}{C_{\max, ^{22}\text{Na}}} = \frac{1}{20} + \frac{0.04}{0.4} = 0.15 \quad (2)$$

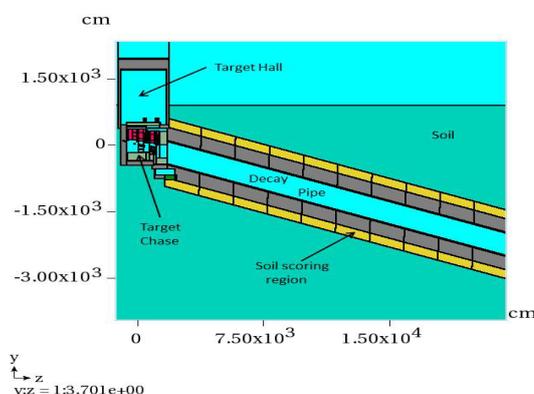
To push the concentration levels down below the limits of detectability, the LBNE Project has adopted the following standard for the sum of concentration ratios:

$$\sum_i \frac{C_i}{C_{\max, i}} \leq 0.1 \quad (3)$$

## Simulation

The MARS Monte Carlo simulation code [7,8] is used to determine the concentrations of the  $^3\text{H}$  and  $^{22}\text{Na}$  radionuclides in the soil which is in the immediate vicinity of the decay pipe. Included in the simulation are various beam line elements such as the target and focusing horns along with the shielding. The reference design for LBNE neutrino beam line is described in the CDR [1]. Unlike the reference design where the decay pipe shield cross-section is box shaped, the MARS model has cylindrical shaped shielding, of 3 m thickness, for ease of calculation. The result provides a more conservative estimate for the radionuclide concentrations if the outer diameter of the shielding is equal to the lateral dimensions of the reference design. Figure 1 shows the full MARS model of the neutrino beam line.

**Figure 1. The LBNE beamline geometry as modelled in the MARS simulation code**



An exponential function is used to describe the radial source term in the soil and concrete for a 3 m thick shield. These source terms are then used to extrapolate the results to other shield thicknesses. The decay pipe shield is subdivided into ten 20-m sections longitudinally and fifteen 20-cm thick subsections radially. The soil immediately outside the decay pipe is likewise subdivided into ten 20-cm thick scoring regions.

### Radionuclide concentration

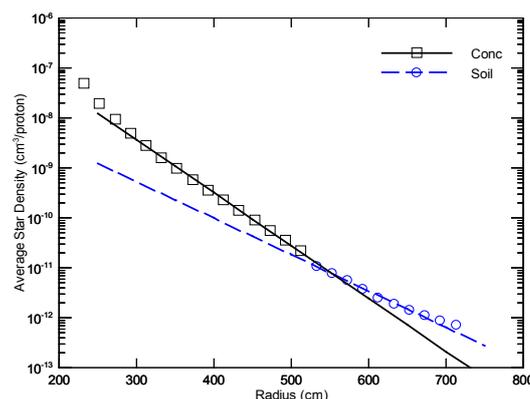
Fermilab has adopted the concentration model [9] to determine the amount of radionuclides produced by an accelerator facility that may propagate into the ground water system. In this model, the concentration of the  $i^{\text{th}}$  radionuclide is:

$$C_i = \frac{N_p K_i L_i S_{av}}{1.17 \times 10^6 R_{vol}} \{1 - e^{-t_{irr}/\tau_i}\} \quad (4)$$

where  $N_p$  is number of incident protons on target per year,  $K_i$  is the number of radionuclides produced per star (inelastic interaction),  $L_i$  is the fraction of radionuclides that are leachable,  $S_{av}$  is the average star density per proton on target over the volume which contains 99.9% of the stars,  $R_{vol}$  is the ratio of the volume of water which will leach 99% of the leachable nuclides to the volume of material from which they are leached,  $t_{irr}$  is the irradiation time, and  $\tau_i$  is the mean lifetime of the radionuclide. The factor  $1.17 \times 10^6$  in the denominator scales the units from Bq to pCi and seconds to years.

The average star density in each of the longitudinal and radial bins in the concrete and soil were extracted to determine the source terms for each longitudinal subdivision of the decay pipe. Figure 2 shows star density distribution per proton for the longitudinal subsections located 50 m into the decay pipe in the concrete and soil. The data points are the MARS results while the solid and dashed lines show the fitted source terms for the concrete and soil respectively. Note that the slope for the soil is shallower than that for the concrete due to the soil's lower density.

**Figure 2. The average star density distribution in concrete (black squares) and soil (blue circles) as a function of radius**

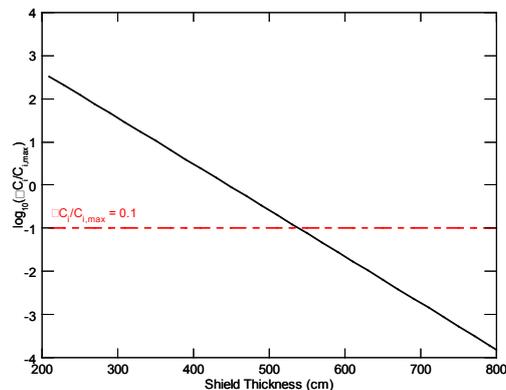


The values for the nuclide production per star ( $K_i$ ) for  $^3\text{H}$  and  $^{22}\text{Na}$  were calculated using MARS running in MCNP [10] mode. Hadron interactions in MARS were modelled exclusively using the LAQGSM2012 [11,12] model. Table 1 lists the input values for the concentration model parameters.

**Table 1. Input parameter list for the concentration model**

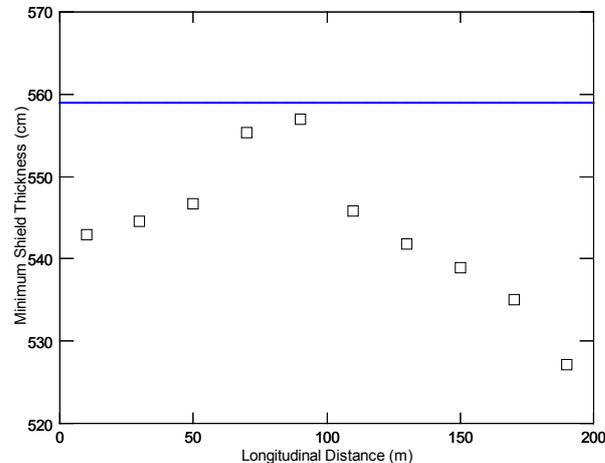
Parameter	Value
$N_p$	$2.5 \times 10^{21}$ protons/year
$K_{3H}$	$(2.9 \pm 0.3) \times 10^{-2}$ $^3H$ /star
$K_{22Na}$	$(2.6 \pm 0.2) \times 10^{-2}$ $^{22}Na$ /star
$L_{3H}$	1.0
$L_{22Na}$	$0.15 \pm 0.05$
$R_{vol,3H}$	$0.90 \pm 0.06$
$R_{vol,22Na}$	$1.88 \pm 0.13$
$T_{3H}$	17.8 years
$T_{22Na}$	3.8 years

The radionuclide concentrations that are leached into the water are calculated using Equation 4 for multiple shield thickness ranging from 2 m to 16 m. Figure 3 shows the sum of the concentration ratios as a function of shield thickness. The minimum shield thickness averaged over all longitudinal subsections was found to be  $549 \pm 10$  cm, which satisfies Equation 3.

**Figure 3. The sum of concentration ratios as a function of shield thickness**

The use of a square shaped shield cross-section reduces the average star density in a fixed area of the soil by a factor of 0.88. This correction will reduce the minimum shield thickness by 5 cm. Figure 4 shows the minimum shield thickness as a function of longitudinal position ( $z$ ) corrected for the shape of the shield cross-section. The blue line in the figure is the conservative value for the average minimum shield thickness. The conservative value of 559 cm is the sum of the uncorrected the average minimum shield thickness (549 cm) and the  $1\sigma$  uncertainty (10 cm). As can be seen in Figure 4, the conservative average shield thickness is greater than the corrected shield thickness calculated for any individual longitudinal subsection. This demonstrates that uncertainties in the calculation are unlikely to result in detectable levels radionuclides in the ground water.

**Figure 4. Minimum thickness as a function of longitudinal distance for a square shielding cross-section**



### Summary

To eliminate any degradation of the water resources by the operation of the LBNE beamline, sufficient shielding must be in place to reduce the concentrations of  $^3\text{H}$  and  $^{22}\text{Na}$  radionuclides that can potentially be transmitted to the groundwater to be below detectable levels. Applying sufficient shielding to maintain radionuclide concentrations in the ground water to be below 10% of the Ground Water Regulatory Standard should be sufficient. The average minimum shield thickness was found to be  $549 \pm 10$  cm. Adding the  $1\sigma$  uncertainties to this value gives a final result of 559 cm for the decay pipe shield thickness.

### Acknowledgements

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