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ES&H Section

E.P. NOTE 20

Calculation of Reduction Factors for Tritium Migration in Booster Soil using the PATCH3D Transport Code

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Introduction

The new prescription on the use of the concentration Model (Co99), analysis of the soil samples from underneath the Fermilab Booster major loss points, and reconfiguration of the Booster components to accommodate the requirements of the Main Injector, has made the calculations presented in this note necessary. A brief description of the Concentration Model is given in EP18 (Va00). Results of site specific geology, from borehole samples collected recently beneath the Booster at two known loss points, combined with dispersion parameters more representative of the actual geology, make these refined tritium transport calculations possible. It turns out that the peak of the tritium activity will reach the aquifer several years after the accelerator operations terminate at this location. Therefore, it is necessary to design a facility based on the maximum activity reaching the aquifer, irrespective of when it actually reaches the aquifer. In this particular case, we calculate that it will take approximately 70 years after start-up for the maximum activity to reach the aquifer. This was found to be true for operating periods of up to 50 years. These results are based on the assumption that the soil does not contain any tritium before the start-up.

We describe below the calculation of the transport of the radionuclides, produced in the soil, to the groundwater for the major loss points of the Booster accelerator. The results are expressed as reduction factors in the concentration of the radionuclides produced in the soil under the Booster enclosure, as they migrate down to the aquifer. These reduction factors are used to limit the operations of the Booster to keep the concentration of the radionuclides in the surface waters and the groundwater below the prescribed and regulatory limits (see reference GWR).

Originally, the reduction factors were 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 always conservative. The latest version of the Concentration Model recommends the use of site-specific geological characterizations as input to transport calculations using the computer code PATCH3D (Co99).

Groundwater Transport Code PATCH3D

The movement of radionuclides in the groundwater is controlled by advection, which is the bulk movement of groundwater, dispersion (mechanical mixing) and molecular diffusion. Compared to mechanical dispersion, molecular diffusion is small and can be neglected. PATCH3D is a computer program that analytically solves the following three-dimensional advection-dispersion equation for the three dimensional transport of radionuclides, in a uniform flow field, in the soil (Su88):

$$\frac{\partial c}{\partial t}+V\frac{\partial c}{\partial t}-D_x\frac{\partial^2 c}{\partial x^2}-D_y\frac{\partial^2 c}{\partial y^2}-D_z\frac{\partial^2 c}{\partial z^2}+\lambda\cdot c=0,$$

Where c is the concentration, V is the vertical seepage velocity, D_s are the dispersion parameters, λ is a decay constant, t is time, and x, y and z are the spatial coordinates. (WCC93)

The vertical seepage velocity is calculated from the hydrogeological properties using Darcy's Law (Fe88),

$$\mathrm{V}=\frac{ik}{n_e},$$

Where i is the hydraulic gradient, k is the hydraulic conductivity, and n is the effective porosity of the layer through which the transport is calculated. The ground around the Booster consists of several intervening soil layers between the radionuclide production point and the aquifer. For this case, the reduction factor, R_i, for each layer is calculated separately and the net reduction factor, $\Re$, is the product of all of them,

$$\Re=\prod_{i=1}^{n} R_i.$$

The calculations for the Booster 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. The dispersivities were determined empirically as described in the reference Co99. Since the transverse dispersivities are a factor of ten smaller than the vertical dispersivity, the patch size does not increase significantly (only a few percent). For this calculation, it was assumed that the horizontal patch size at the beginning of each layer is the same. This assumption will result in a slightly smaller reduction factor, which is conservative.

The hydrogeological input parameters for the Booster major loss regions are based on the information obtained from geological characterizations of the soil near the Booster extraction point to the Main Injector and MiniBooNe. Figure 1 shows the locations where the boreholes were drilled. The relevant points are BB2 and BB3. The results of the characterization are shown in figure 2.

The 1998 Booster shielding upgrade required insertion of pin piles all the way to the bedrock with a bentonite grouting around the pin-piles down to an elevation of 692 ft. This grouting was done to prevent "short circuiting". The transport calculation was therefore, only done to this elevation.

The information, obtained from the geological characterization of booster soil, which was used in the calculation, is given in the following table. The thicknesses of the layers are based on average of values from Fig. 2.

Location of the layer	Thickness (cm)	Vertical seepage velocity (cm/year)
Top (under the enclosure)	610	3
Middle	213	30
Bottom	91	10

PATCH-3D calculations were carried out for each of the three layers. The combined reduction factor in concentrations is the product of the reduction factors of the three layers.

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 beam enclosure is located in the till, tritium is the main contributor to groundwater 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 five, ten, twenty, thirty, forty and fifty-year continuous Booster operation periods. Note in about 10 years of operation, the combination of the decay and the rate of the spread of the plume, causes the maximum concentration ratios to level out. Given the arguments below one can assume a conservative uncertainty of 30%-50% for the predictions. The results of calculations are summarized in the table below.

Location of the layer	Thickness (cm)	Vertical seepage velocity (cm/Year)	C/C0 (5 years)	C/C0 (10 years)	C/C0 (20 years)	C/C0 (30 years)	C/C0 (40 years)	C/C0 (50 years)	Thickness Used for calculation
Top	610	3	0.11E-3	0.21E-3	0.21E-3	0.21E-3	0.21E-3	0.21E-3	6m
Middle	213	30	0.27	0.63	0.69	0.69	0.69	0.69	2m
Bottom	91	10	0.062	0.39	0.57	0.58	0.58	0.58	1m
		Total Reduction	1.8E-6	5.2E-5	8.3E-5	8.4E-5	8.4E-5	8.4E-5	9m

Comparison to Nikolai Mokhov's calculation

Mokhov solved a version of the transport equation used in PATCH-3D, by making several simplifying assumptions, such as ignoring dispersion and using a one-dimensional model (Mo97). Using similar input parameters (vertical seepage velocity, etc.), PATCH-3D calculations agree with Mokhov's predictions within 10% to 15 %.

Comparison to measurements at MP01 and MP02

MP01 has been a loss point for approximately the last 23 years. In 1997, soil samples were taken from under the enclosure down to a depth of six feet. Results from the activation analysis of these samples provided information about the transport of radionuclides through the layer of soil that is similar to the MP02 top layer. PATCH-3D predicts the concentration at six feet below the enclosure, after 23 years of operation, as 8% of the concentration of tritium right under the enclosure. This value agrees reasonably well with the MP01 measured value of 13%.

Tritium analysis results from the MP02 boring were not compared to the above calculations because the amount of activity found was very small and the uncertainty given was only statistical. Other sources of the uncertainty should be included for a more realistic estimate. Larger error bars in the slope of activity variation with depth would make the predictions too ambiguous. Therefore, no attempt was made to compare the results with the calculations.

Closing Thoughts

The vertical seepage velocity of the major soil layer between the Booster enclosure and the groundwater layer is 3 cm/year, which is five times lower than the site-wide assumed average velocity (Ma93). This difference accounts for the new reduction factors. 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 tritium groundwater 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),

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

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.

Fe88 Fetter, C. W. *Applied hydrogeology* (Merrill Publishing Company, Columbus, OH, 1988).

GRW Ground Water Regulations;
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U.S. EPA Regulations (40CFR141)
Illinois EPA Regulations (35 IAC 620)

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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.

Va00 Vaziri, K., P. Kesich "Tritium Concentration Reduction Factors for MI30, MI40, MI52 and MI62 locations", E.P. Note #18. April 2000.

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.

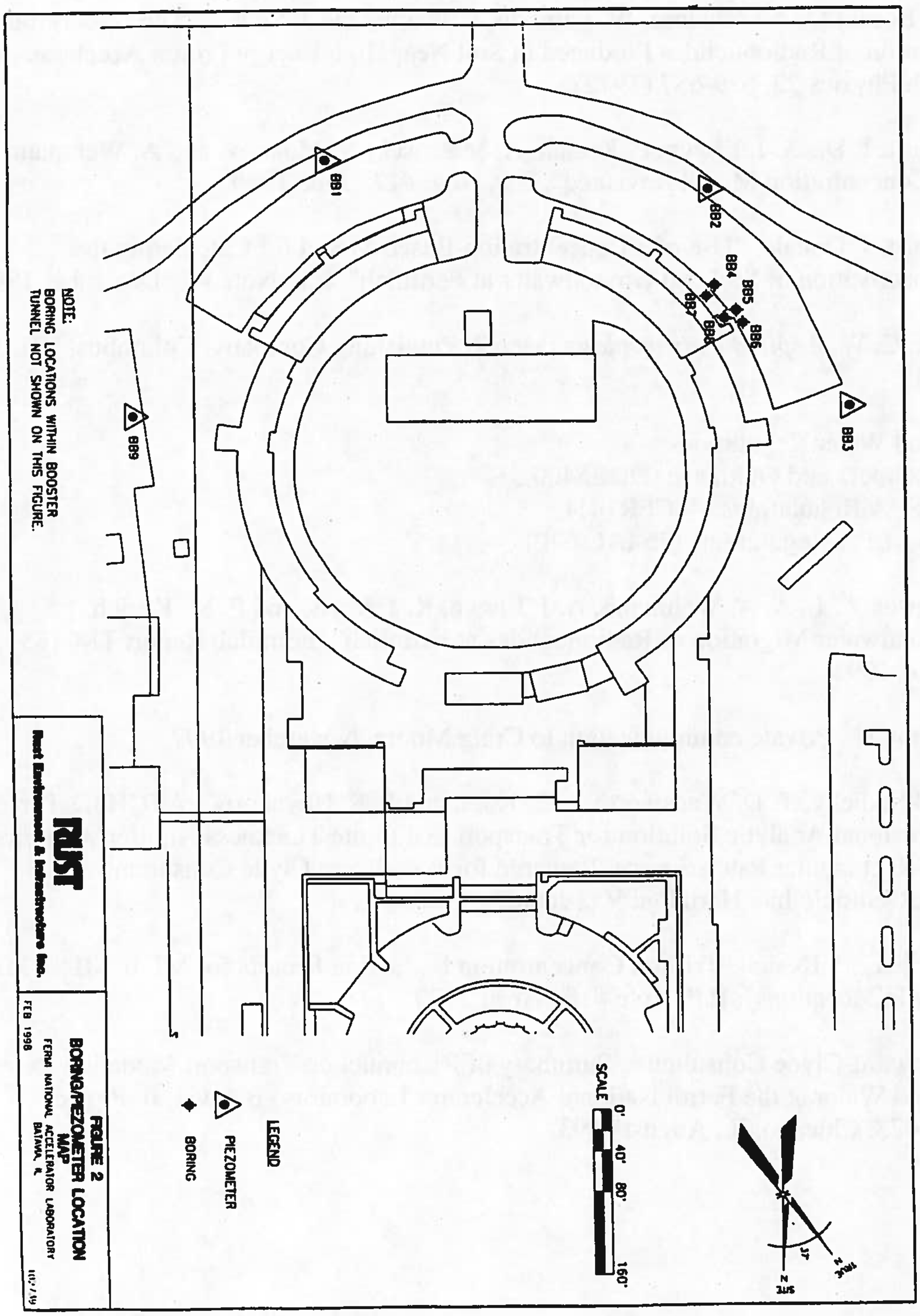

Fig. 1: Location of the boring sites around the Booster.

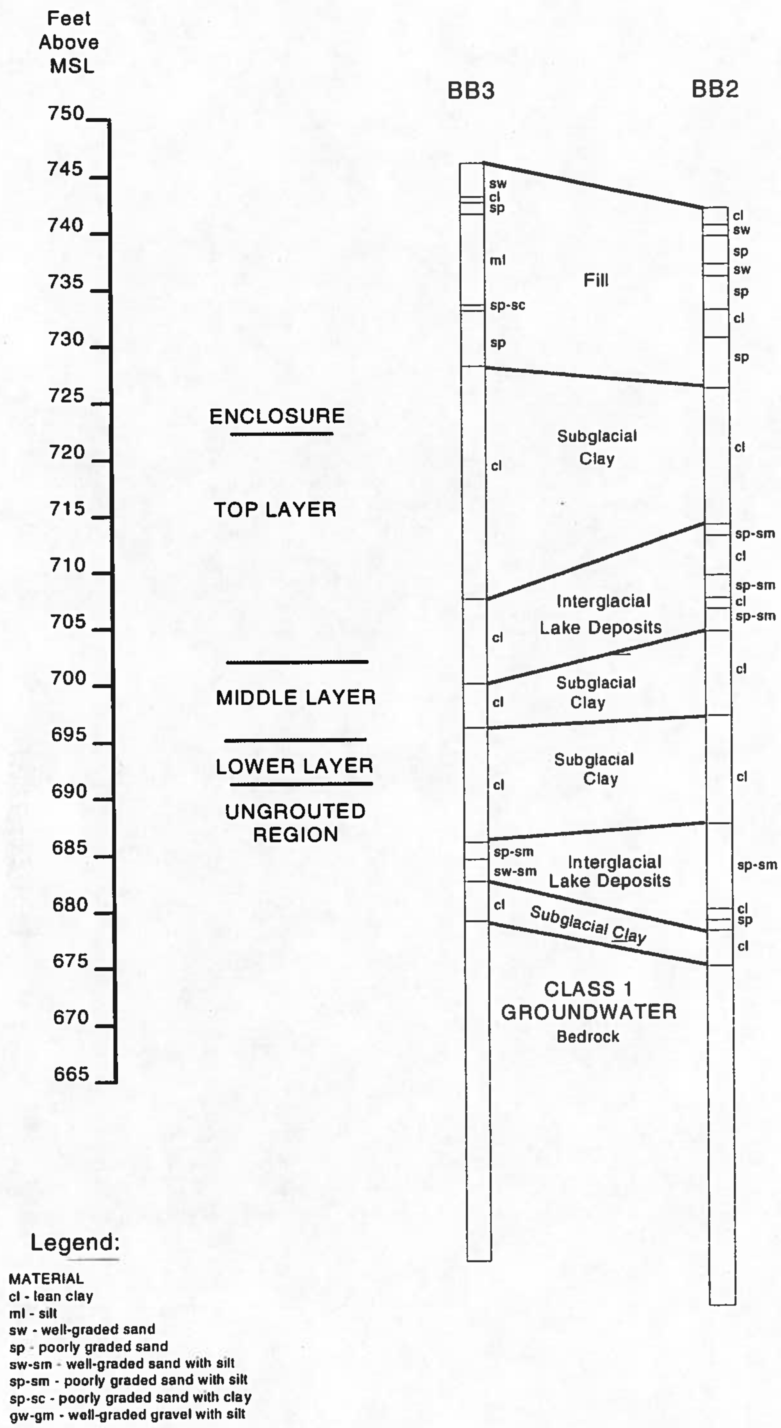

Fig. 2: Cross sectional geological map of Booster area from borehole BB2 and BB3 (not to scale)