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In-Situ Vertical Circulation
Column: Containment System For
Small Scale DNAPL Field Experiments

BY:

D. Sorel, J. A. Cherry, S. Lesage

NWRI Contribution No. 97-118

***IN-SITU* VERTICAL CIRCULATION COLUMN: CONTAINMENT SYSTEM FOR SMALL SCALE DNAPL FIELD EXPERIMENTS**

BY

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SUBMITTED TO

GROUND WATER MONITORING AND REMEDIATION

JANUARY 1997

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MANAGEMENT PERSPECTIVE

Title: *IN-SITU* VERTICAL CIRCULATION COLUMN: CONTAINMENT SYSTEM FOR SMALL SCALE DNAPL FILED EXPERIMENTS.

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NWRI Publication #: 97 -118

Citation: Submitted for publication in *Ground Water Monitoring and Remediation*.

EC Priority/Issue: This work was part conducted under the Toxics issue. It was a collaborative study between the department of Earth Sciences of the University of Waterloo and the Groundwater Remediation Project of NWRI. The object of the experiment was the development of an *in-situ* method for the treatment of chlorinated solvents present as DNAPL in groundwater.

Current Status: This project describes a new testing apparatus that was developed as part of the field testing of the vitamin B12 technology for the remediation of chlorinated solvents in groundwater. The project is now complete and this paper was extracted out of the M.Sc. thesis of Dominique Sorel, a student that was co-supervised by S. Lesage of NWRI and J.A. Cherry, of the university of Waterloo.

Next Steps: The apparatus is now being used by other groups for testing. The method itself is the subject of a patent and the field test will be published shortly in a separate article.

Abstract

The In-Situ Vertical Circulation Column (ISVCC) is a cylindrical containment system consisting of an instrumented steel cylinder used for experimental groundwater studies in sandy aquifers. Vertical flow is imposed inside the ISVCC. Although vertical wells are an option, the ISVCC installed in the Borden aquifer is instrumented with horizontal wells and monitoring ports to avoid creating vertical preferential flow paths in the vertical flow system. The cylinder was driven downward into the aquifer using a small backhoe equipped with a vibrating plate. The ISVCC penetrates the 2.3m thick sand aquifer and is keyed 20 cm into the underlying clay aquitard. The cylinder was installed inside a 2m x 2m steel sheet pile enclosure so that the enclosed segment of aquifer could be conveniently dewatered and then excavated to allow installation of the horizontal wells. The dispersivity of the column was found to be small, similar to literature values for long sand packed laboratory columns. Pure phase DNAPL (tetrachloroethene and 1,1,1-trichloroethane) was slowly pumped into two ports in the center of the column. After, an aqueous solution of vitamin B₁₂ and reduced titanium was circulated through the column to promote degradation of the solvents. Processes observed in the ISVCC include: 1) DNAPL distribution, dissolution and degradation; 2) geochemical evolution of the aquifer and 3) microbiological activity. The ISVCC provides a convenient means for testing *in-situ* technologies in the experimental stage or a selection of proven technologies to find the most effective at a specific site. It is inexpensive, easy to install and maximizes control over flow distribution in a heterogeneous aquifer. Its application will be restricted where low hydraulic conductivity beds are present in the aquifer. Larger diameter versions of the ISVCC would make radial flow experiments possible, which would have advantage in aquifers with strong horizontal bedding or in situations where it is necessary to install vertical wells and monitors.

Introduction

A variety of innovative technologies are currently being developed to address groundwater contamination problems. Before these technologies become commercially applicable at contaminated sites, they should be assessed through several evaluation stages. Cherry et al. (1996) identifies a sequence of four stages: 1) the laboratory experimental stage where initial concepts are tested in simple form; 2) the field experimental stage where small-scale field tests serve to identify problems due to field conditions and potential limitations at an early stage; 3) the emerging stage where pilot-scale and large-site trials are conducted testing the most promising versions of the technology and 4) the proven stage where a technology is commercially available after being successful through the preceding steps. At the early experimental stage, in addition to preliminary laboratory experiments, much can be learned about a technology by conducting very small-scale field trials where temperature, pressure, residence time, heterogeneity, geochemical and microbial conditions are much more representative of field site conditions than can be accomplished in the laboratory.

DNAPLs are a common cause of groundwater contamination but are particularly difficult to remediate. The effectiveness of field trials at actual DNAPL sites is limited by lack of reliable information on the exact location and mass of DNAPL in the groundwater zone. Simple and environmentally secure systems that contain DNAPL are therefore needed for field tests of remediation technologies. Many innovative technologies for DNAPL site remediation involve *in-situ* chemical treatments that are flushed through the aquifer, such as alcohol, surfactants or chemical oxidants. When testing these technologies in the field, it is necessary to contain securely the DNAPL, the treatment chemicals and the reaction

products. It is also generally more appropriate to inject the DNAPL into the formation instead of emplacing the DNAPL by excavating. Injection provides more information about DNAPL migration and dissolution, which can influence the performance of the technology being tested. The ideal small-scale field test method should be inexpensive, rapidly installed, represent many aspects of the "undisturbed" field conditions and present good mass balance prospects. Also, it should provide environmental safety, low cost of maintenance and post experimental cleanup and should be versatile in its compatibility with many chemicals and processes. Finally, the method should have a good monitoring network, which requires a variety of sampling ports or in-situ probes. Considering the above requirements, a design using low-permeability enclosures should be suitable to conduct field experiments.

Enclosures constructed of sealable joint sheet pile (SJSP) cells (Starr et al., 1991) constructed of Waterloo Barrier TM have been used extensively to conduct field experiments at Canadian Forces Base Borden, Ontario, Dover Air Force Base, Delaware (Cherry and Smyth, 1996) and Hill Air Force Base, Utah (Annable et al, 1996). In the enclosures, the water and treatment fluids are circulated horizontally from a set of injection wells to a set of extraction wells. Their size is relatively large (aquifer volume of tens to thousands of cubic meters) and they are therefore most suitable for pilot-scale or large site field experiments. At the other end of the size spectrum, Gillham et al. (1990a and 1990b) have developed the In situ Bio/Geochemical Monitor (ISMTM) that can be used to measure biochemical reaction rates and retardation factors for both organic and inorganic solutes. The ISMTM is made of stainless steel cylinder placed inside a split-spoon sampler inserted in the aquifer. Groundwater vertically penetrates the cylinder from the bottom and is extracted at the top through a screened end plate. A depth adjustable spike

placed in the center of the cylinder is used to collect samples. The volume of aquifer contained in the stainless steel cylinder is very small (300 cm³).

The goal of the *In-Situ* Vertical Circulation Column (ISVCC) method presented in this paper (Figure 1a) is to provide a method that facilitates the transition between the laboratory and the field in a manner that maintains important aspects of field conditions but has considerable convenience of design and operation. The volume in the ISVCC ranges approximately from one to ten cubic meters, which fits between the SJSP cells and the In situ Bio/Geochemical Monitor. This volume is large enough to operate at residence times representative of large-scale operations and yet small enough for convenient volumes of contaminant and remedial treatment to be used. The aquifer inside the test column have little disturbance when the column is installed. Flow is established vertically inside the column. Karlson (1993) indicates that although most remediation schemes up to now have been designed for horizontal flow, horizontal well technology is now practical for vertical circulation in many aquifers. Vertical circulation using horizontal wells allows better contact between the remedial treatment and the contaminant, which generally occurs as horizontal plumes or accumulates in horizontal pools. The ISVCC takes advantage, at the experimental stage, of the vertical flow concept in a horizontally stratified porous media. If horizontal circulation is desired, the ISVCC method can be adapted for use in larger columns in which radial flow can be imposed.

This paper describes the ISVCC design options and presents an example of its first use for containment of a DNAPL zone to test an innovative remedial technology in the Borden sandy aquifer. Laboratory column studies showed that a mixture of vitamin B12, as little as 1 mg/L, and titanium citrate pumped through a column containing 100 ml of

immiscible-phase PCE can completely degrade the PCE to ethene in a few days (Lesage and Brown, 1996). These results have prompted the use of the ISVCC to test the feasibility of remediating an aquifer contaminated with tetrachloroethene (PCE) and trichloroethane (1,1,1-TCA) using vitamin B₁₂ and reduced titanium (Sorel, 1996).

Conceptual ISVCC Design and Installation at CFB Borden

The ISVCC can be installed in granular aquifers that are free of large boulders. It can hang in the aquifer or be keyed into an underlying aquitard serving as an impermeable bottom (Figure 1b and c). In situations where no aquitard is present at shallow depths or if the aquitard is not a good enough protection, the injection of a sealant can be performed to provide an increased degree of safety against leaks.

In addition to keying the cylinder into an aquitard or injecting a sealant, control over the hydraulic gradients around the ISVCC can minimize the probability of releasing DNAPL or remedial treatment to the environment. Figure 1d illustrates that a hydraulic gradient directed towards the treatment zone can be created by lowering the water level inside the ISVCC compared to the surrounding aquifer. If the water table of the aquifer is relatively low and an inward gradient has to be maintained, a significant portion of the aquifer inside the ISVCC could go unused. The addition of an outer enclosure (sealable sheet-pile or large cylinder) would help to artificially raise the water table around the ISVCC and create an inward gradient while using most of the portion of aquifer inside the ISVCC (Figure 1e).

Sampling ports, injection and withdrawal wells, probes for measuring temperature, pressure and other parameters can be installed either vertically or horizontally in the

ISVCC. The design of the wells and sampling ports should facilitate maintenance during the experiment. The simplest way of instrumenting the ISVCC uses vertical wells and ports however, preferential flow pathways could form during vertical flow. To avoid potential vertical pathways, horizontal wells and sampling ports or probes can be installed but this requires addition of a major step in the implementation process. The exterior of the column must be exposed and perforated after the cylinder is driven into the aquifer. In the case of a saturated aquifer, it is necessary to dewater the zone around the cylinder before excavation. Dewatering can be performed by continuously operating pumps to bring the water table below the depth of excavation (Figure 2a) or an outside enclosure can be built (Figure 2b). With the outer enclosure in place, only a small segment of aquifer is excavated because the enclosure, properly installed and braced, can support an excavation with vertical walls. If it is preferred to leave the excavation open during the experiment, a large steel cylinder or an enclosure constructed of sealable joint sheet piles (Starr et al., 1991) are more appropriate than standard sheet piles to minimise groundwater flow or caving of aquifer material into the opening.

Considerations for choosing the type of cylinder are: size, strength, chemical compatibility and cost. Cylinders made of polyvinylchloride (PVC), regular steel or stainless steel, are readily available. When testing a technology involving chemicals such as chlorinated solvents, cylinders made of non-reactive material, like stainless can offer technical advantages. However, they are relatively expensive and sensitive to corrosion if damaged during the installation. Regular steel cylinders are inexpensive and strong enough to be driven to adequate depth into aquifers.

The Borden site presented an ideal geologic setting for the installation of an ISVCC. The 2.5m thick aquifer is composed of fine sand with an underlying clay aquitard. A regular steel cylinder, with a 12 mm wall thickness, 3.3m long and a 76 cm diameter, was used. For installation of horizontal monitoring ports and wells, an outer enclosure was required. A standard L60 sheet pile cell was built and the cylinder was vibrated into the cell using a small backhoe equipped with a vibrating plate.

Figure 3 shows the layout of the ISVCC installed at Borden. The injection and extraction wells were made of 6.4 mm diameter stainless steel tube perforated and wrapped by stainless steel screen on 200 mm. Four sampling levels were evenly distributed between the wells. On each level, four 3.2 mm diameter stainless steel tubes terminated by stainless steel porous cups (25mm long, 40 μ m pore size) allowed discrete sampling in the middle of each sampling level, 20 cm and 10 cm radially away from the wall (Figure 4). An additional sampling port was located below the injection well. Finally a 3.2mm diameter stainless steel contaminant injection well was installed 1.52m above the aquitard. A total of 17 sampling ports were installed in the 0.97 m³ volume of aquifer representing a sampling density of 1/0.054 m³.

Figures 5 illustrates some of the ISVCC installation steps. Prior to driving the steel cylinder into the subsurface, the cylinder walls were drilled, threaded and temporarily plugged where the monitoring and injection ports would be installed. The column was keyed in the clay aquitard on 20 cm. After dewatering the aquifer segment between the sheet pile enclosure and the cylinder, the aquifer segment was excavated around the cylinder down to the clay aquitard (Figure 5 c) to allow the installation of the injection and monitoring equipment. Each port or well in the column was put in an undisturbed and

saturated sand and sealed through the column wall using Swagelock™ fittings (Figure 4). The wells and ports installation steps are described on Figure 6. The ISVCC installation was completed in two days, including building the sheet pile outer enclosure, drilling holes in the cylinder for the ports and wells installation, overnight dewatering, driving the cylinder into the aquifer, excavation, and ports and wells installation. Sorel (1996) provides a more detailed description of the equipment requirements and installation procedure.

Bottom Leakage Determination

After the installation of the ISVCC but before proceeding to an experiment involving the degradation of hazardous chemicals, the hydraulic conductivity of the clay aquitard at the bottom of the cylinder was measured to evaluate leakage. A hydraulic conductivity of $1.6 \times 10^{-5} \text{ cm/s}$ (1.40 cm/d) was obtained, which is high compared to $5.8 \times 10^{-7} \text{ cm/s}$ (0.05 cm/d) obtained by Brown (1993), who conducted similar measurements approximately 5 m away from the ISVCC test site. Visual inspection of all the monitoring ports and wells showed that no leakage was occurring through the sealing fittings. The cylinder may be keyed only into a transition zone, which has higher hydraulic conductivity than the clay aquitard (Foley, 1992). Because the experiment was to be operated in an upward flow mode with the injection well located 50 cm above the aquitard contact, small leakage out of the bottom of the cylinder was not an impediment to the experiments.

Tracer Test

A tracer test was conducted to assess the solute transport characteristics of the aquifer segment inside the ISVCC, to verify the integrity of the injection/extraction wells and monitoring equipment and finally to determine whether short circuiting occurs due to

any disturbance caused by the column emplacement. The breakthrough of a pulse of sodium bromide (NaBr) amended groundwater was monitored through two sampling ports on each of the four sampling levels, at the extraction well and at the single sampling port below the injection well (Figure 7). No bromide breakthrough was detected below the injection well.

Mackay et al. (1986) has shown that bromide performs well as a non-reactive tracer in the Borden aquifer. Background concentrations are very low and it was convenient for on-site analyses. Bromide was selected over chloride because it would not interfere with the chloride mass balance used to monitor the degradation of chlorinated solvents during the experiment. Oostrom et al. (1992) found density effects at NaBr concentration as small as 1100 mg-Br/L ($\Delta\rho/\rho_0 = 1.4 \times 10^{-3}$) and Schincariol and Schwartz (1990) reported similar effects at 620 mg-Br/L ($\Delta\rho/\rho_0 = 8 \times 10^{-4}$) in a horizontal flow regime. A 500 mg-Br/L injection concentration was chosen to avoid density effects and to provide a suitable range for analysis. A flowrate of 180 ml/min provided a residence time of approximately one day in the column. It was chosen empirically based on the capacity of the pumps, the hydraulic gradient and the approximate breakthrough time at the different monitoring ports. The volume of the tracer pulse was 125 L, which is half a column pore volume. This provided a pulse long enough to observe a peak concentration plateau at each of the monitor ports. Breakthrough of the tracer was monitored for 70 hours. At each level, the monitoring ports located in the center and at 10cm from the column wall were sampled to identify any disturbance caused by the installation of the column. As many as nine 20 mL samples were collected simultaneously in polyethylene screw cap bottles using a vacuum manifold connected to each stainless steel sampling port. The samples collected

were analyzed on-site using an ion specific electrode in an air-conditioned trailer to minimize temperature variations ($T=23^{\circ}\text{C}$).

Modeling of the breakthrough concentrations was done with the program Wplusepe (Devlin, 1994 and 1996) solving a one-dimensional analytical solution of the advection-dispersion equation (Sudicky and Cherry, 1979):

$$C(x,t) = \frac{C_0}{2} \left[\operatorname{erfc} \left(\frac{x - \bar{v}t}{2\sqrt{Dt}} \right) - \operatorname{erfc} \left(\frac{x + w - \bar{v}t}{2\sqrt{Dt - w/v}} \right) \right]$$

Equation 1

where $C(x,t)$ is the solute concentration $[\text{M}/\text{L}^3]$, C_0 is the injection concentration $[\text{M}/\text{L}^3]$, x is the distance between the center of the injection well and the sampling point, w is the source width for a conservative substance $[\text{L}]$, \bar{v} is the average linear groundwater velocity $[\text{L}/\text{T}]$, D is the coefficient of hydrodynamic dispersion $[\text{L}^2/\text{T}]$ equal to $\alpha_l \bar{v} + D^*$ where α_l is the longitudinal dispersivity $[\text{L}]$ and D^* is the diffusion coefficient $[\text{L}^2/\text{T}]$. The boundary conditions are $C(0,t) = C_0$ for $t < t_0$, $C(0,t) = 0$ for $t > t_0$, $C(\infty,t) = 0$, $C(x,0) = 0$.

The velocities are in a narrow range with an average value of $2.3 \times 10^{-3} \text{ cm/s}$ except for a higher value measured at sampling port 1D7 located 20 cm directly above the injection well. Using a porosity of 0.33, which was measured by Freyberg (1986) for Borden sand and applying the measured gradient of 0.92, a hydraulic conductivity value of $8.3 \times 10^{-4} \text{ cm/s}$ (0.72 m/d) is obtained. Nwankwor (1985) measured a ratio of vertical to

horizontal hydraulic conductivity in Borden sand of 0.64. This ratio applied to the horizontal hydraulic conductivity reported by Brown (1993) for the site (1.5 to 6×10^{-3} cm/s) gives a vertical hydraulic conductivity range of 1.0 to 3.8×10^{-3} cm/s, which is slightly higher than the value obtained during this experiment.

The dispersivities are in the mm to cm range with an average value of 0.9 mm (Table 1). Sampling ports 2A5 and 2D1 provided relatively high dispersivities. The largest dispersivity value measured at the extraction well can be explained by a larger integration of concentrations over the length of the screen, which is 20 cm long compared to about 2 cm for the monitoring ports (Figure 8a).

Klotz and Moser (1974) conducted a very careful laboratory study of dispersion in long columns (length from 500 mm to 4000 mm and diameter from 10 to 290 mm) packed with quartz sand of various grain size and distribution. They report a dispersion coefficient of 5×10^{-8} m²/s for a quartz sand uniformly packed to a porosity of 0.38 (effective grain diameter 0.75 mm) at 20°C. They also show that dispersivity decreases with decreasing temperature. Using the velocity and the dispersivity obtained in the present experiment, a longitudinal dispersion coefficient of 2×10^{-8} m²/s was calculated for a 10°C groundwater temperature. This result agrees closely with Klotz and Moser values, considering that the lower fluid temperature decreases the dispersivity.

The different breakthrough times (Table 2) between the ports A, at the edge of the column, and D, in the center, at each level can be explained by 1) a longer path length between the injection well and port A compared to port D; 2) compaction along the cylinder wall induced when the column was vibrated in the aquifer and 3) by natural

heterogeneities of the porous media (Figure 9). The path length from the injection well to 1D7, is shorter than the path from the injection to 1A3 (Figure 8b), which explains the earlier arrival time at 1D7. As the solute travels up in the column and samples more heterogeneities, these heterogeneities take over the effect of different path lengths as seen on level 3 where 3A1 arrives earlier than 3D5 (Figure 7). Also, the early arrival at 3A1 suggests that the natural aquifer heterogeneities dominates over the heterogeneities caused by the installation of the column.

The tracer test showed no significant anomalies in the hydraulic behavior of the column. The low dispersivities measured assure that the monitoring ports allow discrete sampling of the pore water. Finally, the absence of tracer in the monitoring port below the injection well indicated that as long as an upward gradient is maintained in the column, no dissolved phase solvent should migrate down into the aquitard.

DNAPL Distribution

Two hundred milliliters of an equimolar mixture of tetrachloroethene (PCE) and trichloroethane (1,1,1-TCA) were injected into the ISVCC through the injection port located 3 cm above sampling level 3. Another fifty milliliters of the same mixture was added in the middle sampling port on level 1 (1D7). In both cases, the DNAPL was slowly pumped into the formation (≈ 1 ml/min) using a peristaltic pump with solvent-inert tubing. DNAPL release experiments conducted in the Borden aquifer by Broholm et al. (1997) and Truax et al. (1997) have shown that DNAPL distribution, after being injected in the saturated sand, is unpredictable. Broholm et al. (1997) observed unexpectedly a major DNAPL residual zone 0.11m above the point of release whereas Truax et al. observed DNAPL penetration much deeper than expected.

The final position of DNAPL in the ISVCC was assessed using dissolved phase solvent concentrations measured at each sampling port. The equilibrium concentration of the PCE and 1,1,1 TCA mixture in the groundwater can be estimated based on the data given in Table 3 and Equation 2 (Banerjee, 1984):

$$C_w = \gamma \alpha S_p$$

Equation 2

where γ is the activity coefficient of the organic phase where infinite dilution is assumed in the water phase as predicted by UNIFAC for the DNAPL mixture, α is the mole fraction of each compound (here 0.5) and S_p is the aqueous solubility of the pure compound. The mixture equilibrium concentration for PCE is 68 mg/L and 575 mg/L for 1,1,1-TCA.

Figure 10 displays the percentage of aqueous phase saturation measured in the ISVCC after both episodes of contaminant injection. The saturation is simply the ratio of measured concentration to the maximum equilibrium concentration for each compound. Pure phase DNAPL was only detected in the sampling port 3D5 located 3 cm below the DNAPL injection well and in 1D7 where 50 mL of DNAPL was injected at the first sampling level. For the 200 mL injection, the maximum concentrations were observed in port 3B7 with 16% and 5% saturation for PCE and 1,1,1-TCA respectively. The second highest saturations are observed in port 4D3 located 35cm above the DNAPL injection. On sampling level 2, only fractions of a percentage of solvent were detected in 2A5 and 2C6. These observations indicate that downward migration of the DNAPL was not significant beyond 3cm below the injection point. Kueper et al. (1993) and Brewster et al.

(1995) measured retention capacities of 8.6 and 3.2 L/m³, respectively, for PCE in the saturated Borden aquifer. Assuming an average retention capacity of 6L/m³, 200 mL of PCE and TCA mixture would occupy a volume of 32 cm x 32cm x 32cm. Instead of traveling downwards, the DNAPL has probably spread laterally with a shift off of the center, along a slightly dipping micro-bed, as indicated by the higher concentration measured in 3B7 and 3A1 compared to 3C3 (Figure 10a). For the 50 mL injection, which would invade a volume of 9.5 cm x 9.5 cm x 9.5 cm assuming a 6 L/m³ retention capacity, the maximum concentrations were observed in port 2D1, 38cm above the point of injection, with saturations of 5% for PCE and >3% for TCA (actual dissolution of TCA is greater than 3% because degradation products were detected). The second and third highest saturations are encountered in port 2C6 and port 1C5. Given those results, it is not possible to assess the downward migration of the DNAPL. Considering the small volume injected, most of the DNAPL residual is likely still around the injection port 1D7.

The low saturation levels probably reflect the fact that not all of the water that flows in the column came into contact with the DNAPL. Also, the sampling ports integrate the concentration of many flow tubes. Thus, the high concentration flow tubes will be diluted by the less concentrated ones.

Other Processes observed in the ISVCC

For vitamin B₁₂ to cause rapid reductive dehalogenation of chlorinated solvents, the pH must be in the range of 7 to 9 and the redox potential must be lowered to below -400 mV. Establishment of these very reducing conditions was the first step, which involved the injection of a solution of reduced titanium and citrate. This caused the Eh to decline from +250 mV to -500 mV (Figure 11a).

Once the chlorinated solvents were introduced in the ISVCC, the process of reductive dechlorination degradation was monitored. Figures 11 c and d show that 1,1,1-TCA was transformed to less chlorinated molecules, such as 1,1- dichloroethane (1,1-DCA), 1,1- dichloroethene (1,1-DCE), vinyl chloride (VC), chloroethane (CA) and chloromethane (CM).

Sodium citrate, an ingredient of the remedial solution, was found to be degraded by indigenous aquifer microorganisms. Aqueous reduced titanium (Ti^{3+}) stability field is limited to very low pH and a narrow Eh range (Pourbaix, 1963). Sodium citrate, a chelating agent added in solution complexes with titanium and increase the range of redox potential and pH under which it remains soluble. After two months of remedial solution delivery, the microbial population was degrading the citrate to acetate, propionate and formate while also producing carbon dioxide and methane gas. The density of the monitoring ports provided recognition of very different microbial and redox conditions across distances of only a few centimeters.

Conclusions

The ISVCC was successfully installed in the Borden aquifer using inexpensive equipment. The bromide tracer test showed no indication of short circuiting and produced values of longitudinal dispersivity similar to laboratory sand columns. The hydraulic performance of the column indicated absence of low permeability layers, which was confirmed by core sampling outside the column. The array of horizontal sampling ports showed the general location of immobilized DNAPL after it was released into the column, the patterns of percent solubility of the water passing through the DNAPL zones, the changes in pH, Eh and transformations of PCE and 1,1,1-TCA. The ISVCC was used for the first time in

the Borden aquifer. We expect that the ISVCC is suitable for application in many other shallow sandy aquifers that are free of boulders or other obstacles that could cause installation difficulties. Its application will be restricted where low hydraulic conductivity beds are present in the aquifer. Larger diameter versions of the ISVCC would make radial flow experiments possible, which would have advantage in aquifers with strong horizontal bedding or in situations where it is necessary to install vertical wells and monitors. The system provides new opportunities for relatively inexpensive *in-situ* studies of contaminant behavior and remediation processes.

Acknowledgments

The University Consortium Solvent-in-Groundwater Research Program funded this project. We thank Dr. Rick Devlin for his advice on the design of the ISVCC. Sam Vales and Paul Johnson are acknowledged for their assistance with the field installation and Stephannie O'Hannesin advice on the tracer test design and for providing sampling and analysis equipment. Jim Roy, Jesse Ingleton, Suzanne O'Hara and Roch Champagne also helped with the column installation and sampling. Finally, we thank Susan Brown and Kelly Millar for their technical support during the vitamin B₁₂ experiment.

Biographical Sketches

Dominique Sorel has recently joined Geomatrix Consultants as a staff hydrogeologist. She holds a B.A.Sc. in civil engineering from the Université de Sherbrooke and a M. Sc. in hydrogeology from the University of Waterloo. Her interests include in-situ treatments for groundwater rehabilitation, behavior of DNAPLs in the subsurface, hydraulic, geochemical and biological limitations and controls on remediation techniques.

John A. Cherry has degrees in geological engineering and hydrogeology and, since 1971, has been a professor at the University of Waterloo where he is a member of the Waterloo Centre for Groundwater Research. For the past 25 years, his research has focused on processes and monitoring of groundwater contamination and on design and implementation of controlled field experiments for various purposes.

Dr. Suzanne Lesage is research scientist in the Groundwater Remediation Project at the National Water Research Institute of Environment Canada in Burlington Ontario. She has more than fifteen years experience in investigating the fate of organic contaminants in groundwater, soils and landfill leachates. Her current research interest is on the use of natural substances in remediation. The projects include the remediation of chlorinated solvents using vitamin B12 and titanium and the use of humic acids in the remediation of petroleum contaminated sites. She edited a book entitled "Groundwater Contamination and Analysis at Hazardous Waste Sites" (1992, 545 pages published by Marcel Dekker Inc.). In 1992 she also chaired an international symposium on In-Situ Bioremediation held at Niagara-on-the-Lake, Ontario. She received a B.Sc. in Biochemistry from the University of Ottawa in 1973 and a Ph.D. in Chemistry from McGill University in Montreal in 1977. She is an adjunct professor in Earth Sciences at the University of Waterloo.

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Table Captions:

Table 1: Breakthrough curve fitting results for the bromide tracer test: velocities and dispersivities.

Table 2: Bromide breakthrough time.

Table 3: Physical and Chemical properties of PCE and 1,1,1-TCA.

Figure Captions:

Figure 1: a) *In-situ* vertical circulation column concept; b) hanging column; c) column keyed in aquitard; d) lower level inside ISVCC, inward gradient prevents loss to the aquifer; e) higher level in ISVCC compared to aquifer but an outer enclosure (sheet pile or cylinder) allows to artificially raise water levels to create inward gradients preventing loss to aquifer.

Figure 2: a) horizontal wells and sampling device installed in a saturated zone, column's side exposed by dewatering and excavating around the ISVCC; b) horizontal wells and sampling device installed in a saturated zone, column's side exposed by dewatering and excavating around the ISVCC inside an impermeable enclosure (standard or sealable sheet piles or large cylinder).

Figure 3: Wells and sampling ports layout in the *In-situ* Vertical Circulation Column installed in the Borden aquifer.

Figure 4: Sampling port and disposable drive point casing.

Figure 5: Installation of the *In-situ* Vertical Circulation Column: a) drilling, threading and temporarily plugging holes for monitoring and injection ports; b) vibrating column in aquifer; c) excavation around the cylinder; e) monitoring port installation.

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Figure 11: Inorganic and organic profiles measured in port 4D3 resulting from the reaction with vitamin B₁₂ and reduced titanium a) Eh b) pH c) 1,1,1-TCA concentration d) 1,1,1-TCA degradation products concentrations.

Table 1: Breakthrough curve fitting results for the bromide tracer test: velocities and dispersivities.

Monitoring Port	Velocity (m/s)	Dispersivity (m)
1A3	2.94E-05	2.02E-03
1D7	6.48E-05	6.34E-03
2A5	1.97E-05	2.16E-02
2D1	2.94E-05	1.46E-02
3A1	2.82E-05	6.84E-03
3D5	2.07E-05	1.00E-02
4A7	2.03E-05	6.18E-03
4D3	2.18E-05	1.67E-03
EXT	2.11E-05	3.70E-02
* average	2.33E-05	9.61E-03

* The average excludes the minimum and maximum values

Table 2: Bromide breakthrough time.

Monitoring Port	Velocity (m/s)	Vertical distance from injection (m)	Breakthrough time (h)
1A3	2.94E-05	0.21	1.9
1D7	6.48E-05	0.21	0.9
2A5	1.97E-05	0.59	8.3
2D1	2.94E-05	0.59	5.5
3A1	2.82E-05	0.97	9.5
3D5	2.07E-05	0.97	13.0
4A7	2.03E-05	1.35	18.4
4D3	2.18E-05	1.35	17.1
EXT	2.11E-05	1.55	20.5

Table 3: Physical and Chemical properties of PCE and 1,1,1-TCA

	MW (g/mole)	Solubility (mg/L)	Density ³ (g/cm ³)	Activity coefficient ⁴	Molecular Diffusion ⁵ cm ² /s
PCE	165.8	150 ¹	1.63	0.904	6.09E-06
1,1,1-TCA	133.4	1352 ²	1.35	0.851	6.60E-06

¹ at 25° C, de Verschueren handbook of environmental Data on Organic Chemicals

² at 10° C, After Pankow and Johnson, 1996 in Cherry and Pankow Eds.

³ at 25° C, After Pankow and Johnson, 1996 in Cherry and Pankow Eds.

⁴ Calculated with UNIFAC

⁵ At 10 °C ,after Hayduk and Laudie (1974) in Schwarzenbzch et al. 1993

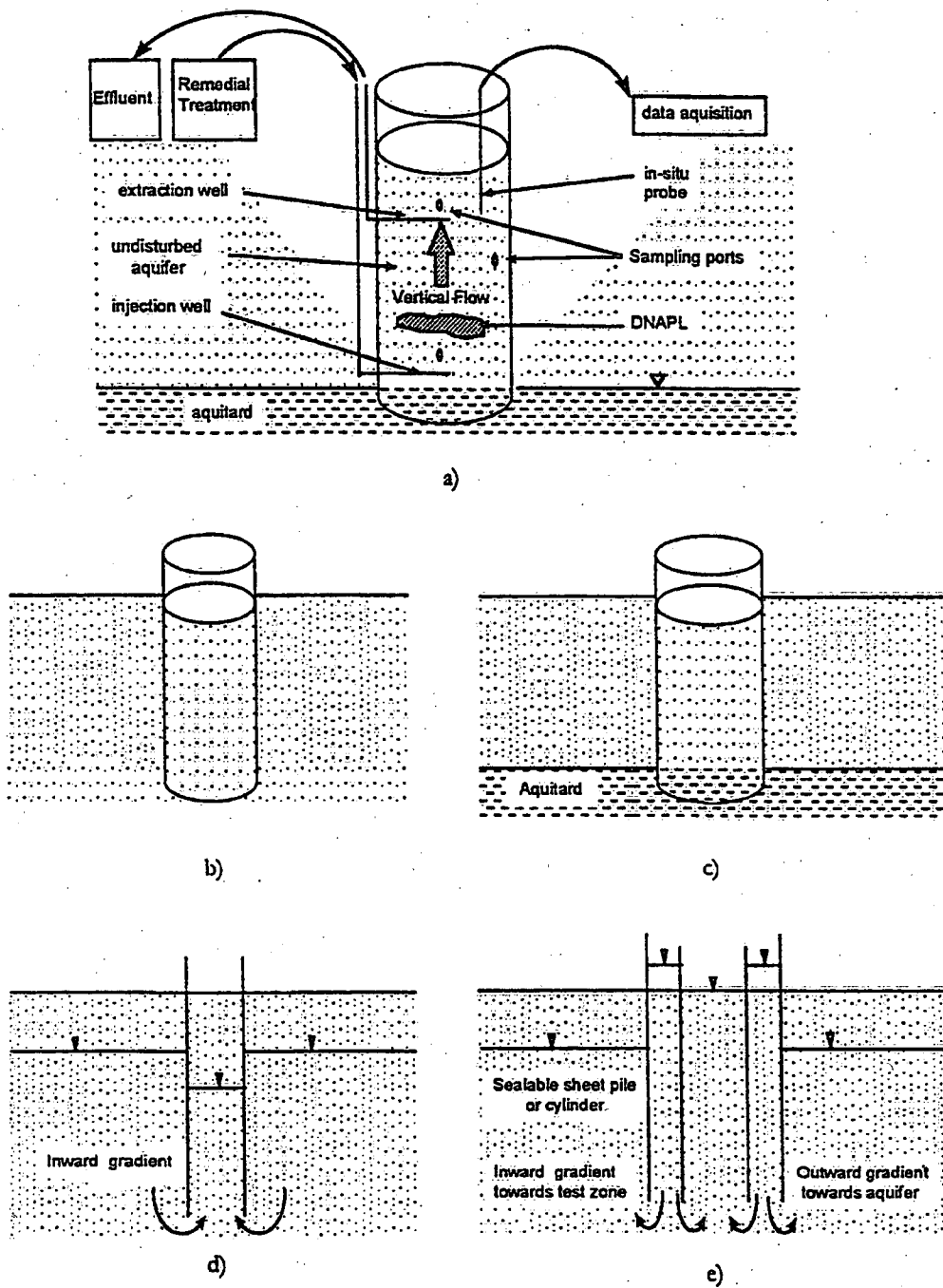
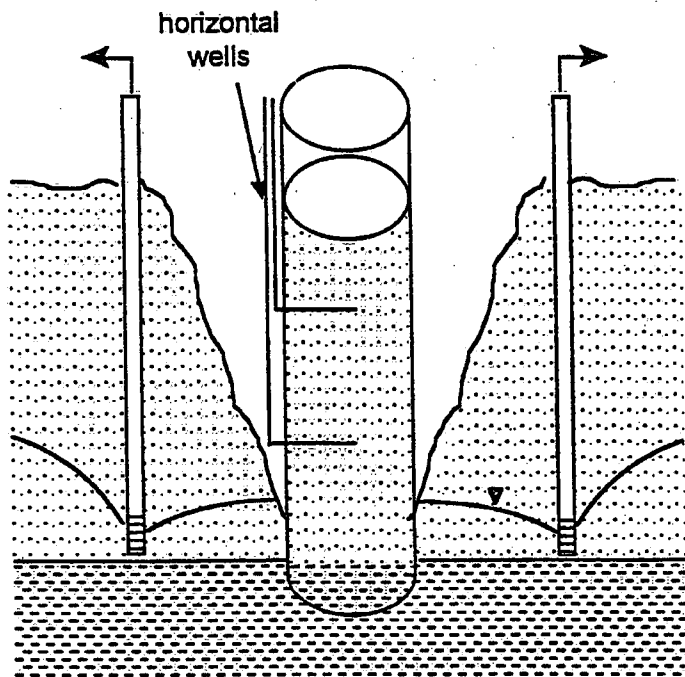
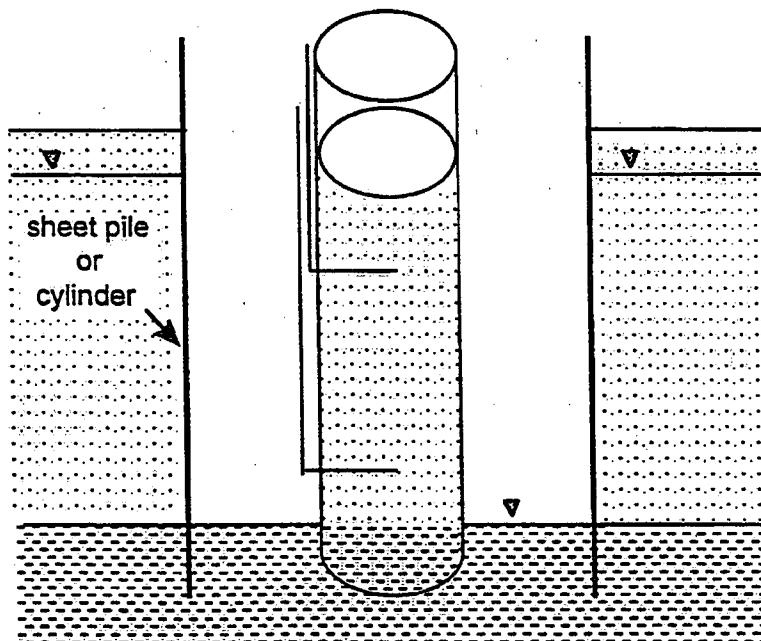


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a)



b)

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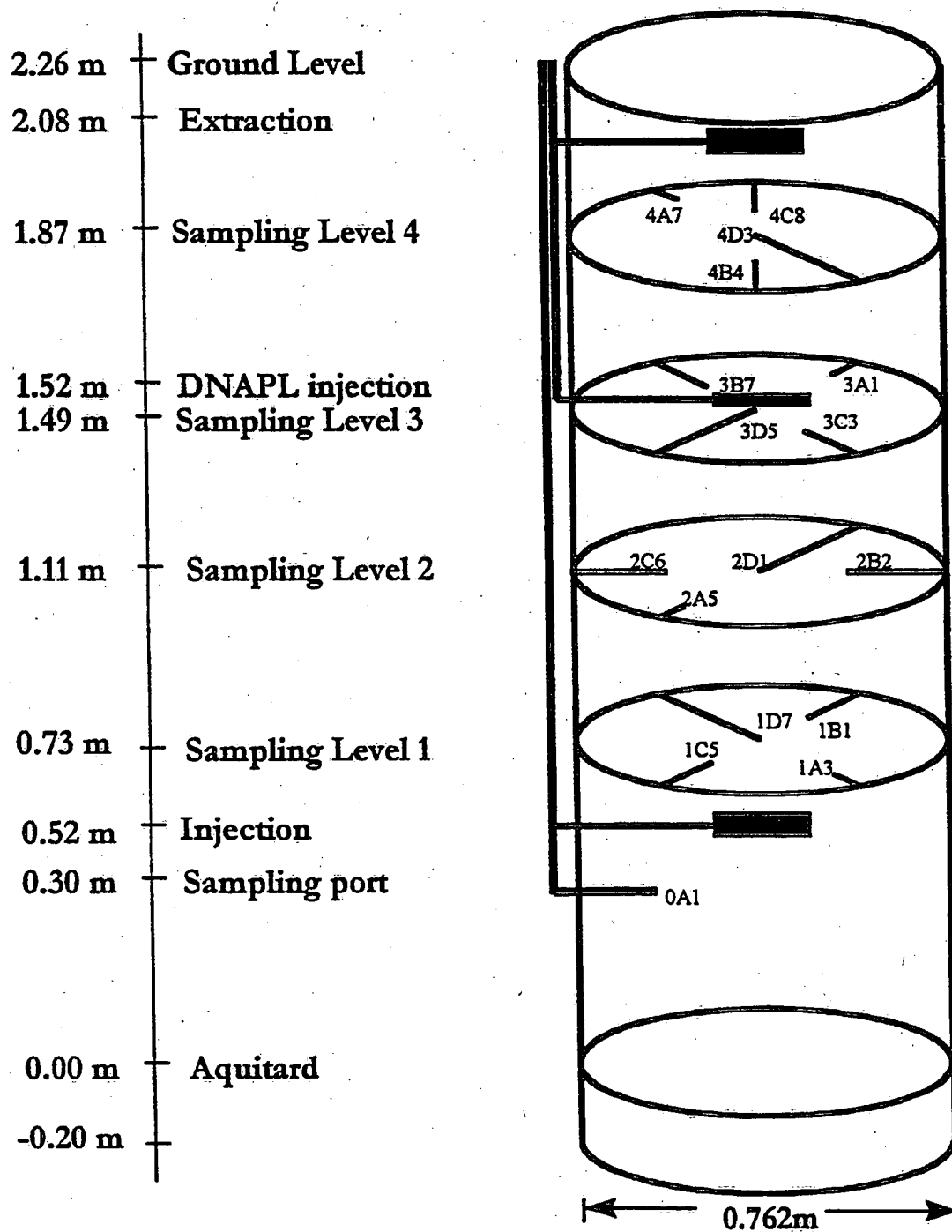


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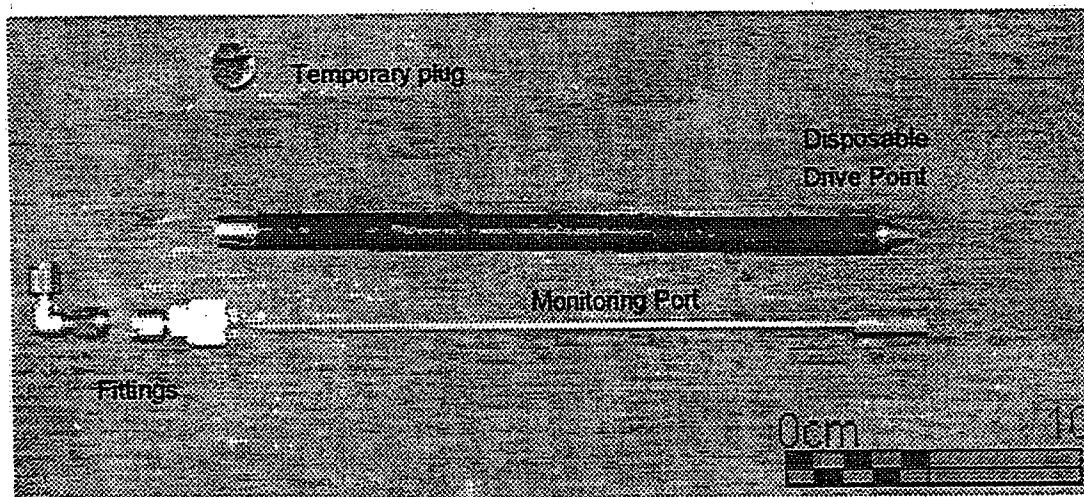


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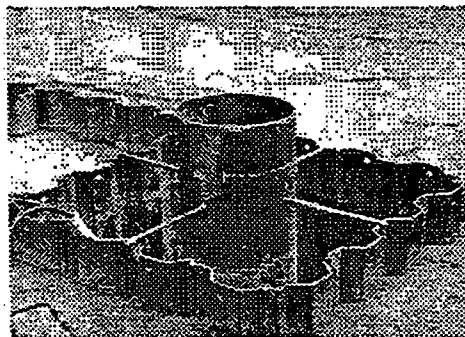
(a)



(b)



(c)



(d)

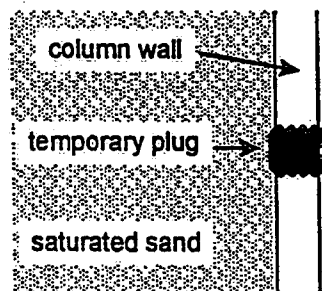


(e)

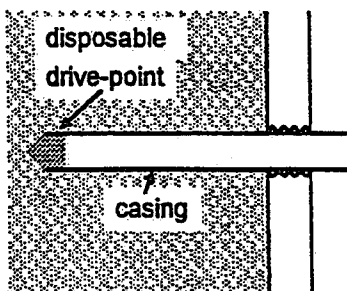


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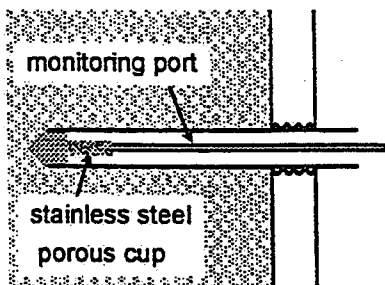
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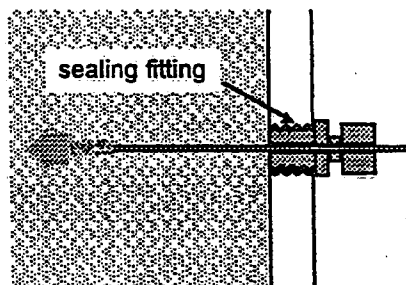
(a)



(b)



(c)



(d)

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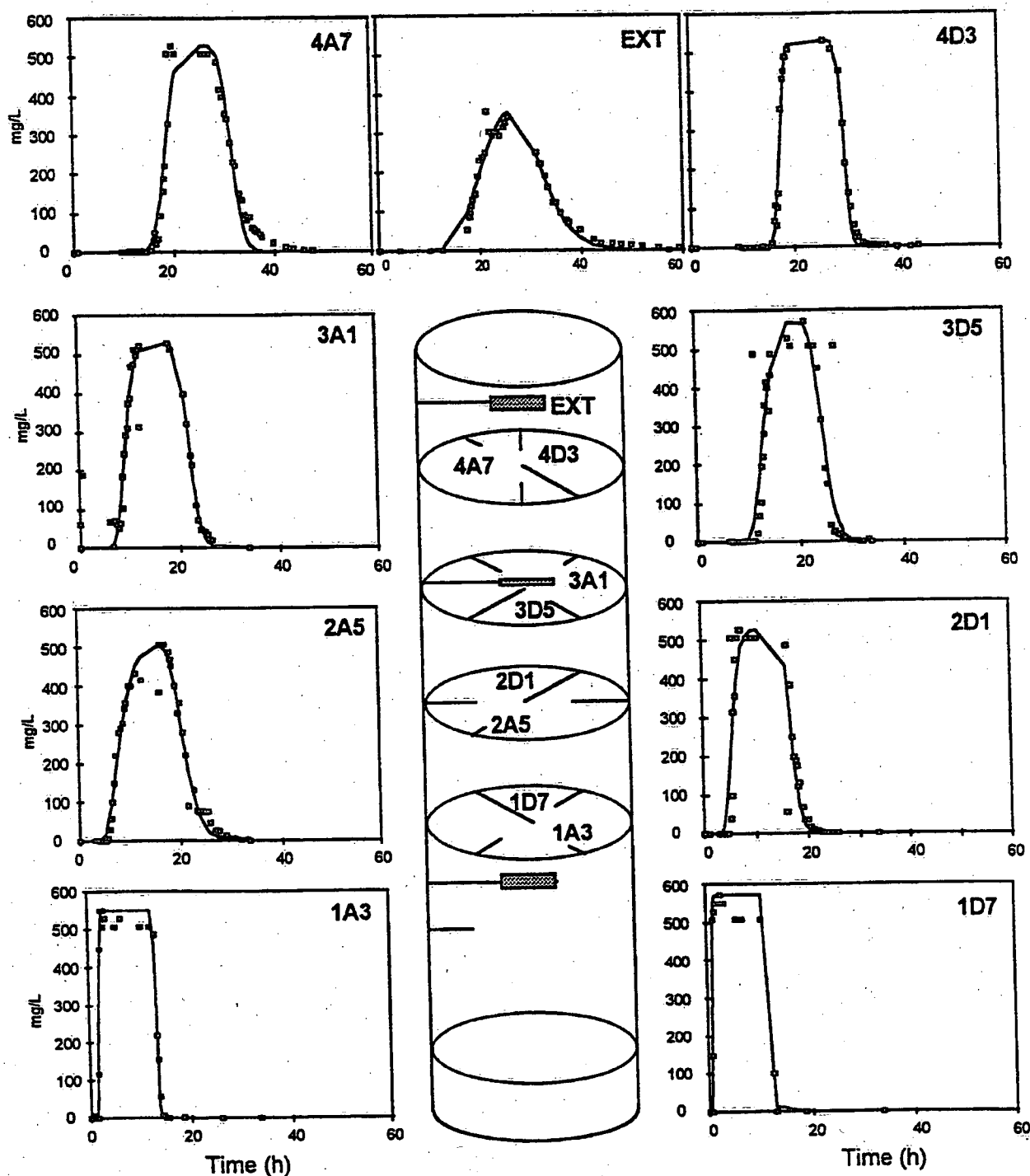
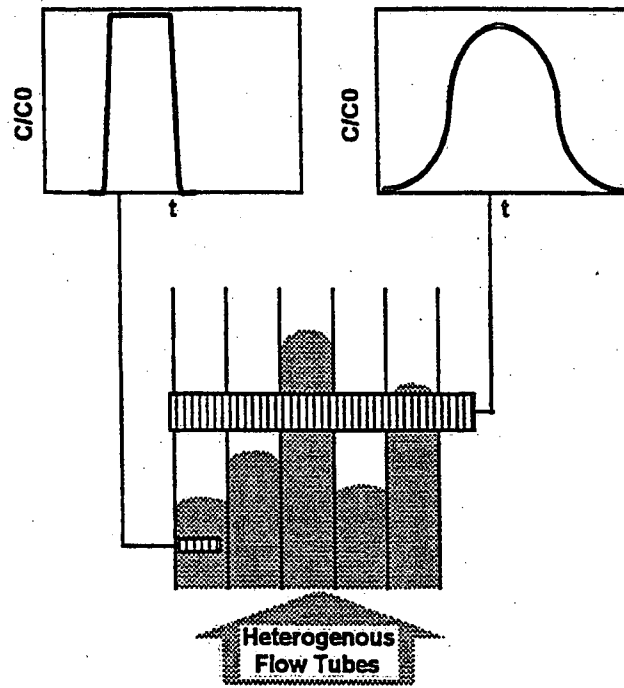
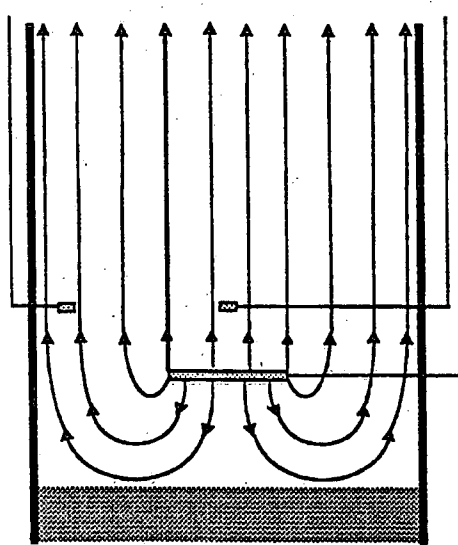


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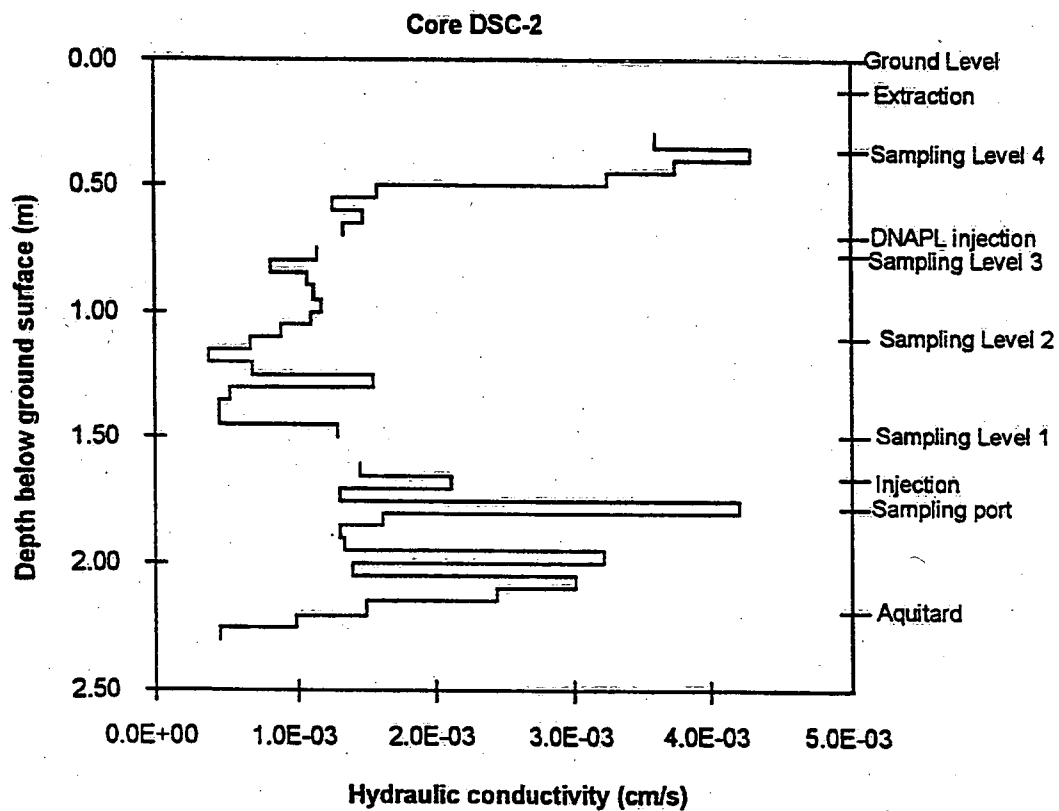


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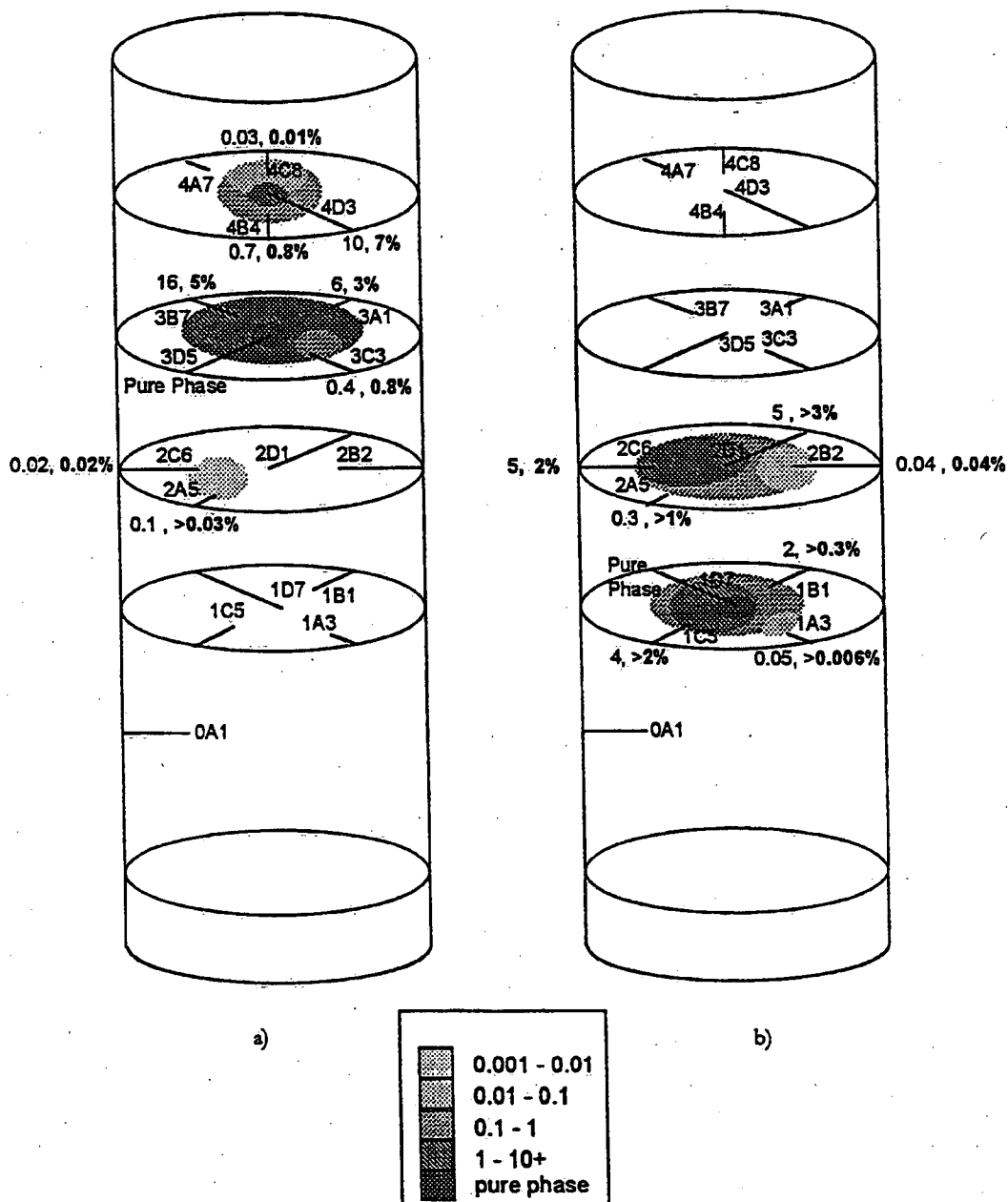
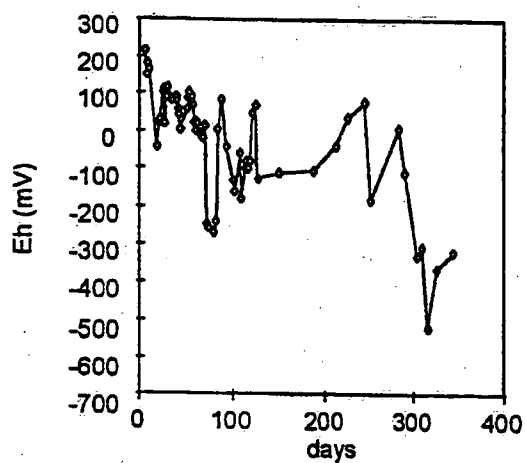
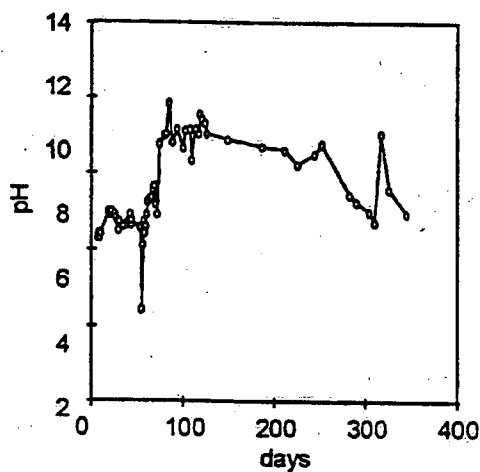


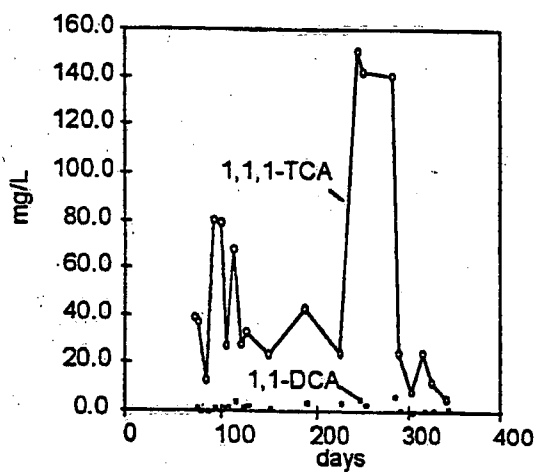
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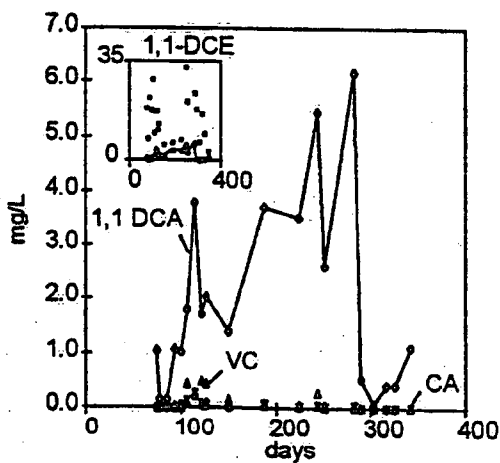
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b)



c)



d)

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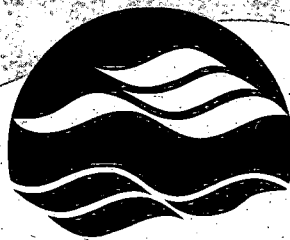
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