Analytical Model for Radial Injection of NORM with a Step-Function Source*

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Abstract

This paper presents information on a model used to analyze the underground injection of wastes containing naturally occuring radioactive material (NORM). This model uses a step-function contaminant source, which models intermittent NORM injection in a continuous brine injection well. The governing equations are presented and transformed into Laplace space, where the equations are solved. The numerical inversion of this solution is detailed. The model is cast in a nondimensional form such that a single model solution is valid for a large number of different field conditions. This paper also presents a case study that compares this analytical model to a simple mixing model for a field demonstration site in west Texas. This case study showed that at distances of more than 100 meters from the injection well, calculated subsurface NORM activities were lower than proposed U.S. Environmental Protection Agency drinking water standards. The comparison also shows that the simple mixing model overpredicts activity levels close to the injection well andunderpredicts activities further from the well.

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Introduction

Dissolving scales containing naturally occurring radioactive material (NORM) and injecting the solute into existing brine disposal wells is a disposal option being considered at a large number of petroleum production sites where NORM-contaminated scales exist. Typical NORM volumes disposed of at these facilities would be small when compared with the volume of the brine being injected. In addition, the NORM would be reinjected into deep formations that are hydrogeologically isolated from potable water resources. Water in these deep formations is generally of low quality, with high concentrations of dissolved solids and, in many cases, significant background radiation.

NORM injection would be intermittent, with small volumes of NORM being injected over short time periods, followed by long periods when no NORM would be injected. Brine injection is generally continuous at the disposal well. This pattern of a short period of NORM injection, followed by a long period in which only brine is injected is the result of a NORM management practice that involves storing NORM scales and wastes on the surface until a sufficient volume has been accumulated to warrant treatment. The NORM wastes are then dissolved and disposed of by injection into a local brine disposal well.

This disposal practice can be modeled conceptually as a continuous injection well with a step-function source term for NORM contamination. The NORM contamination pulse is released into the subsurface and transported away from the well radially while it undergoes advective and dispersive transport along with sorption and retardation. The radius of the contamination pulse gets larger as the NORM moves away from the injection point. This fact, coupled with dispersion, causes the NORM contamination to mix with the connate water, thus reducing the peak concentration. As the contaminant pulse moves further from the well bore, the peak concentration decreases until it approaches the background value for the formation into which the NORM was injected. This conceptual model of NORM injection is distinctly different from a model that uses a continuous source term, such as that found at a dedicated NORM disposal facility, in which there is a mixing front at the leading edge of an injected plume, with constant, high concentrations in the body of the plume. Over time, this high concentration area continues to move further out from the injection well.

Injection of wastes into subsurface formations has been extensively studied. Ogata (1) and Tang and Babu (2) have published analytical solutions to the problem of contaminant transport and radial dispersion from a single injection well with a continuous source term (i.e., NORM is continually injected). Some simple mixing models exist that can be used to model a step-function source term. One has been used for screening level calculations for underground injection of NORM-containing wastes (3). This mixing model is crude and gives only a general estimate of the peak concentration that might occur at a given point in the formation.

A problem with step-function (i.e., noncontinuous) contaminant source term injection is generally solved through the use of numerical means - either finite difference or finite element computer codes (3). Smith et al., (3) demonstrated that for the volume of

NORM expected to be disposed of at a typical site, underground disposal via a brine injection wells is a viable alternative and that the injection of these dissolved NORM wastes into the subsurface results in very low concentrations in the receiving formations and poses little human health risk.

This paper presents an analytical solution for a continuous radial injection well with a step-function contaminant source term. This analytical model can be used to quickly evaluate the disposal of NORM wastes by underground injection. It requires a minimum of parameters and provides general solutions to the injection problem. These general solutions provide more insight into the injection problem than do the single-event solutions provided by more complex numerical models. The equations are nondimensionalized, so that a single solution run can determine the behavior of a large number of individual systems and more clearly define the relationships between the various parameters used in the model and the estimated activity of the NORM plume in the subsurface.

The objective of this paper is to present an analytical solution to the model of the periodic injection of NORM from a single well into a subsurface formation. This model simulates radially advective and dispersive transport of NORM that undergoes sorption and retardation. After the model and solution are presented, a short case study compares this model with a simple mixing model that has been used for screening purposes in previous NORM disposal work (4).

Model Description

Theory

The model presented here assumes that the receiving aquifer is homogeneous, isotropic, and confined and has a uniform thickness. The injection well fully penetrates the aquifer and discharges fluid at a constant rate. These assumptions result in a radially symmetric flow pattern that is in a steady-state condition. Contaminants (NORM) are injected in a step-function manner for a finite period and transported by means of advection and dispersion while undergoing linear sorbtion and retardation.

On the basis of the principle of conservation of mass and the above assumptions, the governing equation (in radial coordinates) for transport for an injected contaminant can be written as:

$$R\frac{\partial c}{\partial t}=\frac{1}{r}\frac{\partial\left(r D_r\frac{\partial c}{\partial r}\right)}{\partial r}-v\frac{\partial c}{\partial r} \qquad \textbf{(1)}$$

where R is retardation, c is the concentration of the contaminant, t is time, r is radial distance, D_r is radial dispersion, and v is velocity.

For radial injection with a constant fluid flux, the velocity, v, at any point r from the injection point is given by the expression:

$$v = \frac{Q}{2\pi b\phi r} = \frac{A}{r} \tag{2}$$

where:

$$A = \frac{Q}{2\pi b\phi} \tag{3}$$

and Q is the volumetric rate of injection, b is the aquifer thickness, and ϕ is the porosity of the porous medium. This radial velocity term is the driving force for advective transport, which is a dominant mechanism near the well bore.

Dispersion is a function of the media through which a contaminant is transported and the advective velocity at which it is transported. The velocity-dependent radial dispersion, D_r is given by the expression:

$$D_r = \alpha v_r = \frac{\alpha A}{r} \tag{4}$$

where α is the dispersivity of the medium (a material property) and v_r is the radial velocity as defined in Equation 2. The subscript denotes radial velocity.

To nondimensionalize the equations, we let r equal r/α and c equal c/c_0 (where c is the current concentration and c_0 is the initial concentration in the step-function source) and substitute Equations 2, 3, and 4 into Equation 1, yielding a nondimensional form of the governing equation:

$$\frac{R\alpha^2}{A}\frac{\partial c}{\partial t} = \frac{1}{r}\frac{\partial^2 c}{\partial r^2} - \frac{1}{r}\frac{\partial c}{\partial r} \tag{5}$$

To further simplify the equation, let:

$$\tau = \frac{At}{R\alpha^2} = \frac{Q}{2\pi b\phi}\frac{t}{R\alpha^2} \tag{6}$$

where τ is nondimensional time variable that is a function of both time (t) and flux (Q), along with several material constants that have been defined above.

Substituting Equation 6 into Equation 5 gives:

$$\frac{\partial c}{\partial \tau} = \frac{1}{r}\frac{\partial^2 c}{\partial r^2} - \frac{1}{r}\frac{\partial c}{\partial r} \tag{7}$$

The solution to Equation 7 can be found by using the Laplace transform technique. The application of the Laplace transform with respect to τ (5) yields the following result:

$$\frac{1}{r}\frac{d^2\bar{c}}{d r^2} - \frac{1}{r}\frac{d\bar{c}}{dr} - S\bar{c} = 0 \tag{8}$$

where $\bar{c}$ is the concentration in Laplace space and s is the Laplace variable; the other variables are as defined above.

Equation 8 is of the general form:

$$\frac{1}{r}\frac{d^2\bar{c}}{d r^2} - \frac{a}{r}\frac{d\bar{c}}{dr} - S\bar{c} = 0 \;\; with \;\; a = 1 \tag{9}$$

Solving this general equation gives a general solution of the form:

$$\bar{c}(r) = c_1 e^{ar/2} Ai\left((r + \frac{a^2}{4s})S^{1/3}\right) + c_2 e^{ar/2} Bi\left((r + \frac{a^2}{4s})S^{1/3}\right) \tag{10}$$

where *Ai* is an Airy function of the first kind, or Ai(z), and *Bi* is an Airy function of the second kind or Bi(z), called Bairy (6). Airy functions of the first and second kind, Airy and Bairy, respectively, are Bessel functions of order one-third.

The constants c_1 and c_2 can be determined from the boundary conditions applied to this problem. One boundary condition for this problem states that as the radial distance approaches infinity, $\bar{c}$ approaches zero. Also as r approaches infinity, Bi(r) approaches infinity - therefore, by inspection, c_2 equals 0 and the second part of the Equation 10 can be ignored. Thus:

$$\bar{c} = c_1 e^{ar/2} Ai\left((r + \frac{a^2}{4s})S^{1/3}\right) \tag{11}$$

The second constant, c_1, can be defined by using the boundary condition at the well bore, the step-function source, which in real space is a Heavyside function. As r approaches 0, the step-function source boundary condition transformed into Laplace space appears as:

$$\bar{c} = \frac{\left(1 - e^{-\Delta\tau s}\right)}{S} \tag{12}$$

Setting $r = 0$ and using Equations 11 and 12:

$$c_1 = \left(\frac{1 - e^{-\Delta\tau s}}{S}\right)\frac{1}{Ai\left(\frac{a^2}{4S}S^{\frac{1}{3}}\right)} \tag{13}$$

On the basis of Equations 11 and 13, the full Laplace space solution can thus be written:

$$\bar{c} = \left(\frac{1 - e^{-\Delta\tau s}}{S} \right) \frac{1}{Ai\left((\frac{a^2}{4s}) S^{1/3} \right)} e^{ar/2} Ai\left((r + \frac{a^2}{4S}) S^{1/3} \right) \quad \textbf{(14)}$$

Numerical Inversion of the Governing Equations

Because analytical inversion of Laplace space equations back to real time and space can be extremely difficult, a number of numerical methods have been developed to calculate these inverses (real time and space solutions) (7). Of these methods, the Stehfest algorithm (8,9) is one of the best known; however, in the presence of sharp amplitude discontinuities (such as those that occur with a step-function source term), this method produces spurious results (7)

Much better computational accuracy can be obtained by using the real portion of a Fourier series to invert the Laplace space solution (10). This method is particularly well-suited for functions that have abrupt amplitude transitions. An improved version of this method was developed by Crump (11), who incorporated both the real and the imaginary terms of a Fourier series in the inversion process as follows:

$$f(t) = \frac{e^{ct}}{2T_m} \left(\left\{ \frac{1}{2} F(c) + \sum_{k=1}^{\infty} \left[\operatorname{Re} F\left(c + \frac{K\pi i}{2T_m} \right) \cos\left(\frac{K\pi t}{2T_m} \right) - \operatorname{Im} F\left(c + \frac{K\pi i}{2T_m} \right) \sin\left(\frac{K\pi t}{2T_m} \right) \right] \right\} \right) \quad \textbf{(15)}$$

where *f(t)* is the concentration as a function of *t* and *Z*, T_m is the maximum time of the calculation, *F(c)* is the Laplace space solution as a function of *c*, *Re* is the real part of the complex function, *Im* is the imaginary part of the complex function, and *c* equals $5/T_m$.

To implement Equation 14 in the form of Equation 15, *f(c)* is required. On the basis of the above equations, *f(c)* is:

$$f(c) = \left(\frac{1 - e^{-\Delta\tau c}}{c} \right) \frac{1}{A_i\left((\frac{1}{4c}) c^{1/3} \right)} e^{ar/2} A_i\left((r + \frac{1}{4c}) c^{1/3} \right) \quad \textbf{(16)}$$

Crump's algorithm also requires *f(c + di)* where *i* is the square root of -1. This expression can be written as:

$$f(c + di) = \frac{1 - e^{-\Delta\tau(c+di)}}{c + di} \frac{1}{A_i\left((\frac{1}{4(c + di)} (c + di)^{1/3} \right)} e^{ar/2} A_i\left((r + \frac{1}{4(c + di)} (e + di\ )^{1/3} \right) \quad \textbf{(17)}$$

Equation 17 can be rationalized to:

$$f(c+di)=\left(\frac{c-di}{c^2+d^2}\right)\frac{(1-e^{-\Delta\tau c}[\cos\Delta\tau d-i\sin\Delta\tau d])e^{ar/2}\,A_i\left(r+\frac{c}{4(c^2+d^2)}-\frac{di}{4(c^2+d^2)}\right)(c+di)^{1/3}}{A_i\left(\frac{c}{4(c^2+d^2)}-\frac{di}{4(c^2+d^2)}(c+di)^{1/3}\right)} \quad \textbf{(18)}$$

Equations 16 and 17 were cast into the form of Equation 15 in a FORTRAN program that was used to numerically invert the Laplace space solution back to real time and space for analysis of the NORM injection problem.

Case Study

BPF Incorporated is currently demonstrating a new technology for the treatment and disposal of NORM scales at petroleum production sites. The technology involves methods for handling, sorting, and dissolving NORM scales at a production site. The resulting NORM-containing solute is then disposed of in nearby brine disposal wells. As part of this technology demonstration, a simple mixing model was used to estimate the maximum concentration of radionuclides at various distances from the wells for a specific site in west Texas.

This case study details the injection site, which is typical for the west Texas region, presents the results of applying this analytical model, and compares these results to a simple mixing model that is described below.

Site Description

The demonstration site is located in Reeves County, Texas, in an area known as the Delaware Basin. The Delaware Basin, which includes all of Reeves County, Texas, is in western Texas and southeastern New Mexico. It covers an area of about 12,000 square miles and forms one of the larger subdivisions of the Permian Basin. It includes the area within the Capitan reef complex, which is of late Permian age; the narrow belt of older and deeper-lying sands in the back reef area; and the reef itself.

The reservoir at the demonstration site occurs near the very top of the Bell Canyon Formation, which is part of the Delaware Mountain group (12). It is above the Cherry Canyon Formation. The brine disposal wells are screened to inject fluids into the Cherry Canyon Formation, which consists of sands and interbedded sandstones and is also part of the Delaware Mountain group. The Bell Canyon consists of fine sands interbedded with hard limy shale. Above the Delaware Mountain group is the Ochoan series of evaporites of late Permian age.

The receiving formation for the brine disposal wells that will be used for NORM injection is the Cherry Canyon Sands, which are part of the Cherry Canyon Formation. Injection will occur at a depth of approximately 4,000 ft below the surface. The Cherry Canyon Sands are hydrogelogically isolated from the shallow surface aquifers by the Bell Canyon Formation, the reservoir rock for this field, and the Ochoan group of evaporites.

The evaporites of the Ochoan group form effective barriers to upward migration of disposed brine or radionuclides. In addition, the Bell Canyon group has a demonstrated ability to trap oil and gas, indicating it is an effective barrier to the heavier brine and radionuclide solutions.

Usable groundwater in the northern part of Reeves County is isolated from the receiving formation and occurs in the Cenozoic Alluvium and Santa Rosa aquifers. The top of the Rustler Formation is generally regarded as the limit of potable water (13) because of the high salt and solids content of water produced from deeper formations. Near the study area, only the Cenozoic Alluvium aquifers produce usable water, and even this water is marginal and not suitable for human consumption. Ogilbee et al. (14) states that groundwater in the northern section of Reeves county is unsuitable for humans, although it is used for livestock. Groundwater wells in this area range from 50 to 320 ft deep, and the groundwater surface is located between 10 to 150 ft below the ground surface

NORM Disposal

For the demonstration, 2,100 gal of solution containing NORM having an activity level of 40,000 to 80,000 *p*Ci/L will be injected. The well injects brine into the Cherry Canyon Sands at a depth of approximately 4,000 ft at a maximum rate of 753,000 gal/d into a formation approximately 100 ft thick.

Water analysis from the well, which is representative of the Cherry Canyon Formation yielded the following information: 40 mg/L barium (Ba), 4,500 mg/L calcium (Ca), 1,300 mg/L magnesium (Mg), 300 mg/L strontium (Sr), 29,000 mg/L sodium (Na) (calculated), 1.7 mg/L iron (Fe), 295 mg/L HCO_3, no carbonate (CO_3) detected, no sulfur (S) detected, 1,280 mg/L SO_4, 52,300 mg/L chloride (Cl), < 109 *p*Ci/L Ra-226, and 122 *p*Ci/L Ra-228.

Simple Mixing Model

When water is injected into a well, the injected water miscibly displaces the connate water. Mechanical mixing occurs at the boundary between the two liquids as a result of dispersion and diffusion. In most injection operations, dispersion is the predominant cause of mixing because of the high velocities close to the well bore. As the water moves away from the injection zone, diffusion can play a larger role. As the injection water and the connate water mix, dilution of the injection water occurs. This dilution can be calculated by using the following equations.

The width of the mixing zone w and the volume of the mixing zone V_m are:

$$w = 4.62\sqrt{D'r} \qquad \text{and} \qquad V_m = 29h\phi\sqrt{D'r^3} \qquad \textbf{(19)}$$

where D is the coefficient of dispersion, r is the radial distance from the wellbore to the center of the mixing zone, h is the thickness of the injection zone, and ϕ is the porosity of the reservoir rock, expressed as a fraction.

When no mixing of the NORM solution is assumed to occur during the injection, dilution ratios can be calculated as follows:

$$\frac{C}{C_0} = \frac{V_i}{V_M} \qquad \textbf{(20)}$$

where V_i is the initial volume of the injected NORM, C is the current concentration, and C_0 is the initial concentration at time 0.

Results and Comparison

Table 1 details the various dilution ratios for injection of 7.95 m^3 (2,100 gal) of NORM at radial distances of 100, 500, 1,000, and 5,000 m. No retardation was used in these scenarios. The mixing model does not take into account either the brine injection rate or the rate at which the NORM-containing solution is injected. Two solutions are given for the step-function source model. In both cases, the brine injection rate is 3.3×10^{-2} m^3/s (753,000 gal/d). In the first case (injection time of four minutes) the NORM solution is injected at the same rate as the brine and is not diluted during the injection process. This means that for four minutes, NORM solution is injected, after which brine injection resumes. The second case assumes that the NORM-containing liquid is mixed with the brine in a ratio of 9:1 of brine to NORM, this lengthens the injection time by a factor of 10 but reduces the initial concentration by the same amount. This type of injection is commonly called slip-streaming. This column can also be used to illustrate the usefulness of nondimensionalized equations. The same solution, a maximum C/C_0 of 2.9×10^{-5} 500 m from the injection well, can be used to evaluate the injection of 21,000 gal (approximately 500 bbl) of 80,000 *p*Ci/L NORM. In this case the maximum activity in the subsurface at a distance of 500 meters from the well bore would be 2.3*p*Ci/L.

Because of a term of the form $e^{f(r)}$ in the equations, the model cannot be used for nondimensionalized r values greater than about 100, which for a dispersion value of 10 m represents a distance from the well bore of 1,000 m. However, as can be seen, for the volumes and activities of NORM expected at production sites, subsurface activities are well below levels of concern at distances less than 1,000 m, so the model can be used effectively for studying NORM injection scenarios.

The table illustrates that for distances close to the well bore (100 m), the simple mixing model underestimates the maximum activity of the injected NORM, while at greater distances from the well bore, it greatly overestimates the activity of the NORM plume. In this case, for distances of more than 500 m, the values provided by the simple mixing model are conservative, providing estimated activities higher than those predicted by the analytical solution.

Once the released NORM has traveled 100 m, activities are below 5 *p*Ci/L, which is the current level being considered by the EPA as a drinking water standard (3). In addition, the NORM solution will mix with the injected brine, creating even higher dilution ratios than those tabulated above.

Conclusions

This paper presented an analytical solution to a model of radial injection with a step-function contaminant source. Because of the current FORTRAN implementation, the model can only compute contamination values to a nondimensionalized distance of 100, which, for a dispersion value of 10 m, maps to a distance of 1,000 m from the injection well bore. At this distance, the activity of the injected NORM is only 1 billionth (1×10^{-9}) of its original activity for a 2,100 gal volume of NORM waste (which is approximately 50 barrels). A second case was run with an injected volume of ten times the original volume (21,000 gal or 500 bbl), which resulted in an activity of 1/100 millionth (1×10^{-8}) of its initial activity 1,000 m from the injection well. Table 1 assumed that this large volume was achieved by mixing the existing NORM waste from the demonstration project with injected brine to lower the source activity.

Since this model was castStarting Dictation... in a nondimensional form, a single solution can be used to study a number of different injection scenarios. As was shown above, the solution for the injection of 500 bbl of 8,000 *p*Ci/L NORM can also be used for an injection of 500 barrels of 80,000 *p*Ci/L NORM. Even this large volume of NORM results in maximum activity levels 1,000 m from the injection well below the current levels suggested by the U.S. Environmental Protection Agency.

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Table 1. Model results at various distances for the two models. Shown are the dilution ratios and the final maximum activity at a distance from the well bore.

Distance from Well Bore (m)	Mixing Model 2,100 gal. of 80,000 *p*Cl/L NORM		Step-Function Source Model 2,100 gal. of 80,000 *p*Ci/L NORM			
			80,000 *pCl/L* over 4 min		8,000 *pCi/L* over 40 min	
	C/C_o	*pCi/L*	C/C_o	*pCi/L*	C/C_o	*pCi/L*
100	1.4 x 10^{-5}	1.1	3.6 x 10^{-5}	2.9	3.6 x 10^{-4}	2.9
500	1.3 x 10^{-6}	0.1	2.9 x 10^{-6}	0.23	2.9 x 10^{-5}	0.23
1,000	4.5 x 10^{-7}	0.036	1.1 x 10^{-9}	8.8 x 10^{-5}	6.2 x 10^{-9}	5.0 x 10^{-5}
5,000	4.0 x 10^{-8}	0.0032	Could not calculate		Could not calculate	

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