

# Cyclodextrin-Enhanced Vertical Flushing of a Trichloroethene Contaminated Aquifer

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## Abstract

**P**ilot-scale testing of an innovative ground water remediation technology was conducted in a source zone of a trichloroethene-contaminated Superfund site in Tucson, Arizona. The technology is designed to enhance the removal of low-solubility organic contaminants from heterogeneous sedimentary aquifers by using a dual-screened vertical circulation well to inject and extract solutions containing a complexing sugar (hydroxypropyl-beta-cyclodextrin (HPCD)). Prior to initiating the pilot test, tracer tests were conducted to determine hydraulic characteristics of the vertical flow field and to evaluate trichloroethene-elution behavior during water flushing. The pilot test involved injecting approximately 4 m<sup>3</sup> of a 20% HPCD solution into the upper screened interval of the well and extracting from the lower screened interval. The results of the pilot test indicate that the cyclodextrin solution increased the rate of trichloroethene removal from the aquifer. The concentrations of trichloroethene in the ground water extracted from the lower screened interval of the well increased by a factor of three (~750 µg/L) in the presence of the cyclodextrin pulse, compared to concentrations obtained during previous water flushing (~250 µg/L). Furthermore, the concentration of trichloroethene in water collected from the circulation well under static conditions was reduced to 6% of the levels measured prior to the test.

## Introduction

Heterogeneous sedimentary aquifers contaminated with sorbed and immiscible-liquid phases of chlorinated solvents are common and difficult to remediate. These aquifers are composed primarily of quasi-horizontal layers and lenses of differing hydraulic conductivities. Attempts to extract contaminants from such aquifers are often performed using horizontal water flushing (e.g., pump-and-treat). The effectiveness of this approach is limited by preferential flow phenomena and the low aqueous solubilities of common chlorinated solvents.

Contaminant removal in such aquifers can be potentially enhanced by inducing vertical flow, perpendicular to the strata, thereby increasing the flushing of the lower permeability zones. This may be accomplished through use of vertical circulation wells (VCW), which are screened at two or more separate intervals. Water is extracted at one interval, treated, and injected into another interval. In systems without a confining layer between the screens, water flows from one screen to the other along parabolic flow lines approximating a dipole. Higher ratios of horizontal to vertical conductivity and greater distances between the screens have been shown to extend the flowlines from the well (Herrling et al. 1991; Herrling et al. 1992). The vertical hydraulic gradients associated with vertical circulation wells may provide more effective flushing of lower-permeability layers associated with typical horizontally stratified sedimentary aquifers than the horizontal

gradients associated with conventional pump-and-treat systems (Knox et al. 1997; Blanford et al. 1999).

Enhanced solubilization technologies have been developed to increase the rate of organic contaminant removal from sorbed or immiscible-liquid phases. Reagents used for enhanced-solubilization flushing include a variety of surfactants, cosolvents such as alcohols, and complexing agents such as cyclodextrins and humic acids. Combining enhanced solubilization with vertical circulation wells may be a viable approach for enhancing mass removal from the areas of highest contamination in heterogeneous aquifers. For example, a pilot test of vertical surfactant flushing demonstrated enhanced removal of trichloroethene, tetrachloroethene, and recalcitrant jet fuel components from a sandy aquifer (Knox et al. 1997; Sabatini et al. 1997).

In the present study, we tested the performance of cyclodextrin-enhanced vertical flushing in a source zone of a trichloroethene-contaminated aquifer in Tucson, Arizona. Hydroxypropyl-beta-cyclodextrin has been shown in laboratory and field studies to enhance the solubility and removal of low-polarity organic compounds (Wang and Brusseau 1993; Brusseau et al. 1994; McCray and Brusseau 1998; Boving et al. 1999). Cyclodextrin is a polycyclic oligosaccharide formed by the degradation of starch by bacteria (Bender et al. 1978). These toroidal shaped molecules have a hydrophilic, polar exterior and a hydrophobic, nonpolar cavity within which low-polarity compounds may partition. Beta-cyclodextrin is composed of seven glucose molecules and has a cavity diameter of 0.75 nm (Voegtle 1989; Wang and Brusseau 1995). HPCD has an aqueous solubility greater than 80% by mass (0.8 kg/L).

Cyclodextrins such as HPCD have many characteristics that make them potentially favorable for field application. Previous research has shown that HPCD under typical aquifer conditions is nonsorbing (Brusseau et al. 1994), does not precipitate (Wang and Brusseau 1995), and that its solubilization potential is independent of pH or ionic strength (Wang and Brusseau 1995; Brusseau et al. 1997). Central to contaminant recovery and reagent reuse considerations, chlorinated solvents can be separated from cyclodextrin solutions by flushing through iron filings (Bizzigotti et al. 1997) or by air-stripping and off-gas activated carbon treatment (Boving et al. 1998) without degrading the cyclodextrin. Once separated, the cyclodextrin solution may be reconcentrated using semi-permeable membranes or evaporation, and reused. The purpose of this paper is to present the results of a pilot test conducted to evaluate the performance of cyclodextrin enhanced vertical flushing for a chlorinated solvent contaminated aquifer.

## Materials and Methods

### Background and Site Description

The experiments were conducted at Air Force Plant-44, Tucson, Arizona, which is located in the southern portion of the Tucson International Airport Authority Superfund site. A large, multisource plume of trichloroethene and

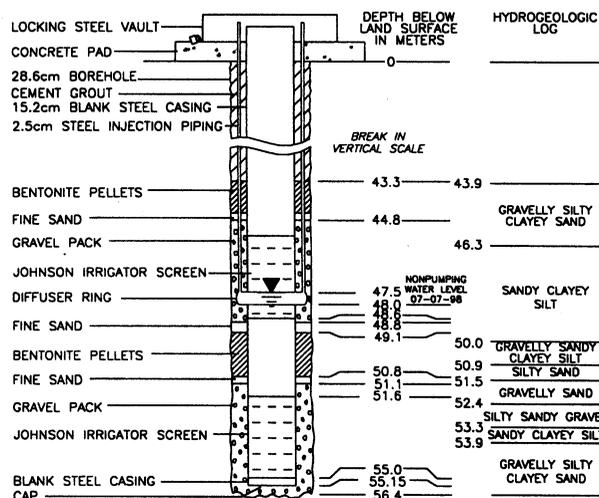


Figure 1. Schematic diagram of construction for vertical circulation well VCW-2.

dichloroethene exists in the upper portion of the regional aquifer. The pilot tests were conducted in the vicinity of former unlined disposal pits that received waste solvents. A large-scale pump-and-treat system has been operating at the site since 1987.

During the last 12 years of pump-and-treat remediation at AFP-44, trichloroethene concentrations in ground water in the vicinity of Installation Restoration Project (IRP) sites 2 and 3 have decreased substantially slower than elsewhere at the AFP-44 site. These sites coincide with the locations of past surface disposal of waste solvents and are considered contaminant source zones. Previous research conducted at the site has identified several factors limiting the effectiveness of the present ground water remediation system (Nelson and Brusseau 1996; Brusseau et al. 1999; Zhang and Brusseau 1999). These factors include diffusion-controlled release from silt and clay layers, for which trichloroethene concentrations appear to be higher than surrounding sand layers, rate-limited desorption, and rate-limited dissolution of immiscible-liquid saturation trapped in the saturated zone. Clearly, it would be difficult to achieve successful remediation of the site by using basic pump-and-treat if one or more of these processes are operable. The use of cyclodextrin-enhanced vertical flushing is one possible method to improve mass removal for source-zone remediation.

### Well Construction

The vertical circulation well, VCW-2, is located at IRP site 2 of AFP-44. It was drilled and constructed between June 26, 1998 and July 2, 1998 by Layne-Christensen Co. Inc. of Tempe, Arizona with a Drill Systems AP-1000 dual-wall reverse air circulation percussion-hammer drill rig. Following drilling of the pilot borehole to a depth of 56.4 m, a 15.2 cm blank steel casing and stainless steel well screen were installed to a depth of 55.15 m. The well was screened over two intervals. The screens were made of stainless steel with 1 mm wide slots and were each 3.17 m long. The bottoms of the upper and

lower screens were 48.6 m and 55.0 m below ground surface (bgs), respectively (Figure 1).

A secondary injection system was installed to increase the ability to recover injected solutions. This system was designed to inject fluid at the bottom of the upper screen, which is the starting location of the shortest flowlines associated with the vertical circulation well. It consisted of a perforated steel diffuser ring fitted around the well casing and located at a depth of 48.0 m. Twelve 0.6 cm holes were drilled on the inside face of the ring to direct water into the lower portions of the upper screen. Two 2.5 cm outside diameter pipes, one for fluid injection and one for water level monitoring, extended from the diffuser ring to the surface.

The lower gravel pack (Colorado Silica Sand 8-12) was installed in the interval from 51.1 and 56 m bgs and about 30 cm of fine sand (Colorado Silica Sand 10-20) was installed on top of the gravel pack. A seal between the screened intervals, constructed using coated bentonite pellets (Pel Plug) was placed in the interval from 49.1 to 50.8 m bgs to limit flow between the screens with the borehole. Following placement of the bentonite pellets, about 30 cm of the fine sand was emplaced on top of the seal. The upper gravel pack was installed in the interval from 44.8 to 48.8 m bgs. The diffuser ring was installed during the emplacement of the upper gravel pack; about 30 cm of fine sand was placed on it. About 1.3 m of coated bentonite pellets were installed on top of the upper gravel pack. Water was added to the borehole to hydrate the bentonite pellets above the upper screened interval. Cement/bentonite slurry was installed in the interval from about 43.3 m to 0.6 m bgs. (Figure 1).

Following completion of well construction operations, well VCW-2 was developed by swabbing, bailing, and pumping for about five hours. Selected measured properties in the initial samples of water pumped from the well following development included temperature (26.5°C), pH (7.58), conductivity (522  $\mu$ S), and trichloroethene concentration (4600  $\mu$ g/L).

### Fluid Delivery System

A system of tanks, valves, pumps, and flowmeters was constructed to generate and control fluid delivery (Figure 2). The system was designed to operate in several modes to give flexibility in test methods. To establish flow in the well prior to initiation of a tracer or cyclodextrin solution injection, the system was operated in a recirculation mode, wherein water extracted from the well was passed through the air stripper and returned to the well. During the bromide tracer and cyclodextrin tests, the system was operated in a single-pass mode. In this mode, potable water-based solutions of bromide or cyclodextrin are injected into aquifer through the upper screen and ground water is pumped from the lower screen and treated with the on-site airstripping system and temporarily stored on-site. Final disposal of the solutions was through AFP-44's water treatment systems. Equipment installed in the vertical circulation well included an electric submersible pump to extract water, an inflatable packer to exclude flow within the casing, polyethylene piping to

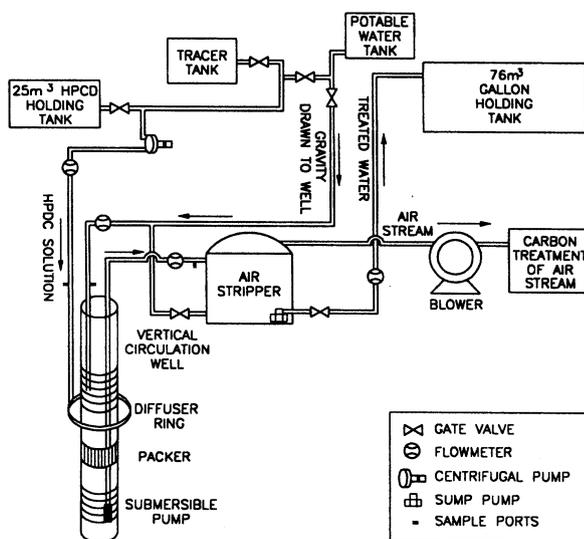


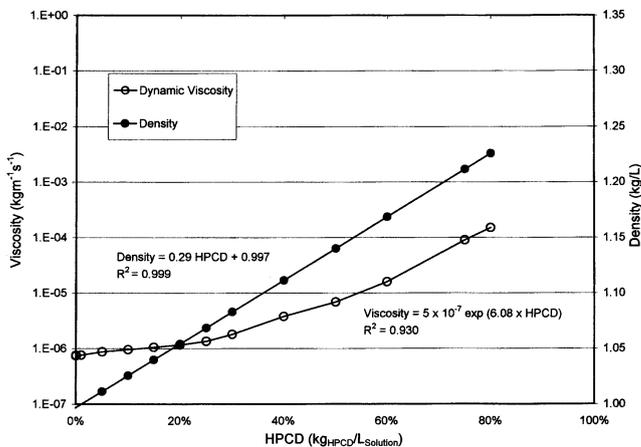
Figure 2. Schematic of equipment setup for pilot tests.

carry ground water from the pump to the wellhead, and flexible PVC hose to transmit water from the surface down to the upper well screen (Figure 2). Pressure transducers were installed to monitor ground water potentials above and below the packer. Flowmeters were installed in the system to record volumes of ground water pumped from and injected into the well.

The portable air stripper used for the experiment (IEG Technologies Corp.) is a self-contained, low profile unit housed in a high-density polyethylene enclosure (Figure 2). Inflowing water passes over a series of baffles positioned in two trays located in the upper portion of the unit. Ambient air drawn into the air stripper unit by a blower is released through pinholes in the bottom of each tray. As the air bubbles move upward through the water, VOCs are transferred from the water to the air stream. During the pilot tests, the air stream was passed through activated carbon (U.S. Filter) to capture the VOCs discharged from the air stripper. From the lower tray, the treated ground water cascades into a 1200 L capacity sump in the lower portion of the air stripper. Water from the sump could be gravity fed back to the vertical circulation well or pumped into a holding tank. A series of preliminary experiments were conducted to evaluate the stripping efficiency of the unit for trichloroethene in water alone and in a 10% HPCD solution. The airstripping system removed 98.00% of the trichloroethene from the 10% HPCD solution and 99.98% from the water solution with the following specified conditions: TCE concentration of 5000  $\mu$ g/L, influent solution flow rate of 30 L/min, and an air flowrate of 13,000 standard L/min.

### Tracer Tests

Tracer tests were conducted to evaluate the travel times and recoveries associated with use of the vertical circulation well system. During each tracer test, samples were also collected to examine elution behavior of



**Figure 3. Dynamic viscosity and density of cyclodextrin solutions.**

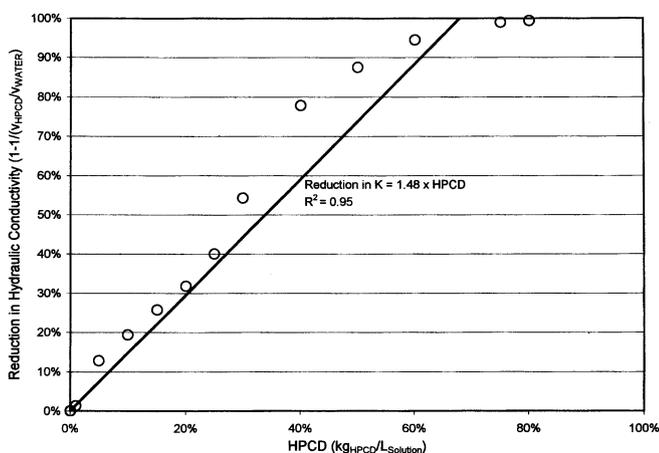
trichloroethene during vertical water flushing. Bromide was used as a nonreactive tracer. The tracer solution was made by dissolving calcium bromide salt (Great Lakes Chemical) in potable water to a concentration of approximately 740 mg/L bromide. The flow scheme for each test consisted of injecting a combination of tracer solution and potable water into the upper screen or into the diffuser-ring and extracting ground water from the lower screen. The extracted ground water from the tracer tests was passed sequentially through the air stripper, then to the holding tank, and finally to the Groundwater Treatment Facility at AFP-44.

A quasi steady-state flow field was established prior to each test. This required two to four hours. Flow conditions were determined from the relative stability of the water potentials in the upper and lower screens. Tracer solution was then injected for a specified interval time and followed by potable water injection until the end of the test. Inflow and effluent aqueous samples were collected. Bromide analysis was performed with an ion-specific electrode (Cole Palmer). Trichloroethene samples were analyzed by gas chromatography with an electron capture detector (Shimadzu, model 17) coupled with a headspace auto-sampler (Tekmar, model 7000).

### Vertical Complexing Sugar Flush

Hydroxypropyl-beta-cyclodextrin (Cerestar) was used as a solubility-enhancing agent for the pilot tests. The cyclodextrin was dissolved to a concentration of 20% by mass of HPCD per total volume in potable water taken from the AFP-44 distribution system. The cyclodextrin solution was then transferred from the mixing tank to a 25 m<sup>3</sup> capacity polyethylene storage tank (Baker Tanks).

The basic flow scheme of the cyclodextrin test was similar to the tracer tests. Preceding the cyclodextrin flush, the vertical circulation well was operated for two hours to establish a quasi steady-state flow field. After steady-state flow conditions were established, approximately 4 m<sup>3</sup> L of cyclodextrin solution was injected. The cyclodextrin solution extracted from the well passed through the air stripper to remove the trichloroethene from the



**Figure 4. Potential reduction in hydraulic conductivity with increasing cyclodextrin concentration.**

cyclodextrin solution. After air-stripping, the cyclodextrin solution was stored in a 76 m<sup>3</sup> capacity steel tank (Baker Tanks) for later treatment. Ground water samples collected during the pilot test were analyzed for trichloroethene and cyclodextrin. The cyclodextrin analysis was performed by fluorescence spectrophotometry (Hitachi, model F-2000) (Wang and Brusseau 1993).

## Results and Discussion

### Influences of Cyclodextrin Content on Fluid Properties

Preliminary laboratory experiments were conducted to evaluate the viscosity and density of the cyclodextrin solutions as a function of cyclodextrin concentration. The viscosity was measured by CTC Analytical (Phoenix, Arizona) with a Canon model M1 constant-temperature-bath viscometer with Canon model 150, 200, and 250 viscosity tubes. The samples were analyzed at a temperature of 40°C. Density was measured by weighing 250.0 mL samples of cyclodextrin with a Mettler Toledo model PG12001-S scale. Figure 3 shows the results for the density and viscosity analysis for cyclodextrin solutions varying in concentration between 0% and 80% wt/vol. Viscosity increases exponentially with concentration, and density was found to be linearly correlated to cyclodextrin concentration. The equations and attendant best-fit lines obtained from regression analysis are presented in Figure 3. The potential reduction in hydraulic conductivity as a function of the dynamic viscosity and density relationships is presented in Figure 4. For the injected solution of 20% cyclodextrin it appears that the hydraulic conductivity may be reduced by not more than 30%.

### Vertical Distribution of Trichloroethene Concentrations

Water samples were collected from well VCW-2 under static conditions to determine aqueous trichloroethene concentrations before and after the pilot test. In both cases, these samples were obtained after the nearby pumping wells associated with the pump-and-treat system

**Table 1**  
Concentrations of TCE in Samples of Aquifer Material Collected During Drilling of Well VCW-2

Concentration Determined by Methylene Chloride Extraction		Concentration Determined by Water Extraction	
Sample Depth	TCE Conc.	Sample Depth	TCE Conc.
(m bgs) <sup>a</sup>	(µg/g) <sup>b</sup>	(m bgs) <sup>a</sup>	(µg/g) <sup>b</sup>
45.4	1.31	45.4	0.126
45.8	4.31	47.4	0.0751
47.4	2.41	48.9	0.558
48.6	0.228	51.9	<0.0003
51.6	2.81	53.2	<0.0003
53.1	0.197		

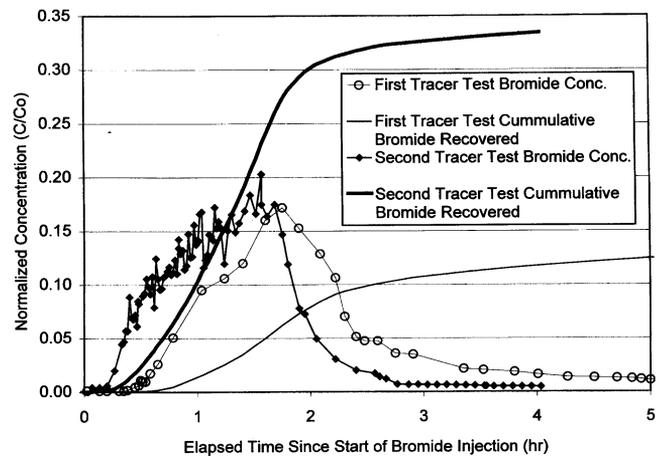
<sup>a</sup>m bgs = meters below ground surface.  
<sup>b</sup>µg/g of soil = micrograms of TCE per gram of sediment.  
 < = TCE not detected at the detection limit indicated.

had been inactive for six weeks to allow formation of natural-gradient conditions. The pre-test trichloroethene concentrations ranged from 1160 to 1950 µg/L. The post-test ranged from 82 to 108 µg/L. The post-test samples averaged 6% of the pre-test levels.

Samples of aquifer material were collected using a California modified split-spoon sampler during drilling of the VCW-2 borehole. Samples were subjected to solvent extraction by methylene chloride and water to determine the amount of trichloroethene associated with the aquifer material. Analysis of these data showed variability in trichloroethene concentrations with little correlation to lithology (Table 1). As would be expected, the concentrations obtained from extraction with methylene chloride were about 13 times larger than those obtained from the aqueous extractions.

An estimate of the in situ distribution coefficient for trichloroethene can be obtained by comparing the trichloroethene concentrations measured in ground water with those measured for samples of aquifer sediments. Representative concentrations are 2 µg TCE per mL of water for the aqueous phase, and 1 µg TCE per gram of sediment for the solid phase. These values result in a distribution coefficient of 0.5 mL/g. Recognizing that this calculation is constrained by a number of assumptions, the calculated distribution coefficient can be compared to sorption coefficients measured in previous laboratory experiments. Values of approximately 0.02 and 0.13 mL/g were obtained for conditions where the trichloroethene was in contact with the aquifer material for one day and two years, respectively (Brusseau et al. 1999).

The estimated in situ distribution coefficient is about four times larger than the laboratory value obtained for the aged samples, indicating that the relative mass of trichloroethene contained in sediment samples from well VCW-2 is greater than the relative mass of trichloroethene sorbed by the sediment samples used in the laboratory experiments. If it is assumed that the two years of aging is sufficient to establish equilibrium conditions, and that the spatial variability of sorption is small, the discrepancy suggests the additional mass of trichloroethene associated with the field samples may occur as another phase (i.e.,



**Figure 5.** Relative concentration of bromide measured in effluent during tests 1 and 2, Well VCW-2.

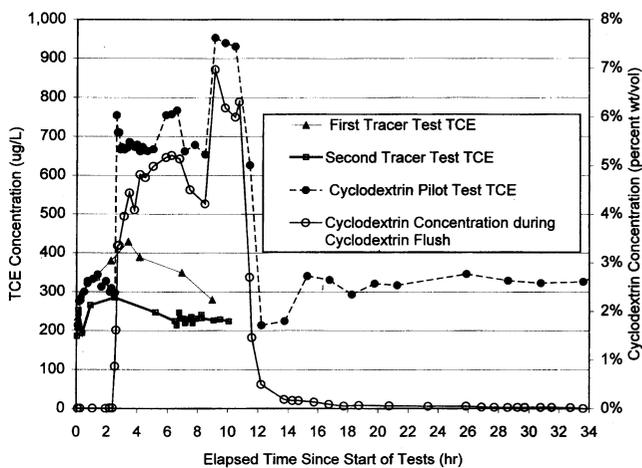
**Table 2**  
Conditions for Tracer and Pilot Tests

	Tracer Test 1	Tracer Test 2	HPCD Test
Test date	10/8/98	10/16/98	10/27/98
Test duration (hrs)	9	10	48
Upper screen injection (L/min)	10.6	7.6	7.6
Diffuser ring injection (L/min)	0	7.6	7.6
Lower screen extraction (L/min)	8.7	14.2	142
Br or HPCD injected conc. (mg/L)	743	733	200,000
Br or HPCD vol. inj. (L)	1006	658	3977
Br or HPCD recovered	12%	34%	54%
Normalized first moment (hrs)	1.2	0.6	1.2

immiscible-liquid saturation). The results of characterization studies conducted at IRP 3 of AFP-44 indicate the presence of immiscible-liquid phase as well as sorbed-phase trichloroethene in the saturated zone. Given the similarities between the two source zones, it is likely that the results obtained for IRP 3 hold for IRP 2 as well. Furthermore, tens of thousands of kilograms of solvent mass have been withdrawn by the soil vapor extraction system operating at IRP 2. Based on mass-balance calculations, it appears probable that immiscible-liquid phase trichloroethene is present in the vadose zone directly above the location of the pilot test.

### Vertical Tracer Tests

Prior to the pilot test of cyclodextrin, two bromide tracer tests were conducted using well VCW-2. In the first test, approximately 1 m<sup>3</sup> of a 743 mg/L bromide solution was injected into the upper screen of well VCW-2 for approximately 1.5 hours. The injection and extraction flow rates for this test were both 10.6 L/min. Relative concentrations of bromide in the water injected and extracted during this test are shown in Figure 5. The peak concentration of bromide in the extracted ground water was less than 20% of the injected concentration. During the test, 12% of the injected bromide mass was



**Figure 6.** TCE and cyclodextrin concentrations in ground water pumped from well VCW-2 during tracer and cyclodextrin tests.

recovered, and the mean travel time of the recovered tracer was 1.2 hours (Table 2).

In an attempt to improve the recovery of the injected bromide solution, a second tracer test was conducted where the tracer solution was injected into the diffuser ring located near the bottom of the upper screened interval of the well (Figure 1). Approximately 0.66 m<sup>3</sup> of a 733 mg/L bromide solution was injected for about two hours. The target tracer injection rate was 7.6 L/min. Concurrent with the tracer injection, potable water was injected into the top of the upper screen at an equal rate. The target extraction rate was equal to the total injection rate of 15.2 L/min. Relative concentrations of bromide in the water injected and extracted during this test are shown in Figure 3. For the second test, the bromide breakthrough curve is similar to that obtained in the first test, but with a shorter travel time and a higher peak concentration. During this test, 34% of the injected bromide mass was recovered and the mean travel time was halved to 0.6 hours (Table 2). The flow configuration of the second tracer test was used for injection of the cyclodextrin solution, which will be discussed below.

The relatively low tracer recovery is a consequence of the short timespan of the study, which was designed to capture only the flowlines of the vertical flow field near the well. It is assumed that the unrecovered tracer mass is associated with the longer flowlines and losses to the regional-gradient flow. As was noted, the travel time for the recovered tracer mass is approximately one hour. Although the travel times are relatively short, it is believed that there was no preferential flow (short circuiting) of the tracer solution through the borehole. The absence of short-circuiting is supported by the existence of the large, stable hydraulic-potential difference between the upper and lower screens intervals (20 m head difference over the 3 m interval) during the tests. In total, the relatively low recoveries and short travel-times of the tracer tests indicate that the area of the aquifer that can be effectively treated in the short duration of the remediation pilot test will be limited to regions in close proximity to the well.

## Vertical Water Flushing of Trichloroethene

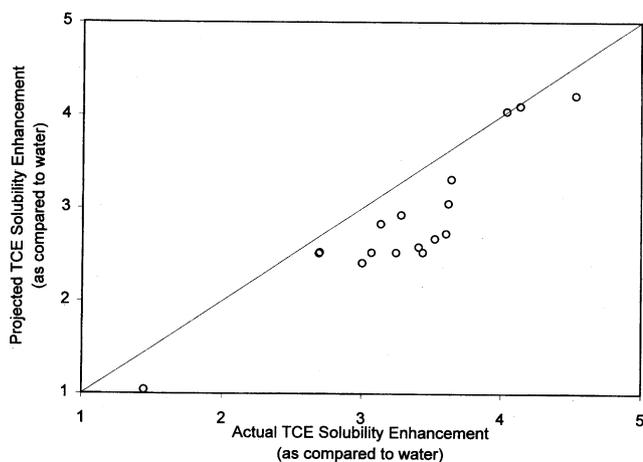
Water and tracer solutions were pumped into and out of VCW-2 four times prior to the cyclodextrin pilot test. Aqueous samples were collected for each event to evaluate the elution behavior of trichloroethene under water-flushing conditions. The first water flush was three hours in duration, during which the concentrations of trichloroethene in the extracted water ranged from 2100 to 3600 µg/L. These concentrations are comparable to the concentrations measured during the initial static-conditions sampling and the well development sampling. The second water flush was two hours in duration during which the concentration of trichloroethene dropped rapidly from 2000 to 300 µg/L. The elution behavior of trichloroethene observed during the first and second bromide tracer tests was similar, with the trichloroethene concentrations remaining relatively constant at approximately 300 µg/L during 10 hours of pumping (Figure 6).

## Vertical Complexing Sugar Flush

On October 27, 1998, 4 m<sup>3</sup> of a 20% by mass solution of HPCD was injected into the diffuser ring of well VCW-2 for 8.5 hours. The target rate of cyclodextrin injection was 7.6 L/min. Simultaneously, potable water was injected into the upper screen at a target rate of 7.6 L/min. Ground water was extracted from the lower screen of VCW-2 at a target rate of 15.2 L/min. The cyclodextrin solution was injected following one hour of recirculating flow and one hour of single-pass flow to establish a quasi steady-state flow field. After the cyclodextrin solution was injected, potable water was injected into the upper screen at 7.6 L/min for 8.5 hours. By the end of the test, approximately 54% of the injected cyclodextrin mass was recovered (Table 2). The mean travel time of the recovered cyclodextrin was 1.2 hours. Both flow rates and water levels were stable during the period of cyclodextrin injection.

The concentration of trichloroethene during the initial phase of water flushing was approximately 300 µg/L, similar to concentrations observed during the previous water flush tests in VCW-2 (Figure 6). The trichloroethene concentration in the extracted ground water increased abruptly to about 800 µg/L soon after introduction of the cyclodextrin solution. This increased concentration was maintained during the 8.5 hours of cyclodextrin flushing. Following the cyclodextrin flush, the system was switched back to water flushing and the trichloroethene concentrations returned to about 300 µg/L in the extracted ground water.

The step change in trichloroethene concentrations is coincident with the arrival of the cyclodextrin pulse (Figure 6). Furthermore, the flow conditions were essentially uniform for the first 15 hours of the test, the time period during which the step change in trichloroethene concentrations occurred. Considering these data, in addition to the fact that the trichloroethene concentrations remained stable at about 300 µg/L during the previous water flush tests, it appears that the introduction of the cyclodextrin solution caused the observed increase in mass of trichloroethene removed from the aquifer system.



**Figure 7. Efficiency of solubility enhancement of TCE.**

The fact that the cyclodextrin solution was able to cause an increase in trichloroethene concentrations indicates that there is sorbed or immiscible-liquid phase trichloroethene mass present in the swept zone. This is consistent with the results of the methylene-chloride extractions and with previous advanced-characterization studies conducted at another source zone within the same trichloroethene plume (Brusseau et. al. 1999). The removal of this mass is apparently constrained during water flushing, and was enhanced by introduction of the cyclodextrin solution. The enhanced removal is consistent with the results of initial bench-scale tests conducted using aquifer material collected from the site, which showed that flushing with HPCD solutions enhanced the contaminant mass removal for systems containing either sorbed-phase or immiscible-liquid phase trichloroethene (Brusseau, unpublished data).

### Comparison of Field and Laboratory Results for Cyclodextrin

It is useful to compare the removal efficiency of trichloroethene observed during the pilot test of cyclodextrin flushing to that expected based on laboratory experiments. The flow conditions during the pilot test were the same as the second bromide tracer test conducted with VCW-2. Thus, the elution of trichloroethene during this second tracer test provides a baseline (i.e., water-flushing performance) for measuring the degree of enhanced trichloroethene removal observed during the subsequent vertical cyclodextrin flush (Figure 6). A solubility enhancement factor can be determined by dividing the trichloroethene concentrations measured for the HPCD flush by those measured for similar times in the preceding water flush of the second tracer experiment. The calculated enhancement factors vary between 1.0 and 4.2.

The estimated solubility enhancement factors based on the pilot-test results can be compared to projected solubility enhancement factors based on laboratory measurements. Wang and Brusseau (1993) determined a linear relationship between apparent trichloroethene solubility and cyclodextrin concentration. For example,

the apparent solubility of trichloroethene in a 5% cyclodextrin solution is 3.5 times greater than the solubility of trichloroethene in pure water. By applying this linear relationship to the measured concentration of cyclodextrin in the ground water extracted during the VCW-2 pilot test, it is possible to calculate the projected trichloroethene concentration enhancement factor for each sample. The actual and projected enhancement factors are presented in Figure 7.

A reference line on the figure indicates a perfect correlation between the degree of enhancement projected from laboratory studies and the degree of enhancement measured from the pilot-tests. The measured degree of trichloroethene removal enhancement correlates relatively well with the expected values. The increase in trichloroethene concentrations caused by the cyclodextrin solution during the VCW-2 pilot test was about 85% of the projected solubility enhancement. Thus, available laboratory trichloroethene solubility data appears to be useful in projecting the performance of cyclodextrin solutions in field applications.

### Conclusions

Removal of contaminants, especially immiscible-liquid contamination, from lower permeability sediments is one of the most challenging problems in site remediation. While cyclodextrin-enhanced vertical flushing does show some promise, the pilot tests have indicated several challenges that would have to be overcome to make full-scale application of this technology practical. The vertical circulation well constructed for the pilot test was intentionally screened over a small thickness of the aquifer so that movement of the injected fluids could be closely controlled and the duration of the pilot test could be minimized. The sediments in the upper portion of the aquifer where this well was constructed are predominantly fine-grained silts and clays that yield relatively small quantities of water. Consequently, the pumping or recharge capacity and the radius of influence of wells completed in these fine-grained units will be relatively small. If vertical circulation wells were installed with the lower screen placed into deeper portions of the aquifer the flow rates and radii of influence would likely be increased. However, previous studies have indicated that the largest trichloroethene concentrations are in the uppermost portion of the aquifer. Thus, installing vertical circulation wells in deeper portions of the aquifer may result in higher pumping rates and larger effective radii, but may not improve the overall removal of trichloroethene from the uppermost fine-grained layers.

The pilot test at IRP site 2 provided evidence that cyclodextrin can increase the rate of trichloroethene removal from the aquifer at AFP-44. In this test, the trichloroethene concentration was increased by a factor of three during the cyclodextrin pulse. The pilot test also showed that trichloroethene can be removed from cyclodextrin solutions using standard air stripping technology with greater than standard air-to-water ratios. As the injected cyclodextrin solution passes through the

aquifer, it becomes diluted with ground water. During the pilot testing, the dilute cyclodextrin solutions pumped from the wells were not reused. The costs of the cyclodextrin solution used in the pilot tests was about \$0.25 per liter. The pilot testing was conducted with a one pass cyclodextrin flush so that a minimum amount of cyclodextrin would be left in the aquifer. The overall costs could be substantially reduced if the cyclodextrin solution were to be reused. If the dilute solutions pumped from the wells were reconcentrated, further cyclodextrin cost reductions could be realized.

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