



ELSEVIER

Journal of Hazardous Materials 68 (1999) 41–71

**Journal of  
Hazardous  
Materials**

www.elsevier.nl/locate/jhazmat

# Design and construction techniques for permeable reactive barriers

Arun R. Gavaskar \*

*Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201-2693, USA*

---

## Abstract

Adequate site characterization, bench-scale column testing, and hydrogeologic modeling formed the basis for the design and construction of permeable reactive barriers for groundwater remediation at various sites, such as Dover Air Force Base, DE and Naval Air Station, Moffett Field, CA. Dissolved chlorinated solvents, such as perchloroethylene (PCE) and trichloroethylene (TCE), have been the focus at many sites because the passive nature of the reactive barrier operation makes such barriers particularly useful for treating groundwater contaminants that can persist in the aquifer for several years. A combination of conventional and innovative site characterization, design, and construction techniques were used at these sites to increase the potential cost effectiveness of field application. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Permeable reactive barriers; Perchloroethylene; Trichloroethylene

---

## 1. Introduction

Permeable reactive barriers are an emerging alternative to pump-and-treat systems for treating groundwater contamination. The main advantage of a reactive barrier (Fig. 1) is the passive nature of the treatment. That is, for the most part, its operation does not depend on any external labor or energy inputs. Once installed, the barrier takes advantage of the in situ groundwater flow to bring the contaminants in contact with the reactive material. Considerable research [1,2], some field-pilot tests [3], and a few

---

\* Tel.: +1-614-424-2403; fax: +1-614-424-3667.

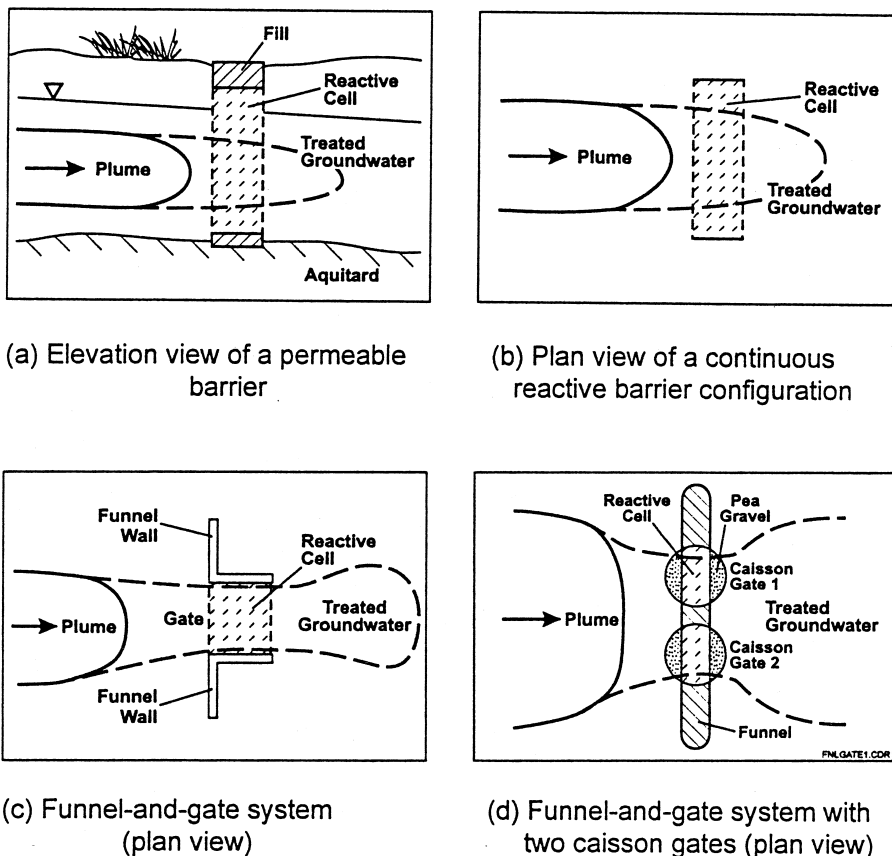
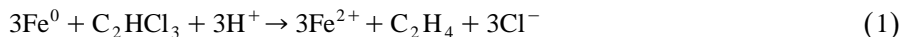


Fig. 1. Different permeable reactive barrier configurations for groundwater treatment.

full-scale applications have been conducted over the last 5 years to demonstrate the potential of this technology. A passive treatment system is especially desirable for contaminants such as chlorinated solvents, where the plume is likely to persist for several hundred years.

The reactive material used in the barrier may vary depending on the type of contaminants being treated. The most common reactive medium used so far has been granular iron. Zero-valent iron is a strong reducing agent that can abiotically reduce dissolved contaminants, such as perchloroethylene (PCE), trichloroethylene (TCE), and other chlorinated solvents.



Ethene and ethane are the main products of TCE degradation. However, indications are that these final reaction products are generated through multiple pathways. By the

hydrogenolysis pathway, TCE degrades to *cis*-1,2-dichloroethylene (DCE), which in turn degrades to vinyl chloride (VC). Both DCE and VC are fairly persistent under the reducing conditions of the iron medium and degrade to ethene and ethane relatively slowly. Fortunately, only 5% or less of TCE appears to take this pathway. Most of the TCE appears to degrade to ethene and ethane by the beta-elimination pathway [4], through the formation of intermediates, such as acetylene. These intermediates are short-lived and quickly degrade to ethene and ethane.

Other contaminants, such as dissolved chromium and uranium, which are amenable to reduction by iron can also be treated by precipitating them out of the groundwater.

The groundwater itself may have some native constituents, such as dissolved oxygen (DO) or carbonates, which react with and consume the reactive medium. Water itself is reduced, although slowly, by zero-valent metals such as iron.



These inorganic constituents could potentially affect the reactive and hydrologic properties of the reactive medium. A possible scenario can be envisioned whereby precipitation of hydroxides and carbonates causes loss of reactive surfaces and reduction in hydraulic conductivity of the reactive medium. This could affect the operation of the barrier by causing the plume to break through or bypass the reactive medium. However, a reactive iron barrier that was installed 5 years ago at Borden, Canada [1] has yet to show any significant effects from such precipitation reactions. With new research underway to rejuvenate the reactivity and hydrologic characteristics of a reactive barrier without resorting to excavation and replacement of the reactive medium, it is hoped that any maintenance required in the future will be relatively infrequent and inexpensive.

The design of a permeable barrier should account for all these variables, including contaminant degradation rates, groundwater flow, and native groundwater constituents.

## 2. Barrier design

Fig. 2 shows the steps in the design of a permeable reactive barrier. These steps involve the determination of:

- Suitability of a site for permeable reactive barrier application,
- Site characteristics affecting barrier design,
- Reaction rates or half-lives (through column testing),
- Location, configuration, and dimensions of the barrier,
- Longevity,
- Monitoring strategy,
- Cost.

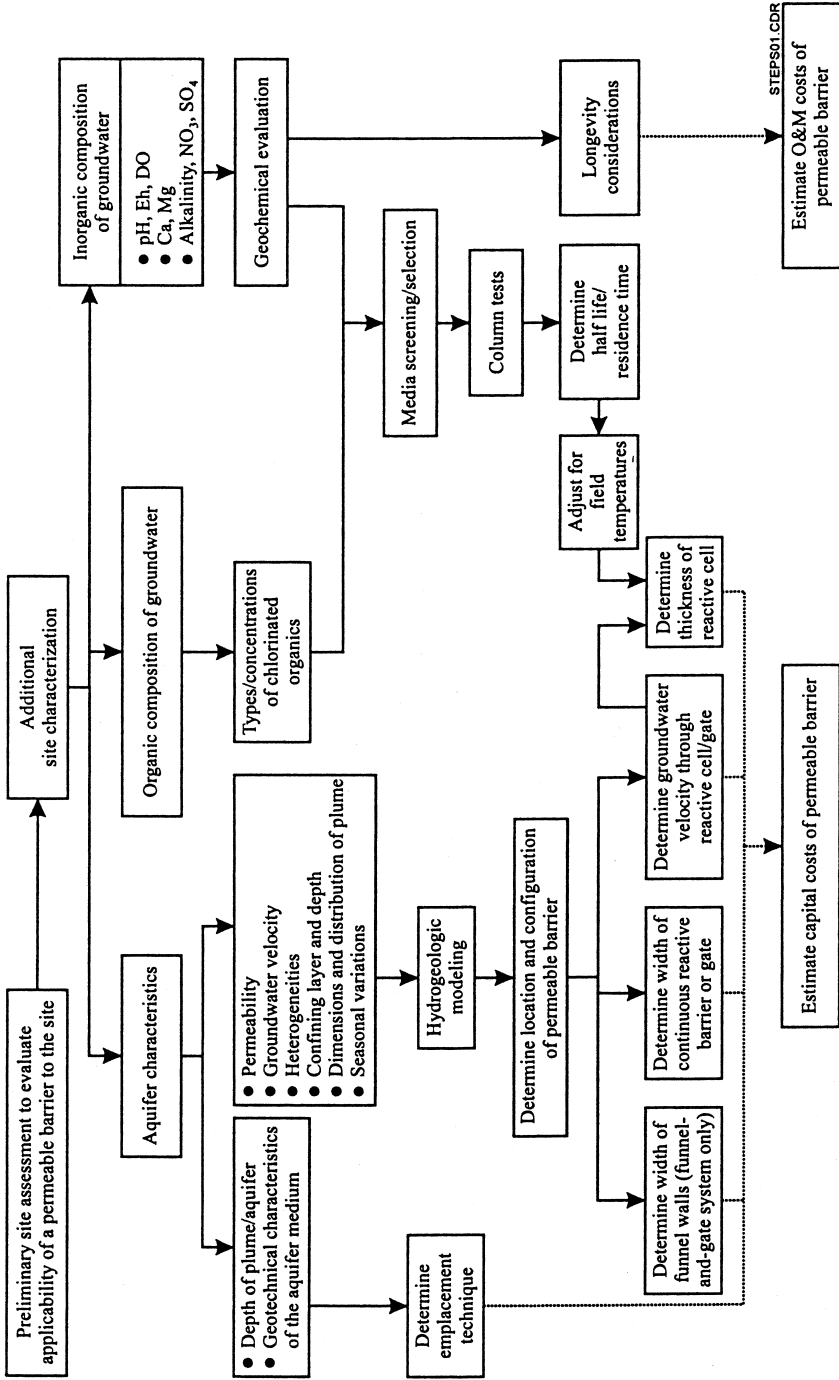


Fig. 2. Steps in the design of a permeable reactive barrier.

### 2.1. Preliminary site assessment

Generally, a review of existing site documents, such as RCRA Facility Investigation (RFI) or Remedial Investigation/Feasibility Study (RI/FS) reports, and a visual examination of the layout of the site form the basis for a preliminary assessment of the feasibility of a permeable reactive barrier. Existing site documents may be scrutinized for the following information.

- *Types of contaminants.* Are the contaminants suitable for degradation by materials, such as iron, that are usable in a permeable barrier. Of course, newer reactive materials could be developed for specific contaminants. But so far, reactive metals (e.g. iron) and magnesium dioxide (oxygen provider) have typically been used in field barriers.

- *Contaminant distribution.* Although the plume and aquifer dimensions are not an insurmountable hurdle, very deep plumes or very wide plumes can increase the barrier cost. That being said, barriers have so far been applied to plumes that are as wide as 1000 ft. (at the Denver Federal Center) and as deep as 40 to 50 ft. deep (Dover Air Force Base and Somersworth Landfill Site). Innovative installation techniques, such as jetting and hydrofracturing, appear promising for overcoming the depth limitation. A competent aquitard is desirable so that the barrier can be keyed in. Hanging barriers (barriers that are not keyed into the aquitard) have been modeled, but great caution would be necessary in the field to ensure that the plume does not find a way under the barrier.

- *Groundwater velocity.* Extremely fast-moving groundwater may require a thicker barrier to ensure adequate residence time (contact time between the contaminants and the reactive medium) and this may increase cost. Extremely slow-moving or stationary groundwater may prevent contaminants from coming into contact with the reactive medium in any reasonable time frame. Most sites are likely to be between these two extremes.

- *Geotechnical considerations.* Access to the plume is a major consideration for application of a permeable barrier. An overlying building or a plume that has moved off property boundaries are factors that may limit access to the plume. Underground utility lines can make installation of a barrier difficult. The presence of cobbles or highly consolidated sediments in the subsurface may impede installation equipment.

None of these factors are insurmountable, but it is important to consider them so that a realistic preliminary assessment of the technical, economic, and administrative feasibility of a permeable barrier is obtained for the site. Prospective locations for the barrier are generally established at this stage.

### 2.2. Site characterization

Unlike a pump-and-treat system, which can be relocated or scaled up or otherwise modified after installation, a permeable barrier is a more or less permanent structure. Once placed in the ground, it would be difficult and expensive to relocate or modify. Therefore, a good understanding of the aquifer and plume characteristics is necessary to enable a good barrier design. Usually, this requires some additional site characterization

with emphasis on the regions surrounding prospective barrier locations. A good conceptual and, most often, a computerized model of the groundwater flow system should be generated with the site characterization data to aid in the design.

The first and foremost site characteristic that should be properly defined, if not already done, is the exact distribution of the contaminants. This includes both the horizontal and vertical extent of the plume. The plume may be defined by one or, at many sites, multiple contaminants. Because achieving maximum contaminant levels (MCLs) for the target contaminants is usually the treatment goal, the outer edges of the plume are defined by these concentrations. Mapping the contaminant distribution well is important for several reasons. It helps in designing a location and configuration of the barrier that optimizes the treatment process. For example, at the Naval Air Station, Moffett Field, CA site, the plume was several hundred feet wide. However, most of the contamination appeared to be flowing through discrete sand channels. In this situation, a funnel and gate system with the gate located in the sand channel and the funnel covering the surrounding fine-grained sediments was found to be an efficient way of capturing and treating the contamination.

Aquifer characteristics are important to define at a localized level in the vicinity of the prospective barrier location. The operation of the barrier depends on the ability of the targeted portion of the groundwater to flow through the reactive cell. If the flow characteristics are poorly understood, the permeable barrier may not efficiently perform its hydrogeologic function of channeling the targeted groundwater through the reactive cell.

The required aquifer information includes the distribution of different hydrostratigraphic units and the hydrologic flow characteristics. Mapping out variations in depth, thickness, and water levels of various hydrostratigraphic units in the subsurface in the vicinity of the barrier is important in design and construction of the barrier. This can be done by drilling and sampling several locations using a conventional drill rig. Recently, new direct push methods such as cone penetrometer testing (CPT) and GeoProbe™ have been used at several sites. These new techniques are quicker than conventional drilling and are useful for mapping localized heterogeneities in the immediate vicinity of the prospective barrier location. These heterogeneities can then be inserted into the groundwater flow model developed for the site.

Fig. 3 shows a geologic cross-section prepared as a result of CPT work conducted at the Dover Air Force Base barrier site. The CPT incorporates a specially-instrumented push rod that is capable of physical measurements, such as tip stress, pore pressure, and friction ratio, that are indicative of different geologic zones. By pushing the CPT rod in multiple locations, the geologic map depicted in Fig. 3 was prepared. It identifies variations in aquitard depth and shows a few clay lenses near the water table. Water levels were measured during the CPT work by installing hollow tubes screened at appropriate depths. These rods also served as temporary wells for collecting groundwater samples for mapping the plume. After measuring water level measurement and sampling groundwater, these tubes were pulled out of the ground and the holes were grouted. Based on historical data, the water levels under seasonal high and low flow conditions were also plotted on the same cross-section. This hydrostratigraphic map was used to determine the depths of the top and bottom of the barrier. At the Moffett Field

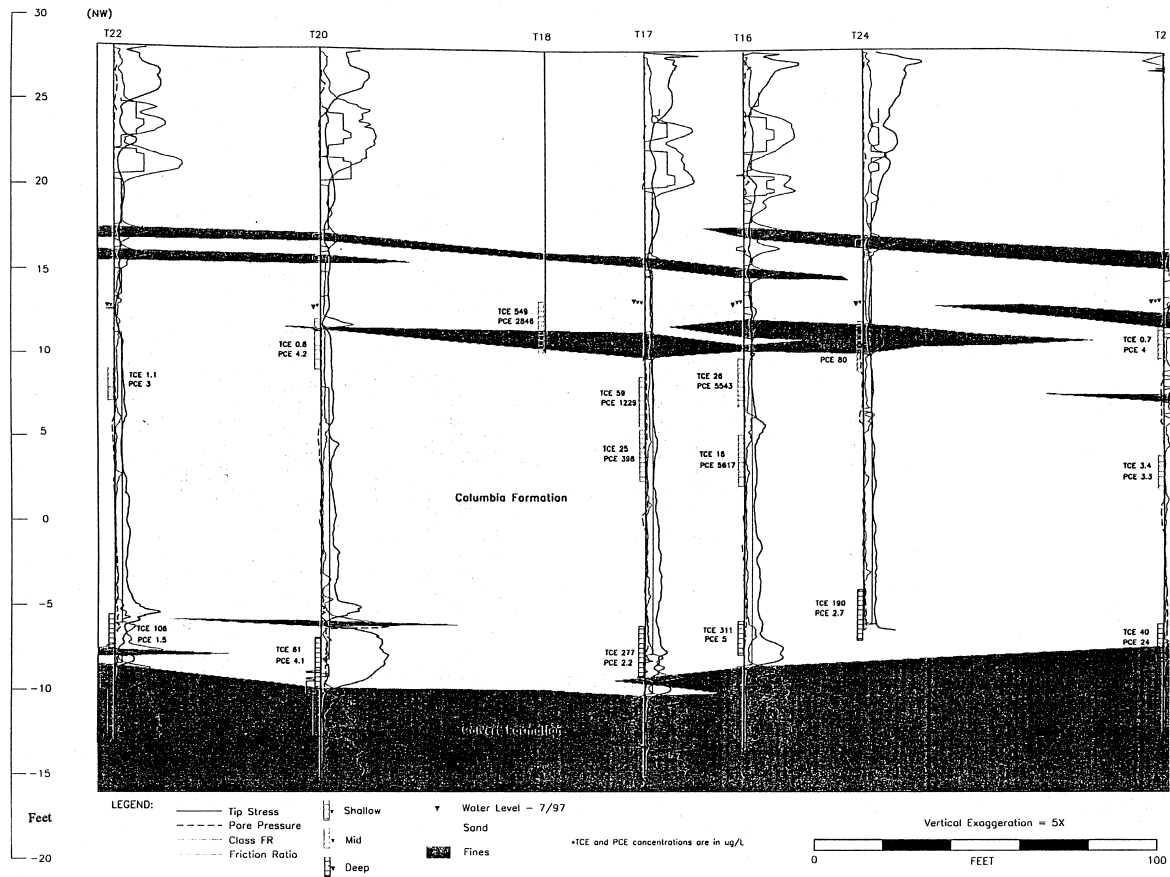


Fig. 3. A geologic cross-section depicting the region in the immediate vicinity of a permeable barrier at Dover Air Force Base.

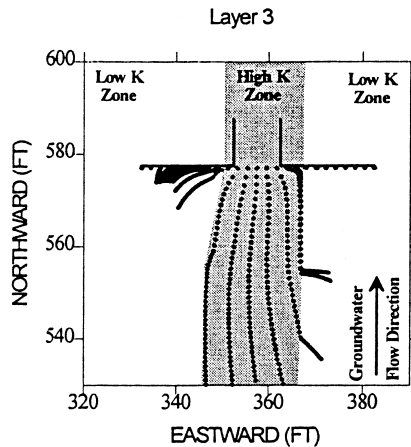


Fig. 4. Locating the gate of a funnel-and-gate system in a sand channel at Moffett Field.

site, CPT work was used to identify the exact location of a sand channel (see Fig. 4) through which most of the contaminated groundwater was flowing. Consequently, the reactive cell was installed in this sand channel. At both sites, localized CPT data supplemented data from more widely-dispersed conventional wells present on the property.

### 2.3. Reaction rates or half-lives of contaminants

Reaction rates or half-lives of contaminants in contact with the reactive medium are necessary to determine the reactive cell thickness that will provide adequate residence time for the contaminants to degrade to their MCLs. Both batch and continuous column tests have been used in the past to determine reaction rates. Because continuous tests better simulate the dynamic groundwater flow environment, testing in columns is by far the most common method.

#### 2.3.1. Test materials and methods

Column testing is a better way of estimating reaction rates. The design of the column apparatus used in a recent test with TCE-containing groundwater obtained from a site in Ohio is shown in Fig. 5. The resulting concentration vs. time data are shown in Table 1. The column was made from Plexiglas™. Strictly speaking, glass should be expected to have the least adsorptive or reactive effect with chlorinated organic compounds; however, no significant loss of organics has been reported using Plexiglas™ columns. All fittings were stainless steel. Tubing is either stainless steel or Teflon™. A small section of tubing through the peristaltic pump was made of Viton™ for more flexibility.

The reactive medium used in this test was granular iron (Peerless Metal Products) in the  $-8 + 50$ -mesh particle size range. The column was packed with the reactive



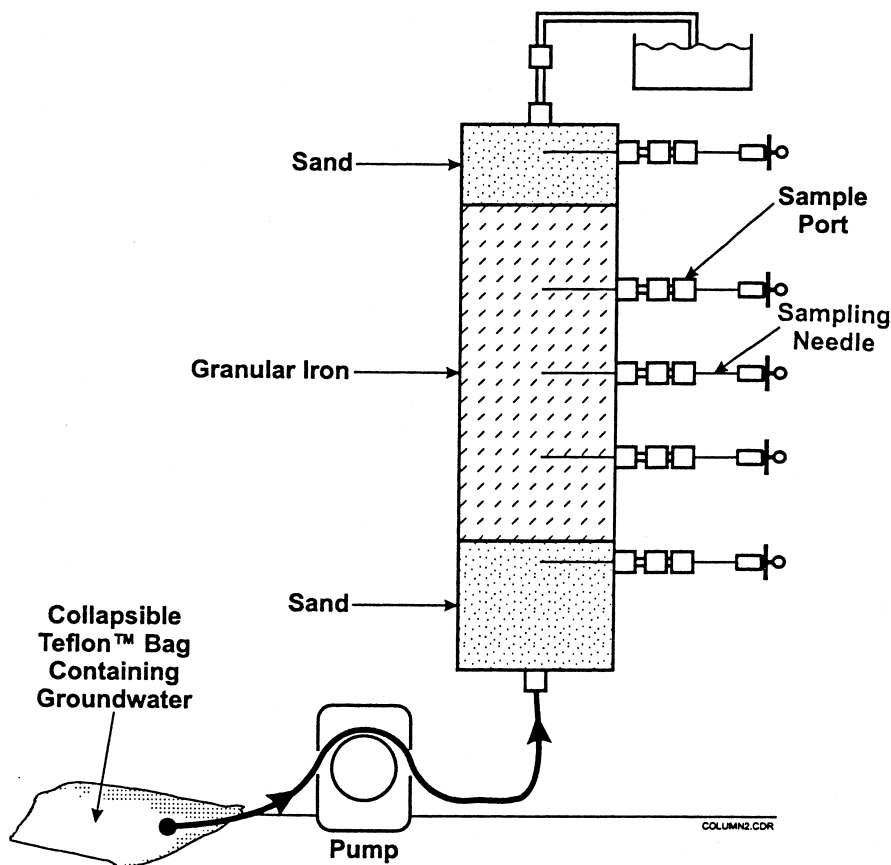


Fig. 5. Column testing set up for estimating contaminant degradation rates.

medium in such a way as to ensure a homogeneous matrix. Layers of sand were placed above and below the reactive medium in the column to ensure good flow distribution. Average bulk density, porosity, and pore volume, were measured by weight.

Table 1

Results of a column test with TCE-containing groundwater from a site in Ohio

Column port	Residence time in iron (min)	TCE ( $\mu\text{g}/\text{l}$ )	DCE ( $\mu\text{g}/\text{l}$ )	VC ( $\mu\text{g}/\text{l}$ )
Influent	0	2644	0	0
A	26	1141	25	6
B	59	645	38	10
C	94	268	46	13
D	131	81	41	14
Effluent	157	61	35	14

The feed water was placed in a collapsible Teflon™ bag to prevent headspace as the bag emptied out. The bag was filled by gravity flow to avoid aeration of the water. Water was circulated in the column from bottom to top to better simulate the flowrates likely to be encountered in the field. Sampling ports were equipped with gastight and watertight fittings. A nylon swage lock fitting was used on the sample port. The sampling syringe needles remained inserted into the column during the test, with the tip at the center of the column. Valves with luer lock adapters were attached to the protruding ends of the needles outside the column. A luer lock plug was used to seal the needle between samples.

Sampling began only after the concentration distribution in the column had reached steady state; that is, the net contaminant mass entering the column was equal to the mass degraded in the column. About 40 pore volumes of contaminated water were required to be run through the column before it reached steady state. Prior research [5] shows that the time (or number of pore volumes of groundwater flow) required to reach steady state varies with contaminant type. For example, water contaminated with PCE requires a longer time to reach steady state than does water contaminated with TCE.

Whenever a sample was to be drawn, a syringe was attached to the luer lock adapter on the needle and the sample was collected after a small amount of water is purged from the needle. The sample was drawn very slowly to create minimum disturbance in the flow. Most researchers conduct column experiments at room temperature. It is important to note, however, that temperature may be an important factor influencing reaction rate.

The flowrate through the columns was set to simulate site conditions. Therefore, it is desirable to have good groundwater velocity data from the site at the location of the proposed barrier. Also taken into account was the fact that local groundwater velocity through the permeable barrier may be different from that in the surrounding aquifer. Actual flowrates through the column were measured by collecting a timed volume of effluent. The experiment was repeated over a range of flowrates to account for seasonal variations and other uncertainties. However, flowrate may not be a critical parameter for column testing. Prior research [6] indicates that degradation rates were insensitive to flowrates in the range tested (59 to 242 cm/day). However, designing the flow through thickness of the reactive cell does require an accurate estimate of groundwater velocity.

Concentration profiles (plots of TCE concentration vs. time or distance in the iron zone) were generated periodically for the chlorinated organics distribution in the column by collecting and analyzing samples from the influent, the effluent, and the intermediate sample ports after every 5 to 10 pore volumes. Redox potential (Eh) and pH profiles of the column were generated less frequently because of the higher sample volumes required for taking these measurements with typical probes. The column influent and effluent were analyzed for inorganics, such as major cations (Ca, Mg, Mn) and major anions (Cl, SO<sub>4</sub>, and NO<sub>3</sub>), and alkalinity (bicarbonate).

Analysis of water samples collected from the column was done by the same general methods used for analyzing groundwater samples during site characterization. Concentrations of chlorinated VOCs were measured using a gas chromatograph–flame ionization detector (GC-FID) with purge and trap equipment. Water samples typically are drawn through sampling needles into a gastight syringe and are injected directly into the purge and trap through luer-lock adapters. Although chlorinated compounds can be

detected using an electron capture detector (ECD), the GC-FID is suitable for general-purpose work because it can detect both a broad range of low-molecular-weight chlorinated compounds (e.g. TCE, DCE, and VC), as well as nonchlorinated hydrocarbon byproducts such as ethene or ethane. The instrument was calibrated to detect compounds at the lowest concentrations feasible. A typical detection limit for chlorinated hydrocarbons is  $2 \mu\text{g}/\text{l}$ , provided that there is no strong matrix interference that requires dilution of the primary sample.

Anions were measured using ion chromatography (IC) and cations by inductively coupled plasma (ICP). Eh and pH were measured by inserting combination electrodes in a flow-through cell, into which water withdrawn from one of the column ports was circulated.

### 2.3.2. Interpretation of column test results

Strictly by Eq. (1), the reaction rate appears to depend on the concentrations of TCE,  $\text{Fe}^0$ , and  $\text{H}^+$ . However, assuming an abundance of  $\text{Fe}^0$  and  $\text{H}^+$  relative to TCE, the reaction rate can be viewed as dependent primarily on the concentration of TCE, thus, making it a pseudo-first order reaction.



Previous research has indicated the validity of this pseudo first-order assumption of the degradation reaction of chlorinated organic compounds with iron [7,2]. Therefore, the reaction rate ( $r$ ) can be expressed in terms of the concentration ( $C$ ) of the reactant (say TCE) and the reaction rate constant ( $k$ ).

$$-r = \frac{-dC}{dt} = kC \quad (6)$$

Therefore,

$$C = C_0 e^{-kt} \quad (7)$$

Or,

$$\ln(C/C_0) = -kt \quad (8)$$

$C_0$  is the initial concentration of TCE; that is, the concentration in the groundwater entering the reactive iron zone. It should be noted that because TCE is being degraded by two competing pathways,  $k$  is the sum of the rate constants. The flow of groundwater through the iron-filled column is assumed to be plug flow, which means that all elements of the influent groundwater experience the same residence time in the column.

The concentrations of TCE, DCE, and VC measured in the influent and effluent and in ports A, B, C, and D in the reactive iron zone are plotted on the graph shown in Fig. 6a. The  $x$ -axis can represent the linear distance traveled by the groundwater from the inlet end of the iron zone or the residence time of the groundwater in the iron zone. The residence times in Table 1 were obtained from measurements of the volumetric flowrate

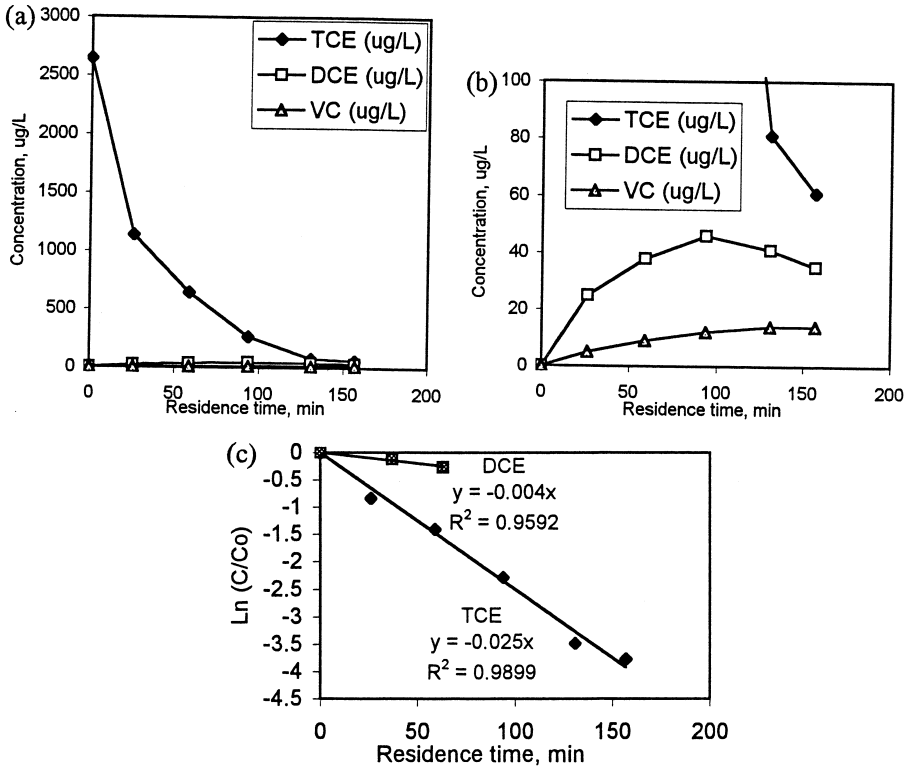


Fig. 6. Plots of chlorinated VOC concentration vs. residence time in the reactive iron.

( $Q$ ), the linear distance traveled in the iron zone ( $L$ ), the cross-sectional area of the column ( $A$ ), and the porosity ( $n$ ) by the equation:

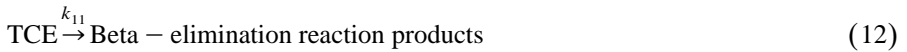
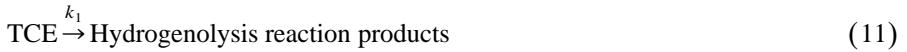
$$t = \frac{LAn}{Q} \tag{9}$$

If instead of plotting  $C$ , as in Fig. 6a,  $\ln(C/C_0)$  is plotted against residence time as in Fig. 6c, the slope of the regression line represents the reaction rate constant  $k$ , based on Eq. (8). For the groundwater from this test site, the slope or  $k$  was 0.025/min for TCE. The goodness of fit ( $R^2$ ) of the linear regression line is almost 0.99 indicating first-order kinetics.

Another way of expressing the reaction rate of TCE is in terms of its half-life with respect to iron. The half-life is the time it takes to reduce the concentration of TCE to half its initial value, that is for  $C = 0.5 (C_0)$ . Rearranging Eq. (8), the half-life can be represented as:

$$t_{0.5} = \frac{\ln 2}{k} \tag{10}$$

For the particular type of iron used with the groundwater from the Ohio site, the half-life for TCE was estimated as 28 min. It should be noted that because of multiple reaction pathways, the  $k$  for TCE degradation is in reality the sum of the individual reaction rates,  $k_1$  and  $k_{11}$ , from the following parallel pathways:



The estimation of reaction rates or half-lives for DCE and VC is not as straightforward, since they are produced as a result of hydrogenolysis of TCE, but are themselves degraded. Fig. 6b shows a close-up of the DCE and VC curves in Fig. 6a. The generation and degradation of DCE can be represented by the first-order series reactions,



The concentration of DCE at time,  $t$ , can be represented by:

$$r_{\text{DCE}} = k_1 C_{\text{TCE}} - k_2 C_{\text{DCE}} \quad (14)$$

However, from a practical sense, since it is  $k$  that is determined experimentally and not  $k_1$ , it would be difficult to estimate both  $k_1$  and  $k_2$  empirically. Therefore, the following simplified approach is used for estimating the half-life of DCE.

As seen in Fig. 6b, until about 94 min, the concentration of DCE continued to rise. As TCE was depleted, the rate of degradation of DCE overtook the rate of generation of DCE, and the DCE concentration started falling. This is because beyond 94 min, the reaction rate of DCE in Eq. (14) is governed primarily by the DCE concentration and  $k_2$ :

$$r_{\text{DCE}} = -k_2 \frac{dC_{\text{DCE}}}{dt}$$

Therefore,  $C_{\text{DCE}} = C_{\text{DCE}_0} e^{-k_2 t}$  beyond the point of maximum concentration. Here,  $C_{\text{DCE}_0}$  is the maximum observed concentration of DCE. Thus, if  $\ln(C/C_0)$  is plotted vs.  $t$ , for  $t > 94$  min, the slope of the regression line is the reaction rate  $k_2$ . For the experimental data in Table 1,  $k_2$  was estimated to be 0.004/min. The  $R^2$  value shows a reasonably good fit for this assumption. The half-life of DCE then is 173 min.

The half-life of VC is difficult to estimate from the experimental data in Table 1, even by the type of simplification used for DCE. In Fig. 6b, the concentration of VC is just beginning to show signs of peaking. To estimate a reaction rate for VC, either the column used would have to be longer or the water flowrate would have to be slowed down enough to see a decline in VC concentration. Then, the same approach could be applied to VC. Using a slower water volumetric flowrate through the column, and using an approach similar to the one used for DCE, the VC half-life was found to be 186 min.

#### 2.4. Design of a permeable barrier at Dover Air Force Base

A permeable barrier was designed and installed at Dover Air Force Base in December 1997 to partially capture and remediate a groundwater plume containing PCE, TCE, and

DCE. The design involved a determination of the barrier location, configuration, and dimensions.

#### 2.4.1. Barrier location

Once the targeted Dover Air Force Base plume had been adequately mapped out, determining a suitable location for the barrier depended on hydrologic, geotechnical, and administrative considerations.

- Hydrologic considerations generally dictate that the barrier be placed just downgradient from the edge of the plume and oriented perpendicular to the groundwater flow for the most efficient capture of the plume. In this way, all of the contamination can be treated and the plume is prevented from moving any further toward potential receptors. The presence of preferential flow pathways (such as sand channels) may also guide the location of the continuous reactive barrier or gate (in a funnel-and-gate system). At the Dover site, the barrier was located within the plume to capture the more contaminated portions of the plume.

- Geotechnical considerations for locating the barrier may include the presence of underground utilities, cobbles, or highly consolidated sediments. These factors will increase the difficulty of installation. The presence of buildings or other aboveground structures may also impede installation in certain areas. Underground utilities at the Dover site were the main concern that necessitated locating the barrier a few feet away from the hydrologically optimal location.

- Administrative considerations guiding the location of the barrier may include a situation where the plume has moved off the property boundaries. At the Sunnyvale, CA site, regulators have been amenable to placing the barrier within the property boundaries while letting natural attenuation take its course on the off-property portion of the plume. In such cases, site characterizations should reveal the presence of degradation byproducts (such as *cis*-1,2-DCE and VC) or other indicators of natural attenuation. At the Dover site, keeping a high-traffic road operational during construction guided, to some extent, the location of the barrier.

#### 2.4.2. Barrier configuration

Two common configurations of the permeable reactive barrier are a continuous reactive barrier and a funnel-and-gate system (Fig. 1). A continuous reactive barrier consists of a reactive zone only. In a funnel-and-gate system, the reactive cell or gate is flanked by impermeable wing walls or funnel. During the initial stages of development of this technology, when the cost of granular iron was around US\$650/ton, the funnel-and-gate configuration was perceived as a cost saving design that enabled the efficient use of iron in capturing a large plume. With the cost of iron dropping to US\$350/ton, the comparative advantages of a funnel (which requires construction of impermeable barrier sections with the associated cost) became less obvious. Recent field installations have been mostly of the continuous reactive barrier configuration. New reactive cell construction innovations such as the continuous trencher and the falling cost of iron have encouraged site managers to absorb the relative inefficiency of iron usage in a continuous reactive barrier as compared with the cost of the impermeable sections of a funnel and gate system.

There may still be some situations where a funnel-and-gate system appears more attractive. At the Dover site, a funnel-and-gate configuration was selected over a continuous barrier configuration for two reasons. Firstly, the aquitard was too deep (at 40 to 45 ft.) for the use of new cost effective trenching techniques, such as the continuous trencher. Secondly, the presence of subsurface utilities in the vadose zone above the plume made installation of a continuous trench difficult. It was easier to install a funnel-and-gate system with two caisson-installed gates and sheet pile funnels. The caisson-installed gates were located between the utility lines. One of the utility lines ran across the proposed funnel location. This line was cut and rejoined over the funnel after installation of the sheet piles. Another situation where a funnel-and-gate system was perceived to be the better option was at Moffett Field, where most of the contamination was traveling through sand channels that were inter-braided with silt and clay deposits. A trench gate was installed in the sand channel to capture the bulk of the contamination and funnel walls were installed in the inter-channel deposits to capture the rest.

#### 2.4.3. Determination of residence time requirements

The required residence time for the groundwater flowing through the reactive zone depends on the half-lives of the contaminants and their influent concentrations. At the Dover Air Force Base site, half-lives of PCE, TCE, DCE, and VC (Table 2) were determined from column tests using groundwater obtained from the site [8]. Because the plume is moving, the barrier is likely to encounter progressively higher concentrations over time. Typically, the maximum concentrations that are likely to reach the barrier are used for barrier design. For the Dover groundwater plume, the conservative design concentrations shown in Table 2 were assumed, although the current concentrations at the barrier locations are much lower.

The residence time estimates in Table 2 are based on the number of half-lives required to reduce the influent concentration of each contaminant to below its clean up

Table 2  
Residence time requirements for the Dover Air Force Base, DE site

Contaminant	Maximum expected concentration ( $\mu\text{g}/\text{l}$ )	MCL ( $\mu\text{g}/\text{l}$ )	Half-life (h)	No. of half-lives to reach MCL	Residence time in iron (h)
PCE	10000	5	0.5	12	6
TCE	1000	5	0.5	8	4
DCE	1000*	70	1.5	4	6
VC	500*	2	1.5	8	12

\* Native concentration plus about 5% of PCE + TCE.

\*\* Maximum residence time based on degradation rates = 12 h.

Temperature correction factor (assuming 10°C in the field vs. 20°C in the laboratory) = 2.

Temperature corrected residence time = 24 h.

Bulk density correction factor = 1.5.

Corrected residence time = 36 h.

Safety factor = 2.

Design residence time = 72 h.

target (MCL in this case). For example, because TCE requires eight half-lives for its concentration to decline below 5  $\mu\text{g}/\text{l}$ , the corresponding residence time is 4 h. Interestingly, VC turns out to be the limiting contaminant with a residence time requirement of 12 h.

#### 2.4.4. Correction factors and safety factors

The laboratory column test was conducted at room temperature, which was around 20 to 25°C. However, the groundwater in the Dover aquifer tends to be cooler at around 10°C. Previous studies have shown that the reaction rate is affected by temperature.

Previous research [9] provides some discussion on the use of Arrhenius temperature dependence to adjust for the effects of temperature on degradation rate of organic compounds. The Arrhenius equation relates the reaction rate ( $k$ ) to absolute temperature ( $T$ ) as follows:

$$k \propto e^{-E/RT} \quad (16)$$

where  $E$  is the activation energy, and  $R$  is the universal gas constant (8.314 J/mol K). Eqs. (5) and (4) can be rearranged as:

$$\ln k = \ln A - \frac{E}{RT} \quad (17)$$

where:  $k$  = the first-order reaction rate constant;  $A$  = frequency factor for the reaction;  $E$  = activation energy;  $R$  = ideal gas constant;  $T$  = absolute temperature.

A plot of  $\ln k$  vs.  $1/T$  should give a straight line with a slope of  $-E/R$  and an intercept on the  $1/T$  axis of  $\ln[A/(E/R)]$ . This approach can be used if the column experiment can be repeated at several controlled temperatures. In the absence of detailed column studies at a range of temperatures, field observations at previous sites can be used as a guide.

Field observations at a reactive barrier site in New Jersey indicate that the degradation rate declined by a factor of 2 to 2.5 at temperatures of 8 to 10°C compared with laboratory rates [10]. Similar results have been observed at other field sites. Based on these field indicators, a factor of 2 was applied as a correction for temperature to the residence time calculated for the Dover site, resulting in a corrected residence time requirement of 24 h instead of 12 h.

Another correction factor that needs to be applied to the measured reaction rate or residence time is one that accounts for the differences in bulk density (or porosity) observed between field and laboratory applications. Recent reports from various sites have indicated that bulk densities of granular iron ( $-8 + 50$  mesh) in field barriers tends to be between 140 to 180 lb/ft.<sup>3</sup> (corresponding to porosities of 0.7 to 0.6). On the other hand, most column studies have reported bulk densities of 210 to 257 lb/ft.<sup>3</sup> (corresponding to porosities of 0.55 to 0.45). This indicates that the field reactive cell is likely to have more voids due to differential compaction than laboratory columns. Although steps can be taken to improve the distribution of iron throughout the reactive cell, differential compaction will probably remain to some extent. This means that the



groundwater flowing through a field reactive cell encounters less iron surface area (and consequently fewer active sites) per unit volume of the cell as compared with a laboratory column. Therefore, as compared to reaction rates calculated with laboratory columns, differential compaction during field application is expected to provide a slower reaction rate, as this rate is dependent on the iron surface area encountered. To offset the reduced iron surface area encountered by the groundwater, the thickness of the reactive cell should be increased by a similar factor. At the Dover site, a bulk density correction factor of 1.5 was applied to obtain a residence time requirement of 36 h instead of 24 h.

In addition to these two known deviations from laboratory conditions, there may be other factors that create some uncertainty in the residence time estimate for the field application.

- The barrier may encounter much higher concentrations than planned for over its useful lifetime if the plume continues to develop. Over time, the influent contamination could contain a relatively higher proportion of DCE and VC if there is some natural attenuation occurring upgradient. DCE and VC typically react more slowly with iron than TCE or PCE.

- There may be some uncertainty in the groundwater velocity estimated in the aquifer and in the reactive cell. Relatively flat gradients at the site can make velocity determination on the localized scale of the barrier difficult.

To account for such uncertainties at the Dover site, a safety factor of 2 was used to obtain a final design residence time of 72 h instead of 36 h. At other sites, the safety factor will depend on the scientific judgement of the project team regarding the perceived magnitude and impact of such uncertainties.

#### 2.4.5. Barrier dimensions

The three barrier dimensions that need to be designed are the thickness, width, and depth. The thickness and width depend partly on the selected configuration (continuous reactive barrier vs. funnel and gate) and are somewhat interrelated.

The thickness ( $b$ ) of the barrier is determined by the groundwater velocity ( $v$ ) and the residence time ( $t$ ) required.

$$b = vt \quad (18)$$

Although the residence time requirement is relatively fixed based on the contaminant reaction rates, it should be noted that the groundwater velocity in this equation is the velocity through the reactive cell and not the velocity in the aquifer. This reactive cell velocity may vary based on the relative porosities and hydraulic conductivities of the aquifer and the reactive cell, as well as the width of the funnel (in a funnel-and-gate system) and funnel-to-gate ratio. These variables have to be optimized to determine design dimensions of the gate.

The width of the barrier and the funnel-to-gate ratio (in the case of a funnel-and-gate system) depends on the relative hydraulic conductivities of the reactive cell and the surrounding aquifer. The higher the conductivity of the reactive cell the lesser the width, because a smaller barrier can capture the same volume of water. The granular iron (– 8 + 50 mesh) used at Dover had a hydraulic conductivity of around 283 ft./day. The

Table 3  
Design parameters for the permeable barrier at Dover Air Force Base

Design parameter	Target value	Expected range based on uncertainties in design
Residence time in iron zone	3 days (72 h)	3 to 15 days <sup>a</sup>
100% iron zone thickness	4 ft.	–
Gate width	4 ft.	–
No. of gates	2	–
Funnel widths (three sections)	15–30–15 ft.	–
Hydraulic capture zone width	30 ft. (targeted portion of plume)	50 to 55 ft. <sup>b</sup>

<sup>a</sup>Accounts for uncertainties in groundwater velocity measurements due to relatively flat gradient at the site.

<sup>b</sup>Extra capture designed to account for changes in seasonal groundwater flow direction.

aquifer conductivity was assigned a range of 10–50 ft./day based on results of several slug tests. The relatively broad range of aquifer conductivities was necessary because a relatively flat gradient at the site made interpretation of the localized water level data difficult. Based on a hydrologic simulation of a range of such scenarios, the design parameters shown in Table 3 were established for the barrier.

The depth of the Dover barrier was determined by the depth of the aquitard. The bottom of the iron cell was keyed 2 ft. into the aquitard. The top of the iron cell was completed to 1 ft. above the historical high water table mark. This is necessary to ensure that during periods of high water table, groundwater does not flow over the iron cell. One issue that is still not well understood is the state of the granular iron near the top of the barrier that is periodically submerged under the water table, and then exposed to the vadose zone air when the water table subsides. There is potential for higher corrosion product build up on the iron in the topmost portion of the barrier. It is not yet clear how this can be avoided.

#### 2.4.6. Barrier orientation

Most standard modeling techniques used at previous sites have assumed groundwater flow perpendicular to the barrier. The groundwater flow direction is modeled based on a determination made during site characterization. A barrier orientation perpendicular to the groundwater flow ensures that the most efficient capture of the targeted portion of the groundwater (or the plume) is obtained. The uncertainty in this ideal scenario is the groundwater flow direction. Determining the exact groundwater flow direction in a very localized setting may be difficult, especially at sites with relatively flat gradients. Even if the regional groundwater flow direction is known, localized flow in the immediate vicinity of the barrier may vary. In addition, flow direction may change seasonally. At times when the groundwater flow is not exactly perpendicular to the face of the barrier, part of the plume may flow around the barrier, even though the barrier is still capturing approximately the same amount of water. To overcome these difficulties, the Dover design included two steps.

- Examination of historical water levels data to determine variation in flow directions under seasonal high flow and low flow conditions. Based on this approach, the localized groundwater flow direction at the Dover site was found to vary seasonally by about 30°.

- Modeling multiple hydrologic scenarios to account for (a) anticipated changes in seasonal flow directions and (b) any unanticipated deviations in flow direction due to the uncertainty in defining localized flow.

This type of sensitivity analysis required that the barrier width be larger than that determined in a single scenario that assumes the groundwater to be perfectly perpendicular to the face of the barrier.

### 2.5. Longevity considerations

Because chlorinated solvent plumes may be expected to persist for several decades or even centuries, it is of interest to know for how long a permeable reactive barrier will maintain its reactivity and permeability. Formation and deposition of inorganic precipitates on the reactive medium surfaces would be the probable cause of an eventual decline in the barrier performance. A geochemical evaluation of data collected during site characterization and column testing can provide indications of the type of precipitates that may be formed. Inorganic constituents, such as calcium, magnesium, and alkalinity, in the column influent and effluent groundwater can be analyzed and compared to estimate losses due to precipitation in the iron medium. Computerized geochemical models can also be used to predict the types and quantities of precipitates formed. However, it is unclear how much of the precipitate formed is actually retained in the reactive medium. Some precipitate particles that are colloidal in size could be transported out of the reactive medium with the groundwater flow.

From an empirical perspective, long-term or accelerated column tests in the laboratory and/or appropriate monitoring of the barrier in the field may serve as useful predictors of long-term barrier performance. Accelerated tests involve running groundwater through a column filled with reactive medium at rates much faster than those observed at the site. By increasing the number of pore volumes of water, the behavior of the barrier over several years of operation can be simulated. However, the contact time of the groundwater constituents (in each pore volume of water) with the reactive medium is reduced and careful extrapolation of the results may be required.

One factor that can affect the longevity of a reactive barrier is DO. DO reacts quickly with the iron in the barrier and the resulting precipitation can be seen in column tests forming on the first few inches of iron along the flow path at the influent end. This precipitation is a concern because the upgradient end of the reactive zone can clog even as the rest of the iron remains mostly clean. At the Dover site, the two gates contain a pre-treatment zone (PTZ) through which the groundwater flows before entering the 100% iron reactive zone. The PTZ in the gate contains a mixture of 10% iron and sand. This mixture slows down the DO reaction rate by reducing the iron surface area available per cubic feet of the mixture. Any precipitates formed are spread over a larger volume. The other gate incorporates a PTZ consisting of a mixture of 10% pyrite and sand; this mixture is being tested to see if pyrite can remove oxygen and control pH to provide better precipitation control.

A separate study [11] examined the effects of long-term exposure of reactive metals media to groundwater. In this study, a slight decline in reactivity of the iron was noticed after 1200 pore volumes of water were run through the column. The half-life of TCE

rose from about 30 min to about 40 min. Tracer tests conducted before and after the passage of 1200 pore volumes did not show any difference in the hydraulic residence time. In fact, previous modeling [3] indicated that the hydraulic conductivity of the granular iron ( $-8 + 40$  mesh) would have to decline by more than a factor of five before any significant hydrologic impacts (in terms of residence time or hydraulic capture zone changes) were noticed. This indicates that the effects of long-term exposure to groundwater on reactivity may become noticeable before the effects on hydraulic flow. In this study [11], preliminary results indicated that flushing the iron medium with a solution of 0.01 M of acetic acid restored its reactivity. Long-term performance of reactive barriers is an area of interest for future research.

### 3. Barrier construction

Because permeable barriers may in fact involve both permeable and impermeable sections (as in a funnel-and-gate system), construction techniques involving both may be required. The selection of a construction technique for a permeable barrier depends mainly on site characteristics.

- *Depth to aquitard.* This is probably the most important consideration that determines which construction technique is used. Depth also is an important driver of construction cost, with most shallow installations costing less than deeper ones. Deeper installations generally involve more specialized equipment, longer construction time, and higher cost.

- *Geotechnical considerations.* The presence of cobbles or highly consolidated sediments may impede some construction technique. The presence of subsurface utilities or closeness to aboveground structures, such as buildings or fences, may also determine the type of construction technique selected and the degree of difficulty involved.

- *Waste generation.* Some construction techniques generate more spoils than others do. This can be a consideration from the perspective of waste handling and disposal costs, as well as from administrative concerns regarding disruption of daily activities and visual impact in high-traffic areas.

- *Health and safety.* Construction techniques that involve entry of personnel into excavations may require relatively more precautionary measures and oversight. Use of environmentally toxic materials is generally avoided during construction.

#### 3.1. Backhoe excavation

This is the simplest of all the construction techniques and has been used at several permeable barrier sites, such as Sunnyvale and Denver Federal Center. A backhoe has a hydraulically operated arm with a bucket at the end that can be used for excavating trenches. In the case of a continuous reactive barrier, the trench is filled with the reactive medium. In the case of a funnel-and-gate system, the trench can be filled with a soil–bentonite or cement–bentonite slurry to create an impermeable funnel. A standard backhoe can excavate down to 25 or 30 ft. A modified backhoe can be used to excavate down to 80 ft., but is relatively more expensive. Spoils generated from backhoe

excavation may or may not have to be disposed as hazardous waste depending on the type and concentration of the contaminants involved. Most excavation techniques need a contained area to store the soil temporarily and allow the water to drain out. Depending on the contaminants and their concentrations, this water may or may not be allowed to run off into the ground or into stormwater drains.

Backhoes have a higher production rate than clamshells, but may require a slightly more room to operate. For excavations deeper than the length of the dipper stick of the backhoe, the ends of the trench are likely to be sloping and the trench at ground level will be longer than at the base. This may be a consideration at sites where the bottom of the trench has to be close to a building or a utility line, or a road that has to remain open for traffic during construction (which was a consideration at the Dover site). Highly consolidated sediments and cobbles may slow down the production rate of a backhoe, but need not halt the operation.

### *3.2. Clamshell excavation*

Clamshells and draglines are similar in that they both have a boom with a cable running over a point sheave at the top of the boom. This hoist cable is used to vertically lower or raise the excavator bucket. A second cable is used to open and shut the bucket to capture a load of soil. In a dragline, the second cable drags the end of the bucket toward itself to scoop up the soil. In a clamshell, the second cable is used to open or close the two shells of the bucket. Both dragline and clamshell can be used for deeper trenches down to 150 ft. A dragline can be used if the sides of the trench can be flattened. A clamshell is probably more useful than a dragline for permeable barrier applications and has been used for construction of the barrier at Borden, Ontario. A clamshell can operate in smaller spaces where the excavation has to be closer to the machine. As long as there is sufficient overhead space for the boom, the clamshell can excavate deep vertical sides for the trench. It can be particularly useful for excavating between braces or dividers. Braces may sometimes be required to hold up dividers in barriers where the trench has to be compartmentalized (e.g., to add pea gravel sections before and after the reactive medium). Clamshells have a lower production rate than a backhoe and are relatively more expensive to use. Any rocks encountered may have to be broken up for the clamshell to operate efficiently.

### *3.3. Caisson excavation*

Caissons are load bearing enclosures that are used to protect an excavation. Caissons may have any shape in cross-section and are built from common structural materials. The caissons can be pre-fabricated and transported to the site or they can be built in sections, with each section welded on top of the next as the caisson is driven in at the site. At the two permeable barrier sites, Somersworth Landfill Site and Dover Air Force Base, where this technique has been used, the caissons have been 8-ft. diameter circular cylinders open at both ends. In spite of the steel edges at the bottom of the caisson, it does not sink through soil under its own weight because friction along the sides of the caisson is high and can range from 300 lb/ft.<sup>2</sup> to over 1000 lb/ft.<sup>2</sup>. A vibratory

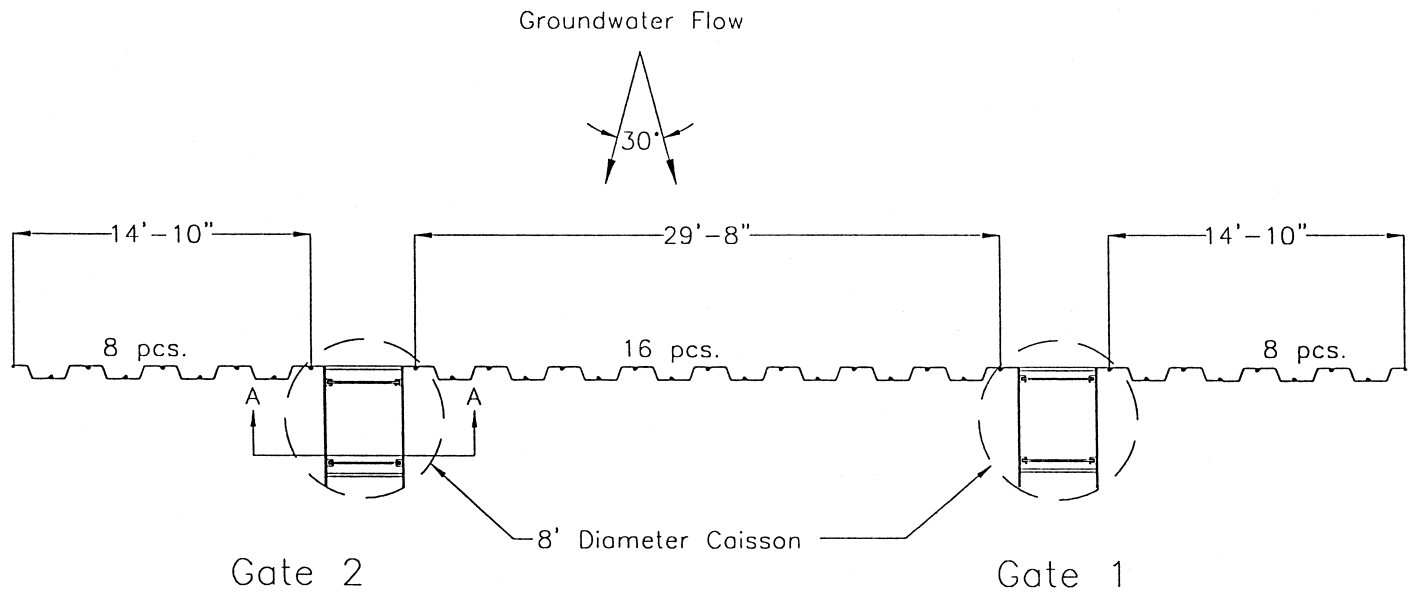


Fig. 7. (a) Design layout of the two caisson gates and sheet pile funnel at Dover Air Force Base. (b) Design of one of the caisson gates at Dover Air Force Base.

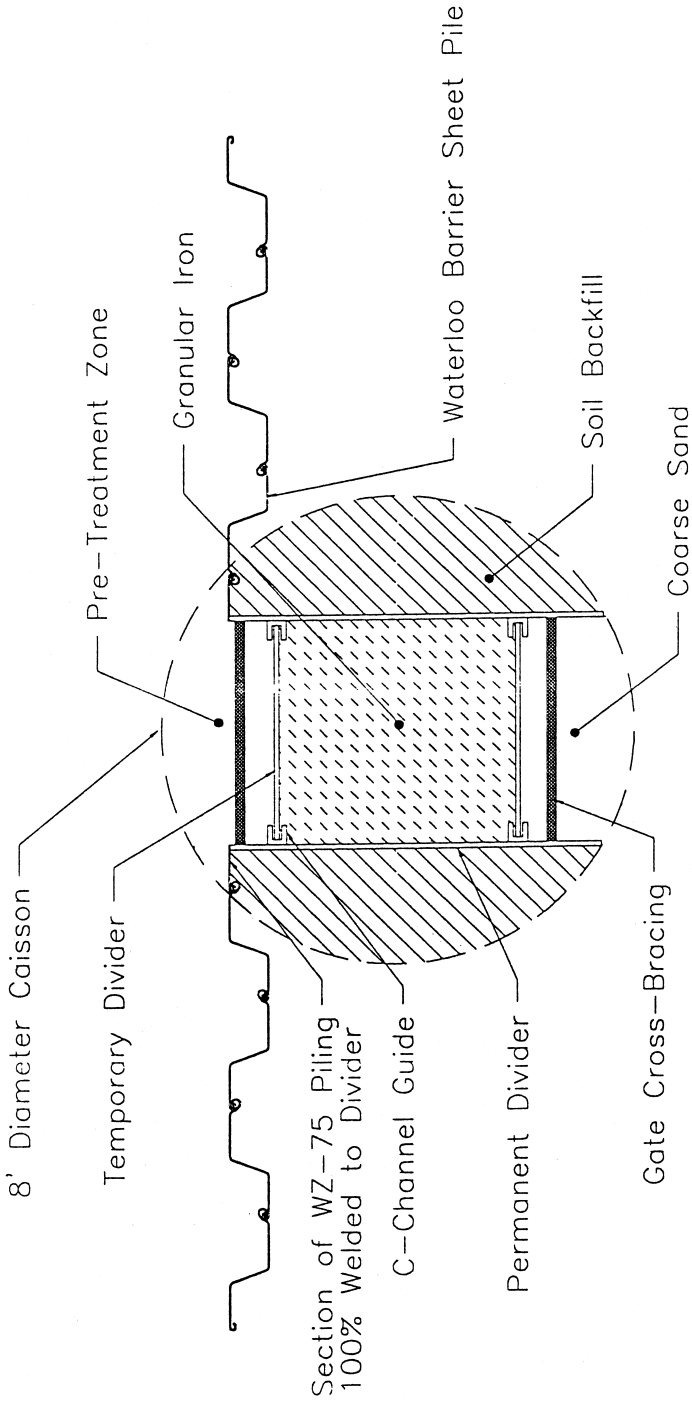


Fig. 7 (continued).

hammer was used to drive the caisson in. The interior of the caisson was excavated with a large auger to make room for the reactive medium.

Pulling the caisson out may prove to be more difficult than driving it in, especially with the pressure from the reactive iron medium inside. A vibratory hammer was used to pull the caisson out at both sites. At Somersworth, the caisson got stuck after it was withdrawn a few feet. Cobbles and/or highly consolidated sediments were thought to be the cause of the impedance. Extraordinary measures had to be taken to dislodge the caisson and pull it out the rest of the way. At Dover, both caissons were withdrawn easily in spite of the presence of an intermediate clay layer. However, the 0.5-in. thick structural steel material of the caisson, which held up fairly well when the caisson was driven in, started tearing near the vibratory hammer grip when it was being pulled. When the caisson continued to tear despite changing the position of the grip a few times, a 1-in. thick steel collar was built around the top edge of the caisson. No further problems were encountered.

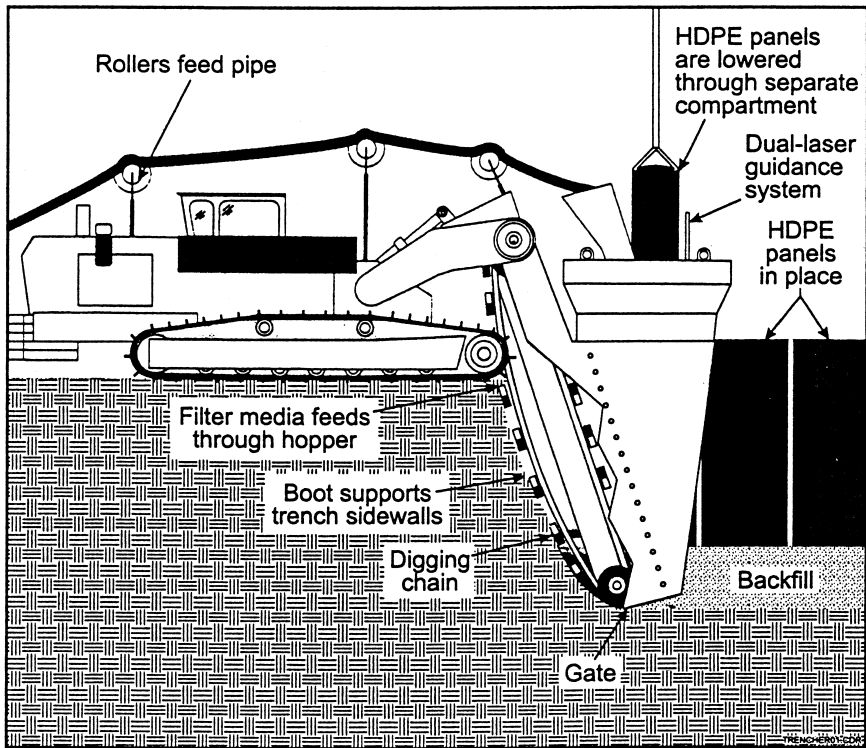
At both sites, the caisson-based excavation formed the gate in a funnel-and-gate system. The permeable barrier at Delaware had two gates to capture a wider plume (Fig. 7a). At Somersworth, a modified backhoe was used to install a slurry wall along both sides of the caisson to serve as the funnel. At Dover, sheet piling was used to create the funnel. Granular iron was the reactive medium at both sites.

Caissons are a relatively inexpensive way of installing reactive cells at depths inaccessible with a standard backhoe. The Somersworth and Dover barriers have been installed to depths of 50 and 45 ft. respectively. Ensuring a good seal between the caisson gates and the funnel wall in a funnel-and-gate system is an important consideration. At Somersworth, the slurry in the slurry wall funnel was allowed to set around the caisson to form a seal before it was pulled out. The loose iron medium consolidates into the annular space left behind by the caisson walls. At Dover, the iron medium subsided by about 2 ft. when the caisson was pulled out. Part of this subsidence was due to the reactive medium entering the thin annular space left behind by the caisson walls. But some subsidence was probably due to the granular iron itself consolidating under the vibrations from the caisson. At Dover, interlocks were welded on the two side dividers (Fig. 7b). The first sheet pile of the funnel wall on either side of the gate was guided into this interlock and the joint was grouted to obtain a good seal.

### *3.4. Continuous trenching*

At a permeable barrier site in Elizabeth City, NJ, a continuous trencher was used to install the reactive medium in the ground. This trencher cuts through the soil using a chain saw type apparatus mounted on a boom (Fig. 8). The boom is lowered to the ground and trails a crawler-mounted vehicle which moves in the direction of the planned trench. The trench is excavated continuously behind this vehicle. A hopper attached to the vehicle can be used to simultaneously fill the trench with the reactive medium. This trencher is claimed to be able to excavate an up to 2-ft. wide trench down to 30 or 35-ft. depth in a single pass. At the Elizabeth City site, a barrier 2 ft. wide, 24 ft. deep, and 150 ft. long was installed in 6 h with this unit [12]. Although the mobilization costs are relatively high, the high production rate may make the unit cost-effective for larger





Reprinted with permission of Groundwater Control, Inc. (1996).

Fig. 8. Continuous trencher in operation.

barriers. The boom can be lowered almost vertically into the ground, thus, avoiding sloping ends and conserving space. At an aircraft maintenance facility in Oregon, a 650-ft. long slurry wall funnel for a funnel-and-gate type barrier was installed using a similar continuous trencher [13].

### 3.5. Slurry wall

Slurry walls have been used as subsurface impermeable barriers for containment of wastes at Superfund sites. Their use in permeable barriers is for creating impermeable funnel walls in a funnel-and-gate system. Soil-bentonite slurry walls have been most commonly used in remediation. The slurry trench is excavated with a backhoe, modified backhoe, or clamshell, depending on the depth. A soil-bentonite slurry is then placed in the trench to maintain trench stability. As the slurry permeates into the sides of the excavation, a fully hydrated filter cake of bentonite is formed along the sides. Finally, soil-bentonite backfill is placed in the trench. Soil-bentonite slurry walls have a hydraulic conductivity of as low as  $10^{-7}$  or  $10^{-8}$  cm/s. Prior to construction, a

chemical compatibility test is usually done in a laboratory to evaluate the ability of the slurry wall materials to withstand local groundwater constituents and contaminants.

Other types of slurry wall containment include cement–bentonite slurry walls and composite walls. Cement–bentonite walls ( $10^{-5}$  or  $10^{-6}$  cm/s) do not generate as low a hydraulic conductivity as soil–bentonite walls and, therefore, their use to contain wastes in remediation has been limited. However, they could possibly be considered for funnel-and-gate type applications as long as the conductivity contrasts between the gate and the funnel and between the funnel and the surrounding aquifer are significant. In a funnel-and-gate system installed at a site in Sunnyvale, CA, one funnel wing wall that had to be placed under a building was made of cement–bentonite [14]. Because of the limited space available inside the building, a cement–bentonite slurry was easier to mix and install than a soil–bentonite slurry.

In composite walls, a geomembrane is inserted in the slurry trench. The composite protection of the slurry material and the geomembrane further lowers the hydraulic conductivity of the wall and improves its resistance to chemical attack by the environmental contaminants.

Slurry wall construction has a higher mobilization cost relative to sheet piling because of the set up and time required to prepare the slurry and backfill. Space requirements are also relatively higher, especially for soil–bentonite walls. However, for larger barriers, a slurry wall, which has lower incremental cost (per square feet of wall), may be more cost effective.

### 3.6. Sheet piling

Barriers made of a series of steel sheet piles driven into the ground have been used in the construction industry for retaining soil. In order to adapt this technique for remediation applications, where both soil and water movement have to be restricted, the University of Waterloo, Ontario has patented a technique for sealing adjoining sheet piles by pouring grout into the joints. Fig. 9 shows cross-sections of a sealable-joint sheet pile barrier. Sheet pile barrier integrity can be maintained to depths of about 50 ft. Beyond this depth, the sheet piles can be driven in, but it is unclear how well the integrity of the sealed joints is maintained. About 40- to 45-ft. long sheet piles can be easily transported to the site. Beyond this length, sheet piles have to be transported in sections to the site, and then welded together during installation.

Sheet pile barriers can be installed relatively quickly at most sites. They are especially useful when the barrier has to be installed under horizontal space limitations. Because sheet piles are relatively thin and can be driven straight down, this type of barrier was used at the Dover site for the funnel sections because of the proximity of the funnel walls to subsurface utility lines and a road that had to stay open during construction. In fact one of the utility lines was cut and rejoined over the sheet pile wall after the barrier was completed. A 100-ft. crane with a vibratory hammer was used to drive the sheet piles 45 ft. into the ground with a 2-ft. key in the aquitard. Another reason for choosing a sheet pile barrier instead of slurry wall at the Dover site was because the sheet pile barrier generates much less spoils. Sheet piles are also useful as dividers when the reactive cell or gate has to be divided into sections to house different

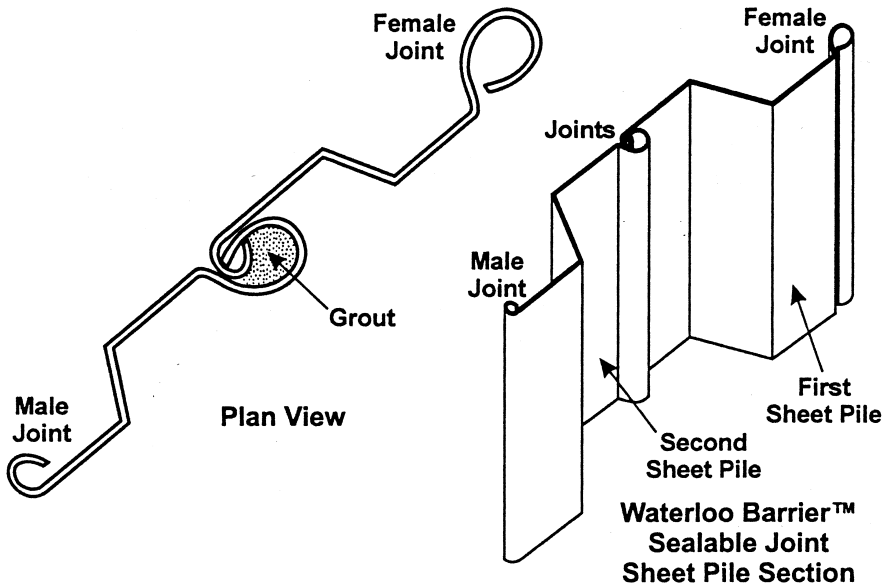


Fig. 9. Sealable-joint sheet piling barrier.

media. Sheet piles were used at the Moffett Field site to form the funnel for the barrier. For the Moffett Field permeable barrier, sheet piles supported by cross-bracing were also used to keep the trench (gate) open after excavation so that the iron medium could subsequently be emplaced.

### 3.7. Hydraulic fracturing

Another promising technology for construction of deeper barriers is hydraulic fracturing, a technique that is currently being tested at a site in Cape Cod, MA. A series of wells are installed along the length of the proposed barrier. A controlled vertical fracture is initiated through the well with a special down-hole tool inserted in each well [15]. The fracture can be oriented along the required azimuth and depth. The tool is withdrawn and a packer is installed in each well. An iron–gel mixture is then injected through the series of wells to form a reactive barrier. The propagated geometry of the fractures is monitored in real time to ensure that coalescence or overlap of the fractures takes place as desired. This is done by introducing electrical energy in the fractures and monitoring it through down-hole resistivity sensors.

The gel used is a water-based cross-linked gel. Hydroxypropylguar, a polymer used in the food processing industry as a thickener is typically used for this application. The viscosity of the cross-linked gel ensures that the granular iron remains suspended during mixing, handling, and subsequent pumping. When the gel degrades, a 3- to 4-in. thick reactive barrier is left behind in sandy soils. Some variability in barrier thickness can be expected if the advancing fracture encounters heterogeneities such as cobbles or consolidated sediments. To some extent this variability can be addressed in the design

by injecting a slurry that provides a barrier thickness greater than the minimum required for treatment. Until more field experience is obtained with this technique, at least two parallel fracture reactive barriers may be considered [16].

This technique may also be used for installation of an impermeable barrier (funnel) by injecting a soil–bentonite slurry instead of an iron–gel mixture.

### 3.8. *Vibrating beam*

In this technique, an H-beam or mandrel with a sacrificial shoe at the bottom is used. The beam is driven into the ground with a vibratory hammer creating a void. As the beam is raised, grout is injected into the void through special nozzles at the bottom of the beam. An impermeable barrier is thus installed by driving at overlapping intervals.

This technique is currently being tested at a site in Florida to see if it can be used to install a permeable reactive barrier [17]. In the first test, dry iron was installed in the void through a hollow mandrel driven with a vibratory hammer. The mandrel was used to create a 4-in. thick, 32-in. long void down to 45-ft. depth with each entry. A total of 32 overlapping panels were installed. No spoils were generated. In the second test, a 36-in. I-beam with a high/low pressure nozzle was driven into the ground. Water was sprayed through the high pressure side of the nozzle to help create the void. An iron–guar gum slurry was introduced into the void through the low-pressure side of the nozzle as the beam was brought up. During the installation of 24 panels, approximately 24 tons of soil and 4000 gal of liquid were generated.

### 3.9. *Jetting*

Jet grouting has been used for infrastructure development in Japan and Europe since the 1970s. The technique is being increasingly used in the US for reducing the permeability of soils for infrastructure development and impermeable barrier placement for remediation. More recently, there has been some interest in substituting the grout with an iron–guar gum slurry to install a permeable reactive barrier at deeper sites. A field demonstration of this technique is underway at Dover, DE [18].

Jet grouting involves the injection of grout at high pressures into the ground. The high velocity jet erodes the soil and replaces, some or all of it, with grout. Jet grouting systems are classified into three types depending on the delivery mechanism. In a single rod system, the fluid injected is grout. In a double-rod system, grout and compressed air are injected. The combined effect of the high-pressure grout and air results in a greater percentage of soil being removed and replaced with grout. The remaining soil–grout mixture is called soilcrete. In a triple rod system, grout, air, and water are jetted. This triple combination enables an even higher percentage of soil to be removed, and the system can be used for almost complete replacement of the soil with grout. The triple rod system offers better control over injection rates and results in better quality of soilcrete. While the single and double rod systems can be used in loose sandy soils, the triple rod system can be used in most types of soil.

If the injection rod is rotated as it is brought up, a column of soilcrete can be installed. A continuous impermeable barrier can be created by installing a row, or

multiple rows, of overlapping columns. Alternatively, a thin panel of soilcrete can be installed by not rotating the rod. A continuous barrier, sometimes referred to as a thin diaphragm wall, is formed by installing a row of overlapping panels.

It is the triple rod system that is projected as being suitable for installing permeable reactive barriers. Grout can be used to install impermeable sections or funnel. A slurry made of granular iron and guar gum is used to install the reactive section.

### 3.10. Deep soil mixing

This is a technique that has been used for in situ stabilization of soils and has been proposed for permeable barrier application. A device with three large augers is used to mix grout (impermeable barrier) or iron slurry (permeable barrier) with subsurface soil. Depths of 120 ft. are claimed to be possible with this technique.

### 3.11. Construction quality control

Because a barrier works by changing the hydraulic conductivity of a targeted aquifer region, it is important to ensure that this objective is being achieved. In the case of the permeable reactive sections of the barrier, the key is to ensure that (a) the required hydraulic conductivity (which is usually designed to be higher than that of the surrounding aquifer) is being achieved, and (b) that the reactive medium is continuously and uniformly distributed in the installed reactive cell zone. In the case of impermeable sections (funnel), the key is to ensure that (a) the designed reduction in conductivity is being achieved, and (b) that this lower conductivity zone is continuous and uniform. These objectives can be achieved through quality control steps undertaken during the pre-installation, installation, and post installation phases. For both permeable and impermeable sections, quality control also improves the longevity of the barrier.

Examples of quality control issues that can be addressed in the pre-installation phase are as follows.

- In the case of slurry wall, the soil–bentonite slurry mix can be tested for chemical compatibility with the site groundwater. If a cement–bentonite slurry is used, this test is not as critical and a conservative mix can be designed.
- Mapping the detailed hydrogeologic characteristics of the site in the immediate vicinity of the planned barrier.

Examples of quality control issues that can be addressed in the installation phase are as follows.

- Ensuring that the reactive medium is packed properly in the reactive cell. In a trench-type installation, workers would actually enter the trench to physically press the granular iron into place with each 1-ft. layer of medium installed. However, safety issues associated with confined space entry could dictate the use of other remote means of doing this.
- In a funnel-and gate type system, it is important to obtain a good seal between the impermeable and permeable sections. At the Dover site (see Fig. 7b), steel sheets with an interlock were installed on either side of the reactive cell. The male joint of the first

sheet pile of the funnel on either side was driven through this interlock and the joint was grouted.

Examples of quality control issues that can be addressed in the post-installation phase are as follows.

- Performance monitoring that goes beyond just compliance issues. For example, measuring the redox potential at various points along the flowpath through the reactive medium can give a good indication of the uniformity and continuity of the reactive medium.
- Individual construction techniques often have their own special quality evaluation techniques associated with them. For example, for installation by hydraulic fracturing the developers have adapted a technique of electrical resistivity measurements to evaluate the geometric distribution and continuity of fractures.

#### 4. Discussion

An optimal design for a permeable reactive barrier can be achieved by a comprehensive examination of the site that includes reaction rates of the contaminants and the site hydrogeology. Depth of the installation is the main factor that drives the selection of a construction technique for permeable barriers. A geochemical evaluation based on the inorganic constituents of the aquifer and long-term monitoring of the barrier can be done to evaluate the longevity of the barrier.

#### Acknowledgements

The author would like to acknowledge the US Air Force representatives, Lt. Dennis O'Sullivan and Greg Jackson, who provided site access and guidance for the Dover Air Force Base Permeable Barrier Project. Charles Reeter and Steve Chao from the US Navy provided site access and guidance for the Moffett Field barrier site. John Vogan of Environmental Technologies, Inc., provided additional technical guidance during the implementation of these projects.

#### References

- [1] R.W. Gillham, S.F. O'Hannesin, Enhanced degradation of halogenated aliphatics by zero-valent iron, *Ground Water* 32 (1994) 958–967.
- [2] T.M. Sivavec, D.P. Horney, Reductive dechlorination of chlorinated ethenes by iron metal, Preprints of the Papers Presented at the 209th ACS National Meeting, Anaheim, CA, April 2–6, 1995, pp. 695–698.
- [3] A.R. Gavaskar, N. Gupta, B.M. Sass, R.J. Janosy, D. O'Sullivan, *Permeable Barriers for Groundwater Remediation; Design Construction and Monitoring*, Battelle Press, Columbus, OH, 1998, 176 pp.
- [4] A.L. Roberts, L.A. Totten, W.A. Arnold, D.R. Burris, T.J. Campbell, Reductive elimination of chlorinated ethylenes by zero-valent metals, *Environ. Sci. Technol.* 30 (9) (1996) 2654–2659.
- [5] D.R. Burris, T.J. Campbell, V.S. Manoranjan, Sorption of trichloroethylene and tetrachloroethylene in a batch reactive metallic iron–water system, *Environ. Sci. Technol.* 29 (11) (1995) 2850–2855.

- [6] R.W. Gillham, S.F. O'Hannesin, Metal-catalyzed abiotic degradation of halogenated organic compounds, *Proceedings of the IAH Conference: Modern Trends in Hydrogeology at Hamilton, Ontario, May 10–13, 1992*, pp. 94–103.
- [7] W.S. Orth, R.W. Gillham, Dechlorination of trichloroethylene in aqueous solution using  $\text{Fe}^0$ , *Environ. Sci. Technol.* 30 (1) (1996) 66–71.
- [8] US Environmental Protection Agency, Selection of media for the Dover AFB Field demonstration of permeable barriers to treat groundwater contaminated with chlorinated solvents, Preliminary Report to US Air Force for SERDP Project 107, August 4, 1997.
- [9] P.M. Jeffers, L.M. Ward, L.M. Woytowitch, N.L. Wolfe, Homogeneous hydrolysis rate constants for selected chlorinated methanes, ethanes, ethenes, and propanes, *Environ. Sci. Technol.* 23 (8) (1989) 965–969.
- [10] EnviroMetal Technologies, Personal communication from John Vogan, EnviroMetal Technologies, Guelph, Ontario, January 1997.
- [11] A.R. Gavaskar, B.M. Sass, E. Drescher, L. Cumming, D. Giammar, N. Gupta, Enhancing the reactivity of permeable barrier media, *Proceedings of the First International Conference on Remediation of Chlorinated and Recalcitrant Compounds*, at Monterey, CA, Vol. C1–6, May 18–21, 1998, pp. 91–96.
- [12] D.W. Blowes, R.W. Puls, T.A. Bennett, R.W. Gillham, C.J. Hanton-Fong, C.J. Ptacek, In-situ porous reactive wall for treatment of Cr(VI) and trichloroethylene in groundwater, *Proceedings of the International Containment Technology Conference*, St. Petersburg, FL, February 9–12, 1997, pp. 851–857.
- [13] J.R. Romer, Installation of a reactive iron permeable barrier using continuous trenching, *Presentation Materials for the RTDF Permeable Reactive Barriers Action Team Meeting*, Beaverton, OR, April 15–16, 1998, pp. 39–40.
- [14] C.L. Yamane, S.D. Warner, J.D. Gallinatti, F.S. Szerdy, T.A. Delfino, D.A. Hankins, J.L. Vogan, Installation of a subsurface groundwater treatment wall composed of granular zero-valent iron, *Preprint of Papers Presented at the 209th ACS National Meeting*, Anaheim, CA, Vol. 35, No. 1, April 2–7, 1995.
- [15] G. Hocking, S.L. Wells, R.I. Ospina, Design and construction of vertical hydraulic fracture placed iron reactive walls, *Proceedings of the First International Conference on Remediation of Chlorinated and Recalcitrant Compounds*, at Monterey, CA, Vol. C1–6, May 18–21, 1998, pp. 103–108.
- [16] D.W. Hubble, R.W. Gillham, J.A. Cherry, Emplacement of zero-valent metal for remediation of deep contaminant plumes, *Proceedings of the International Containment Technology Conference*, St. Petersburg, FL, February 9–12, 1997, pp. 872–878.
- [17] E.G. Marchand, P.A. Shirley, K.A. McNelis, T.L. Fiorillo, New installation techniques in side-by-side demonstrations at Cape Canaveral Air Station, *Presentation Materials for the RTDF Permeable Reactive Barriers Action Team Meeting*, Beaverton, OR, April 15–16, 1998, pp. 23–24.
- [18] R. Landis, Potential use of jetting to emplace permeable reactive barriers, *Presentation Materials for the RTDF Permeable Reactive Barriers Action Team Meeting*, Beaverton, OR, April 15–16, 1998, p. 51.