Fermilab
ES&H Section

E.P. NOTE 21

Tritium Concentration Reduction Factors for MiniBooNE Target Area

Kamran Vaziri and Paul Kesich

(June 2002)

Author: K. Vaziri Date: 6/14/02

Author: P. Kesich Date: 06-14-02

Reviewed: A. Elwyn Date: 6/18/02

Approved: D. Cossairt, Associate Head, Radiation Protection Date: 6/14/02

Approved: P. Kesich, Associate Head, Environmental Protection Date: 06-14-02

Approved: Bill Griffing, Head, ES&H Section Date: 6/18/02

E.P. NOTE 21

Tritium Concentration Reduction Factors for MiniBooNE Target Area

K. Vaziri and P. Kesich

(June 2002)

Introduction

The concentration Model (Co99) is the methodology used at Fermilab to predict the production and subsequent migration of radionuclides in the soil around the beam targeting or loss areas. The predictions of this model are used in the design of new facilities and the operation of the existing facility to keep the concentration of the radionuclides in the surface waters and the ground water below the prescribed and regulatory limits (see reference GWR).

This note describes a calculation of the transport of the radionuclides produced in the soil, to the groundwater, for the MiniBooNE target area.

A Brief Description of the Concentration Model

The concentration model uses the star density produced in the soil. This is usually obtained from a standard Monte Carlo code that simulates beam loss and the subsequent production of radionuclides in the soil in the vicinity of the enclosures. Star density, number of protons lost, the radionuclide yield, half life and leaching parameters, in conjunction with some soil parameters, are used to calculate the concentration of the radionuclides, C_i, right outside the enclosure. This concentration can be directly compared with the allowed concentration values for discharge to the surface waters.

The next step in the concentration model calculation is the transport of this initial concentration from the production level, immediately outside the enclosure walls, to the aquifer. The radionuclide plume moving through the soil will decay and expand, therefore reducing its concentration. This reduction is taken into account through the calculation of a reduction factor R. Thus the final concentration of the radionuclides, C_f, in the aquifer will be;

$$C_f = C_i * R.$$

The radionuclide plume moves through the glacial till, the glacial till-dolomite interface, and within the dolomite, in its transport to a well. IEPA standards imply that one should assume no reduction factors due to migration through the till-dolomite interface and transport in the dolomite - both regions designated as Class I groundwater resources. Therefore, the reduction factor R, used in the calculation is only due to the transport through the glacial till.

Originally, the reduction factor was calculated based on one site-wide average vertical seepage velocity (Ma93, Co94). Further experience and investigation of the loss points at different locations at the lab showed that the use of one site-wide average velocity is neither correct nor conservative. The latest version of the concentration model (Co99) recommends the use of site-specific geological characterizations as input to transport calculations using the computer code PATCH3D (Su88).

Groundwater Transport Code PATCH3D

PATCH3D is a computer program that analytically solves a three dimensional advection-dispersion equation for the vertical transport of radionuclides in the soil (Su88). The calculations for the MiniBooNE presented below were done by transporting a 3.7m by 3.7m-rectangular patch containing the initial radionuclide concentration in a direction perpendicular to the patch, downward to the aquifer. This code requires values for the vertical seepage velocity within the layer, the decay constant of the radionuclide, the thickness of the layer, and longitudinal and transverse dispersivities. The dispersivities were determined empirically as described in the reference Co99.

The vertical seepage velocity is calculated from the hydrogeological properties - gradient, hydraulic conductivity and effective porosity of the layer through which the transport is calculated. For the cases where there are several intervening layers between the radionuclide production point and the aquifer, the calculations here were done for the total distance between the production point and the aquifer using one average velocity. The migration of the radionuclide through each layer is dependent on the thickness and vertical seepage velocity for that layer (WCC93).

The hydrogeological input parameters for the MiniBooNE are based on the information obtained from geological characterizations of the soil samples from boreholes S-1248 (Fig. 1), near the MiniBooNE target regions.

Results

Measurements and calculations (Bo72 and Ma93) have shown that, of all the radionuclides produced in the soil, ^{3}H and ^{22}Na are the most significant due to their yields, half lives, transportability in the soil, leachability from the soil, and the allowed concentrations in the groundwater. In usual cases at Fermilab, where the enclosure is located in the till, tritium is the main contributor to ground water contamination. ^{22}Na, due to its smaller production cross section, half life and distribution coefficient (Bo72) has a much larger reduction factor. Therefore, the following calculations were only done for the transport of tritium.

The calculations were done for one year, five-year and ten-year continuous accelerator operation periods. Using the latest geological parameters at or near the loss points, the calculations indicate that it will take about 450 years for the maximum tritium activity produced to get to the aquifer. It is this maximum activity on which the reduction factors shown here are based.

Geology

As seen from Table 1 and Fig.1, of the five different layers, the third and the fifth (Lemont formations) are mainly responsible for retarding the migration to the dolomite. Even though the third layer is about five meters deep, care must be taken not to disturb or “short circuit” the integrity of these critical layers.

There are 90 cm of Lemont formation under the MiniBooNE enclosure (elevation 715'). If in the calculation of C_i (initial tritium concentration), S_{ave} represents an average over a 90 cm thick soil layer around the enclosure, then the net reduction factor should be correct by taking out the effect of the first layer. The results are given in Table 1 below. Where;

$$\text{Net Reduction Factor} = \prod_j (C_f / C_i)_j$$

where index *j* is for the layers from top to bottom.

Table 1. MiniBooNE reduction factors for different periods of operation.

Soil Layers from the top	Layer thickness (cm)	Seepage velocity (cm/year)	C/C0 (1year pulse)	Years for max to reach boundary	C/C0 (5year pulse)	Years for max to reach boundary	C/C0 (10year pulse)	Years for max to reach boundary
1	91	3.1	9.30E-03	21	0.0457	20	0.08795	20
2	427	14.1	0.0118	19	0.0575	21	0.09149	20
3	244	0.3	3.00E-10	174	1.50E-09	182	2.85E-09	180
4	61	14.1	0.202	4	0.6195	6	0.766	10
5	243	0.2	2.10E-12	219	1.02E-11	223	2.00E-11	220
				437 years		452years		450years
		Net Reduction Factor (1yr)=	1.40E-26	Net Reduction Factor (5yr)=	2.49E-23	Net Reduction Factor (10yr)=	3.51E-22	
All layer	1066	Harmonic Mean=0.692			9.6E-15		9.7E-15	

The variation, by factors of two, of the patch size did not affect the results significantly (±13%). Experience with measurements and calculation at other location leads us to assume a conservative uncertainty of 30%-50% for these predictions.

Closing Thoughts

A comparison of the above reduction factors with that calculated using a standard parameterization for the whole site (Ma93) shows that the present results are smaller by several orders of magnitude. The main reason for this difference is that the standard model assumes 15 cm/year vertical seepage velocity. None of the cases studied so far, have such a large vertical seepage velocity. Since, the velocity folds in exponentially, the difference in reduction factors becomes large.

When using the results presented in this note, the following issues should be kept in mind.

1) As mentioned earlier, the reduction factors for the transport of ^{22}Na are much larger than for tritium for the cases calculated above. However, when the tritium concentrations become comparable to the groundwater limit, factors for sodium should be explicitly calculated and included in the final concentrations.

2) If there is more than one radionuclide produced that can reach the aquifer, then a combination of the radionuclides concentrations should be used to limit the operation of the machines. For example as it is common at Fermilab, only tritium and ^{22}Na have shown any significant mobility. Then the following equation should be used to predict the maximum allowable beam intensity and control the production of these two radionuclides (Co94),

$$\frac{C_{tritium}}{20\,pCi/ml}+\frac{C_{Na-22}}{0.4\,pCi/ml}\leq 1.0$$

3) A large reduction factor for the tritium migration to the groundwater does not necessarily set the operating limit of the beam intensity/beam loss. Beside the regulatory groundwater tritium limit of 20 pCi/ml, Fermilab is also bound by a 2000 pCi/ml limit for discharge to surface water. Therefore, the initial tritium concentration calculated using the Concentration Model should not normally be larger than the surface water discharge limit.

4) Following item 2 above, for the surface water, one should use the following relation to obtain the allowable beam intensity (Co94),

$$\frac{C_{tritium}}{2000\,pCi/ml}+\frac{C_{Na-22}}{10\,pCi/ml}\leq 1.0$$

In cases where there are multiple layers, there are actually two methods of calculating the transport of the tritium. The first method is to calculate the reduction factor for each layer. Then the final reduction factor is a product of all of the individual ones. The second method is to use the harmonic average velocity for all the layers, as described above. This is a fast and conservative method of calculation, since it involves the total depth and one average velocity (last row of table I).

References

Bo72 T. B. Borak, M. Awschalom, W. Fairman, F. Iwami, and J. Sedlet, "The Underground Migration of Radionuclides Produced in Soil Near High Energy Proton Accelerators." Health Physics 23, 679-687 (1972).

Co99 Cossairt, J. D., A. J. Elwyn, P. Kesich, A. Malensek, N. Mokhov, and A. Wehmann " The Concentration Model Revisited", E.P. Note #17. June 1999.

Co94 Cossairt, J. Donald "Use of a Concentration-Based Model for Calculating the Radioactivation of Soil and Groundwater at Fermilab" E.P. Note #8. December 1994.

GWR Ground Water Regulations;
DOE Orders and Guidance (DOE5400.5)
U.S. EPA Regulations (40CFR141)
Illinois EPA Regulations (35 IAC 620)

Ma93 Malensek A. J., A. A. Wehmann, A. J. Elwyn, K. J. Moss, and P. M. Kesich, "Groundwater Migration of Radionuclides at Fermilab", Fermilab Report TM-1851, August 1993.

Su88 E. A. Sudicky, T. D. Wadsworth, J. B. Kool, and P. S. Huyakorn, PATCH3D-Three-Dimensional Analytic Solution for Transport in a Finite Thickness Aquifer with First-Type Rectangular Patch Source. Prepared for Woodward Clyde Consultants, HydroGeologic Inc. Herndon, Va., January 1988.

WCC93 Woodward-Clyde Consultants, Summary of Radionuclide Transport Modeling for Ground Water at the Fermi National Accelerator Laboratory, Batavia, Il. Project 92C3073, Chicago, Il., August 1993.

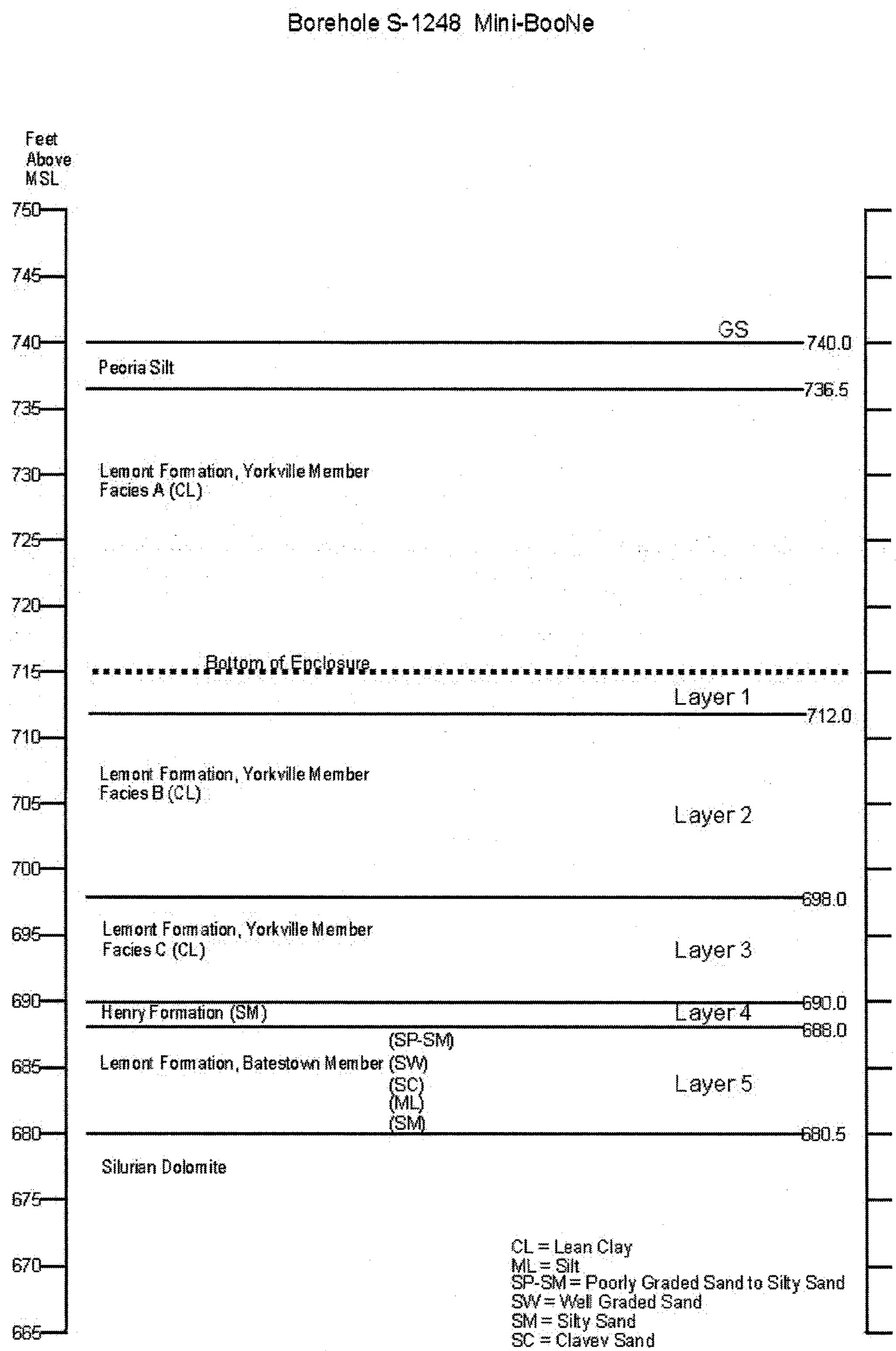

Fig. 1: Cross sectional geological map of MiniBooNE target area from borehole S-1248 (not to scale)