한국지하수토양환경학회 춘계학술대회
2002년 4월 12-13일 서울시립 대학교

Partitioning Interwell Tracer Test for NAPL Source Characterization: A General Overview

Tony R. Lee · A. Lynn Wood · Seung-Woo Jeong*
U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Subsurface Protection and Remediation Division.
** National Research Council Research Associate (Jeong.Seung-Woo@epa.gov)*

ABSTRACT

Innovative and nondestructive characterization techniques have been developed to locate and quantify nonaqueous phase liquids (NAPLs) in the vadose and saturated zones in the subsurface environment. One such technique is the partitioning interwell tracer test (PITT). The PITT is a simultaneous displacement of partitioning and non-partitioning tracers through a subsurface formation. Partitioning tracers will partition into the NAPL during their transport through NAPL-contaminated formations. Mean travel times of partitioning and non-partitioning tracers are used to estimate the quantity of NAPL encountered by the displaced tracer pulse. Travel times are directly proportional to the partitioning coefficient and the volume of NAPL contacted in the subsurface environment. This paper discusses the conceptual background, design and implementation of PITTs. (This document has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.)

Key words: nonaqueous phase liquid (NAPL), remediation, groundwater, partitioning interwell tracer test (PITT)

1. Introduction

Soil and groundwater contamination by hazardous organic chemicals raise concerns about risks to humans and the environment. Many contaminated sites have zones which contain non-aqueous phase liquids (NAPLs). These highly contaminated zones are referred to as source zones because they provide a long-term source of dissolved phase contaminants that feed and maintain down gradient plumes. Knowledge of the occurrence and distribution of these NAPLs is important for estimating risks and for designing remediation programs. The partitioning tracer test is a minimally invasive method that has been proposed and used for quantifying NAPL within a source zone [1-4].

2. Conceptual Background

Partitioning is used here to denote the distribution of tracers between water and a non-aqueous phase liquid (NAPL). The linear form of this partitioning relationship is

$$K_{NW} = C_N / C_W \quad (1)$$

whrer K_{NW} is the tracer partitioning coefficient between the NAPL (N) and aqueous phase (W), C_N is the concentration of the tracer in the NAPL phase, C_W is the concentration of tracer in the aqueous phase. If a suite of tracers having a range of K_{NW} is displaced through a porous medium containing NAPL, the rate of transport will be inversely proportional to the K_{NW} and NAPL saturation, S_N. Conservative tracers (K_{NW}= 0) do not partition into the NAPL phase and will move unretarded through the formation. The degree of retardation of the partitioning tracers is given by

$$R = 1 + (K_{NW} S_N)/ (1- S_N) = t_p / t_n \quad (2)$$

where R is the retardation factor of the tracer; t_p and t_n are the mean travel times of the partitioning and non-partitioning tracer pulses, respectively.

Equation (2) forms the basis for estimation of the NAPL content of a formation swept by tracers. The mean travel times are typically determined by moment analysis of tracer breakthrough curves (BTC). The NAPL saturation for the swept volume is determined using [1].

$$S_{N,i} = (t_{pi} - t_{n,i})/[t_{pi} - t_{n,i} (K_{Nw} - 1)] \quad (3)$$

Thus, a partitioning tracer test provides a spatially integrated estimate of the NAPL residual saturation within the volume of formation swept by the tracers.

3. Partitioning Tracer Test Implementation Design Implementation

3.1 Selection of Tracers

Jin [1] suggested that partitioning tracers should have a retardation factor (R) between the recommended range of $R \geq 1.2$, and $R \leq 4$. An injected tracer suite typically includes both a non-partitioning (conservative) and partitioning tracers. The conservative tracers provide information about the mean travel of the mobile-phase. Partitioning tracers should have K_{NW} values that permit reliable resolution of breakthrough curves and estimation of R. Because R depends on both K_{NW} and S_N and the S_N value is unknown, a suite of tracers having a range of K_{NW} is recommended (Table 1). Other characteristics of desirable tracers include 1) nontoxic; 2) low volatility; 3) non-hazardous; 4) non-degrading; 5) moderate costs and availability of tracers; and 6) tracers that can be quantified easily in the presence of various NAPL constituents. Samples collected periodically from extraction wells are monitored for the tracer concentration and mean travel times are determined from the resulting breakthrough curves. Differences in mean travel times of partitioning and non-partitioning tracers are used to estimate the volume of NAPL with the swept volume [5].

Tracers selected for the PITT should be evaluated for degradation and sorption properties that could interfere with the PITT efficiency and effectiveness. A suite of tracers with minimal degradation should be selected. Tracer sorption to sedimentary organic carbon or mineral surfaces will increase retardation and can cause NAPL saturation to be overestimated especially when NAPL saturation is low [6].

Table 1: Example of some tracers and their partitioning coefficients [7]

Tracer Name	Abbreviation	Partitioning Coefficient (Volume Ratio)
Bromide		0
2-Propanol	IPA	0
3-methyl-3-pentanol	3M3P	4.5
1-hexanol		18.6
2,4-dimethyl-3-pentanol	2,4DM3P	38.2
1-heptanol		163.1
1-octanol		389

3.2 Injection/Extraction Well Design

By definition, PITTs incorporate 1 or more injection well(s) and 1 or more extraction well(s) [1, 2, 8]. During the PITT, a tracer suite is injected through the injection well(s), displaced through the formation and extracted at recovery wells. Injection and extraction flow rates are balanced to maintain constant swept volume. Field applications of PITTs have used a variety of well configurations and flow patterns. For example, the following well configurations have been used for tracer tests conducted at the Dover National Test Site: 1) double five spot, 2) inverted double five spot, 3) line drive, and 4) multiple vertical circulation wells. The multiple vertical circulation pattern was used to promote predominantly vertical flow through the formation.

Flow rates should be used that permit near-equilibrium partitioning of tracers between the fluid phases. The tracer solution is mechanically mixed and then pumped into the injection well(s) and extracted from the extraction well(s) under a constant flow rate. Fluid fluxes are required for determination of swept pore volumes. Thus, flow rates should be carefully monitored. The volume of the injected tracer pulse and the concentrations of the tracers in this pulse are important factors in the design of a PITT. The shape and magnitude of tracer BTCs will be a function of these factors.

3.3 Tracer Breakthrough Curve Monitoring

Extraction Well samples should be taken throughout the PITT experiment and injection well samples taken during the tracer pulse injection. Sampling intervals should be selected that will ensure good resolution of tracer breakthrough curves. Thus, appropriate sampling frequencies will be dependent on the rate of change of tracer concentrations. Tracer concentrations and fluid fluxes from extraction wells are measured throughout the test. For formations containing non-uniform distribution of NAPL, partitioning tracer retardation is often exhibited in the tail of the breakthrough curve. Thus, it is important to define as much of the breakthrough curve tail as possible. In addition, multi level samplers and/or monitoring wells can be added if more detail of the spatial distribution is required.

3.4 Data Interpretation

Although several methods can be used to establish R (retardation factor) from tracer breakthrough curves, moment analysis is the most common and straightforward approach. The zero-th and first temporal moments provide information on tracer mass recovery and mean travel times of the tracers. The data can then be used to estimate the average NAPL saturation and the total NAPL volume within the swept zone of interest.

4. References

[1] Jin. M., M. Delshad, V. Dwarakanath, D.C. McKinney, G.A. Pope, K. Sepehrnoori, C. Tilburg, and R.E. Jackson. *Partitioning* Tracer Test for Detection, Estimation and Remediation Performance Assessment of Subsurface Nonaqueous Phase Liquids. *Water Resour.Res.,* 31(5), p. 1201-1211, 1995.

[2] Annable, M.D., Rao, P.S.C., Hatfield, K.H., Graham, W.D., Wood, A.L., Enfield, C.G., 1998. Partitioning tracers for measuring residual NAPL: Field-scale test results. *J. Envir. Eng. ASCE* 124(6), 498-503, 1998.

[3] Nelson, N.T., Brusseau, M.L. Field study of the partitioning tracer method for detection of dense nonaqueous phase liquid in a trichloroethene-contaminated aquifer. *Envir. Sci. Tech.,* 30(9), 2859-2863, 1996.

[4] Jawitz, J.W., Sillan, R.K., Annable, M.D., Rao, P.S.C., Warner, K. In-situ alcohol flushing of a DNAPL source zone at a dry cleaner site. *Envir. Sci. Tech.,* 34(17), 3722-3729, 2000.

[5] Jin, M., R.E. Jackson, G.A. Pope, and S. Taffinder, Development of partitioning tracer tests for characterization of non-aqueous phase liquid-contaminated aquifers SPE 39293. *In Proceedings of SPE 72nd Annual Technical Conference,* Richardson, Texas, Sep. 19-30, 1997

[6] Edgar, J.R., Laboratory evaluation of partitioning tracers. M.S. Thesis, Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, 1997.

[7] Young, C.M.; Jackson, R.E.; Jin, M.; Londergan, J.T.; Mariner, P.E.; Pope, G.A.; Anderson, F.J.; Houk, T. Characterization of a TCE DNAPL Zone in Alluvium by Partitioning Tracers *GWMR,winter issue,* pp. 84-94, 1999.

[8] Pope, G.A., Jackson, R.E., Characterization of organic contaminants and assessment of remediation performance in subsurface formations. U.S. Patent 6,003,365, U.S. Patent Office, Washington, D.C., 1999.