# Remediation of Tetrachloroethene in Fractured Sandstone – A Case Study in Initial Successes and Long-Term Technological Barriers to Timely and Cost-Effective Closure

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## Abstract

In the summer of 1994, two railroad tank cars containing tetrachloroethene (PCE) derailed in a rural area of the Midwest. The impact of the derailment resulted in the release of approximately 22,000 gallons of PCE into an adjacent intermittent stream channel.

Immediate response actions were taken to recover PCE and contain the release. The actions included installation of recovery trenches to recover PCE and construction of a bentonite wall around the stream channel to contain the PCE affected groundwater. A temporary geomembrane cover was placed over the 5-acre contained area to reduce infiltration of precipitation. The bentonite cut-off wall was keyed into the underlying sandstone bedrock. A groundwater extraction system was then installed within the contained area. A treatment system was also constructed on the site to separate free phase PCE from water and to treat the extracted groundwater for surface water discharge.

Following the initial response actions, site characterization was completed using geophysical techniques and a network of wells and well nest clusters. The geology of the site is generally characterized by a thin layer of silty and sandy clay overlying fine-grained, fractured sandstone. The upper 1 to 4 feet of the sandstone is highly weathered and fractured, but becomes more competent with depth.

By January 1995, approximately 7,500 gallons of free-phase PCE was recovered by trench recovery process. Exposure pathways at the site were controlled by the installation of the pump and treat system, placement of the cover and installation of a perimeter fence. The groundwater monitoring data supported the conclusion that PCE-affected groundwater was contained on-site. The initial response actions were considered a success.

After approximately 10 years of pumping and treating groundwater in the fractured sandstone, the amount of free phase PCE removed by the extraction system has dwindled to a negligible amount, but the influent PCE concentration to the treatment system is at approximately 13,000 μg/l. The observed dissolved-phased PCE concentrations in groundwater suggest continued presence of free phase PCE in the fractured sandstone. The elevated PCE concentrations coupled with the limited ongoing recovery of free phase PCE indicates that the immiscible-phase liquid is inaccessible, likely due to diffusion of the PCE into the fractured sandstone matrix. Presently, while the pump-and–treat system continues to be effective at containing the plume on site, only a small volume of accessible PCE is being removed from the bedrock.

A remedial alternatives evaluation was completed in 2003 to identify and evaluate alternatives to expedite site closure. The evaluation revealed that the available remedial technologies are impractical, ineffective, or cost prohibitive due to the inaccessibility of immiscible-phase PCE within the sandstone matrix. This paper highlights the specific limitations of the available remedial technologies to attain regulatory closure at sites that are affected by the presence diffused immiscible-phase chlorinated VOCs in the bedrock matrix.

## PCE Release and Immediate Response Actions

In 1994, two rail tank cars containing tetrachloroethene (PCE) derailed in a rural area in Midwestern United States. The location of derailment and other site features are illustrated in Figure 1.

The tank cars reportedly released approximately 22,000 gallons of PCE into the surrounding environment. The PCE infiltrated the soil and flowed over the surface along an intermittent stream channel extending northeast from the derailment site. The channel flows into a designated wetland and ultimately to a lake. Emergency response actions were initiated immediately following the derailment to recover PCE and contain the spill. The emergency procedures included:

- Pumping PCE from the ruptured tank cars, ditch and stream bed into holding tanks.
- Completing a soil gas headspace survey to determine the extent of the PCE plume along the intermittent stream.
- Installing PCE recovery trenches across the drainage way.
- Installing a bentonite barrier wall keyed into the local bedrock around the perimeter of the spill area. The bentonite barrier wall consists of hydrated bentonite chips and has a hydraulic conductivity that is several orders of magnitude lower than the surrounding soil or bedrock. The location of the bentonite wall is shown on Figure 2. The area interior to the bentonite wall is known as the "Containment Area".
- Installing a network of monitoring wells and piezometers to assess and monitor the groundwater quality and the effectiveness of the bentonite wall in containing the PCE plume.

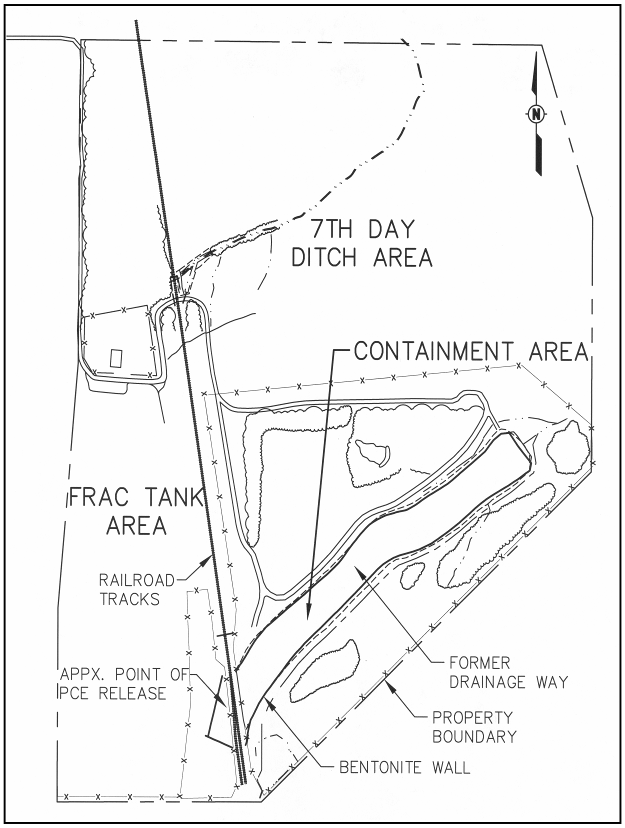

Figure 1: Site Features

In addition to the Containment Area, two other areas (Frac Tank Area and Seventh Day Ditch Area) shown in Figure 1 were also affected by the PCE release, albeit to a less significant extent than the Containment Area. This paper focuses on the Containment Area although the challenges posed by the local Hydrogeologic conditions and the contaminant distribution that are highlighted in this paper apply to the other two areas as well.

During the immediate response action, approximately 7,500 gallons of PCE were reportedly recovered and disposed of off-site. PCE was observed to have reached the weathered bedrock surface and to have infiltrated the upper portions of the bedrock. The amount of free-phase PCE that evaporated or has been recovered since at the time of the release is uncertain based on existing records because disposal of PCE historically occurred in the form of PCE-water mixture. Thus, the available records are insufficient to calculate a mass balance of released, recovered, and remaining PCE.

Following immediate response actions, long term remedial action was implemented on the site. The local geology and hydrogeology played a vital role in determining the success of the on-going remediation and supplemental future remedial efforts. Therefore, prior to discussing the long term remediation (on going and future), it is essential to understand the local geology and hydrogeology.

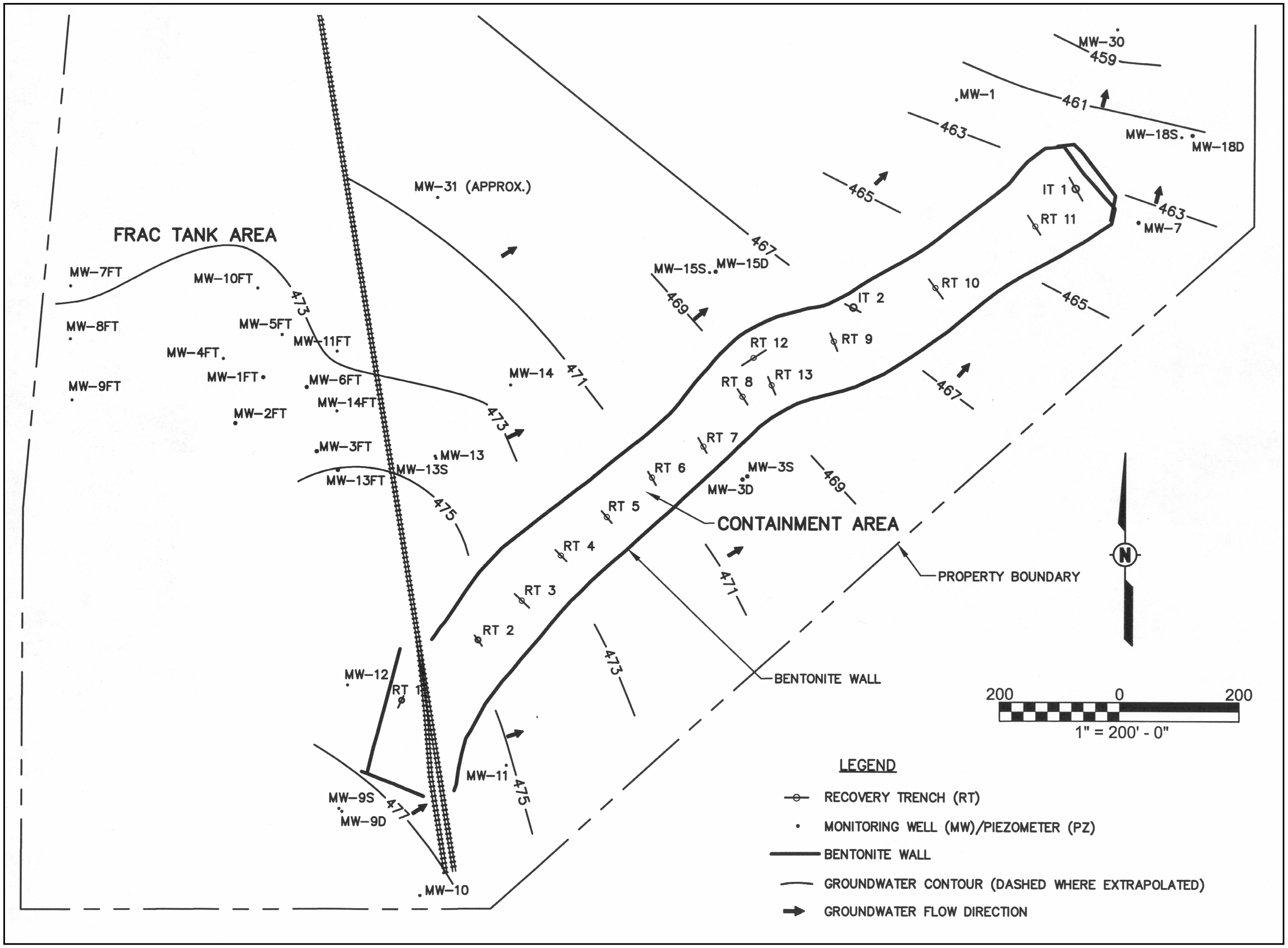

Figure 2: Containment Area – Well Location and Groundwater Contour Map

## Geology and Hydrogeology of the Area

*Geology*

The general subsurface geology of the region is mapped as the unconsolidated Quaternary Stage deposits overlying Pennsylvanian Age bedrock. Groundwater can be located within several strata, including unconsolidated deposits, as well as several of the Pennsylvanian Sandstones. Unconsolidated deposits at the site are mapped as a calcareous, brown, fine-textured diamicton of the Glasford Formation (Willman et al., 1975). Locally, the Glasford Formation is undifferentiated, with no obvious members identified.

Unconsolidated deposits encountered in the on-site borings were light tan and reddish brown mottled silty clay (USCS classification of "CL") that was moderately expansive when reacting with water. The hydraulic conductivity of glacial deposits at the site range from $1 \times 10^{-7}$ cm/sec to $6 \times 10^{-8}$ cm/sec.

According to Willman et al. (1975), bedrock at the subject property consists of shale overlying sandstone. Willman et al. (1975) further indicates that the sandstone identified at the site is the Trivoli Sandstone Member of the Modesto Formation. The Trivoli is identified as a sheet facies type of sand with a locally thick channel facies (up to 80 ft. thick). The overlying veneer of shale may be undifferentiated mudstones of the uppermost Modesto Formation or the lowermost Bond Formation, which outcrops in the area.

The on-site boring logs indicate that weathered tan to brown sandstone bedrock is encountered at less than 5 feet below ground surface (BGS) east of the railroad tracks (near the Containment Area). The weathered sandstone is fractured. The hydraulic conductivity of the weathered sandstone is on the order of $1\text{x}10^{-4}$ cm/sec. Interbedded layers of dark gray shale and sandstone were encountered below the weathered sandstone to depths ranging from 78 to 117 feet BGS. The shale and sandstone layers are underlain by more highly-cemented gray sandstone. The hydraulic conductivity of the less weathered sandstone is in the order of $1\text{x}10^{-8}$ cm/sec. Figure 3 shows a typical cross-section and idealized groundwater flow across the Containment Area.

Seismic and electromagnetic geophysical studies at the subject site were performed to understand the potential PCE transport pathways, specifically with respect to identifying potential bedrock channels which are common in this area. Seismic lines east of the railroad tracks defined two acoustically mappable layers. The first layer included a combination of the unconsolidated soil deposits and the weathered sandstone layer, while the second deeper layer consisted of the gray sandstone bedrock. Because the thickness of the unconsolidated deposits overlying the weathered sandstone was less than 5 to 10 feet thick in general, the unconsolidated and weathered bedrock layers could not be well distinguished. Although weathered bedrock channel formation was observed to west of the tracks, none were observed east of the tracks, in the Containment Area.

*Hydrogeology*

The relatively thin veneer of clayey unconsolidated materials is not conducive for transmission of large quantities of groundwater. As with many locations in the region, most potable water comes from surface impoundments. At the subject site, water within the recovery areas is largely transmitted at the unconsolidated/weathered bedrock interface. As was observed during the recovery trench installation, the PCE generally follows the upper weathered bedrock surface zone, and has not apparently permeated the harder, more highly-cemented sandstone deposits found below the weathered sandstone. This observation was supported by, the absence of PCE in wells screened in the deeper, more highly cemented gray sandstone. At the subject site, deeper bedrock observed during well installations indicated that these sandstone deposits were not exposed to extensive weathering, and therefore have not developed secondary porosities of sufficient volume to transmit groundwater like the weathered sandstone zone.

Groundwater equipotential lines and flow directions in the surficial and shallow bedrock aquifers are shown on Figure 2. The groundwater flow direction on east side of the tracks is typically to the east and northeast along the former drainage way. The groundwater flow velocities are low with an average of 0.35 ft/year through the unconsolidated soils. The vertical gradients in groundwater are predominantly upwards in the Containment Area. However, seasonal reversals in vertical gradients were observed in some well nests. The vertical gradient measurements confirm that the former drainage way feature within the Containment Area is the main groundwater discharge feature on the site.

A study of movement of surface water, infiltration water, and groundwater in and out of the Containment Area suggested that approximately 95 percent of the inflow into the Containment Area results from vertical upward migration from the sandstone into the former drainage way. Figure 3 illustrates a typical cross section of the Containment Area and a schematic of the expected groundwater flow pattern.

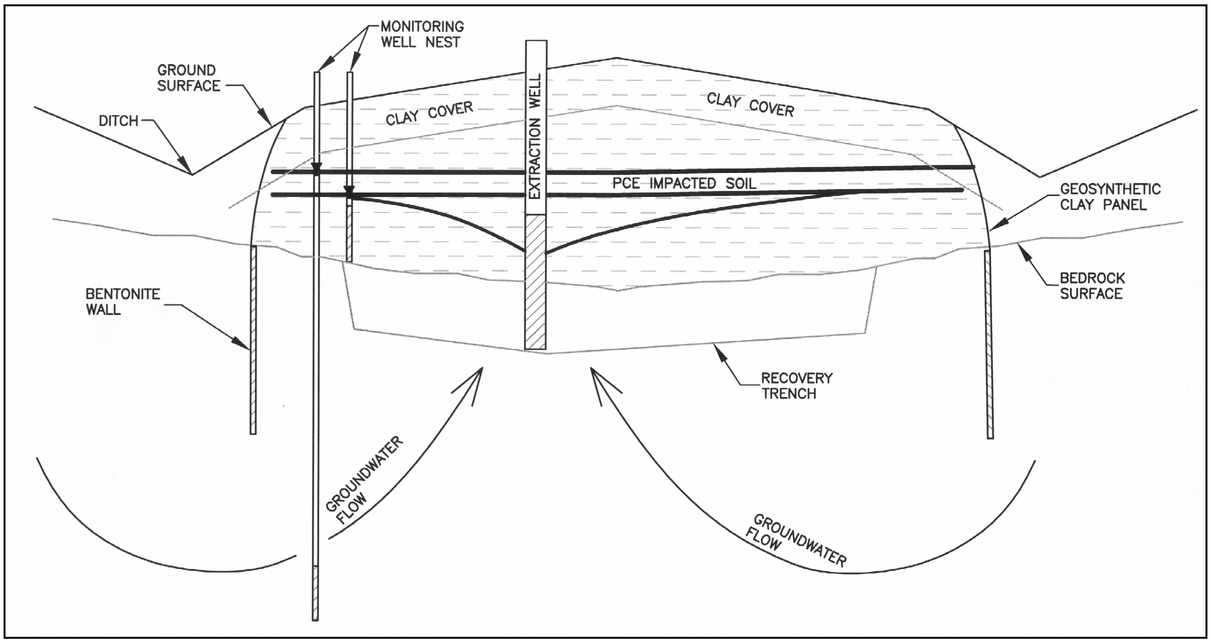

Figure 3: A Typical Cross-Section of the Containment Area.

## Long Term Plume Containment and Mitigation

After the immediate response action, long term remedial action was implemented in 1995 to contain and mitigate the PCE plume. The remedial action involved the following components:

- Installing recovery wells, sumps, and trenches as part of a groundwater recovery system, within the Containment Area.
- Constructing a treatment system to separate free-phase PCE from groundwater, and treatment of the groundwater using a combination of air stripping and carbon polishing.
- Constructing an exposed-membrane cap over the Containment Area.

In the Containment Area, the pump and treat system is successfully maintaining inward gradients of groundwater and the analytical results show that the PCE is being contained by the combination of the bentonite wall and the groundwater extraction system. Table 1 provides a summary of recent groundwater analytical results. Shallow and deep monitoring wells located around the bentonite wall do not indicate detectable concentrations of PCE. Well pairs that were installed to monitor the groundwater inside and outside the bentonite wall (denoted by BWI and BWO suffixes, respectively) suggest a significant drop in PCE concentration across the wall.

Presently, the treatment system treats approximately 1.2 million gallons of impacted water per year. However, the system is able to remove PCE at a rate of 183 pounds per year in dissolved-phase. It is estimated that since the groundwater extraction system began operation nine years ago, approximately 1,700 pounds or 126 gallons of PCE have been removed.

The average PCE concentration in the treatment system influent, which represents the PCE concentrations extracted from the Containment Area, continues to be steady at approximately 16,300 µg/L, which is approximately 8% of the pure PCE solubility limit. According to a USEPA document, the conditions that indicate the potential for the presence of DNAPL (or free-phase PCE) at a site include groundwater concentrations that are greater than 1% of the solubility limit (Publication 9355.4-07FS, 1992). Figure 4 provides a graph of PCE concentrations in the treatment system influent since 2002. As seen in Table 1, the PCE concentrations in the monitoring and extraction wells within the Containment Area also suggest the presence of free-phase PCE. Accordingly, we conclude that residual free-phase PCE is present within the soil voids and upper weathered bedrock zone in the Containment Area (at or below the recovery well depth) that is no longer being recovered in the free-phase by the groundwater extraction system. While this source of PCE remains, the documented inward gradients across the bentonite barrier wall and upward gradients within the area enclosed by the bentonite barrier wall continue to ensure capture of PCE-affected groundwater. The absence of detectable PCE concentrations in bedrock wells outside the Containment Area supports this conclusion.

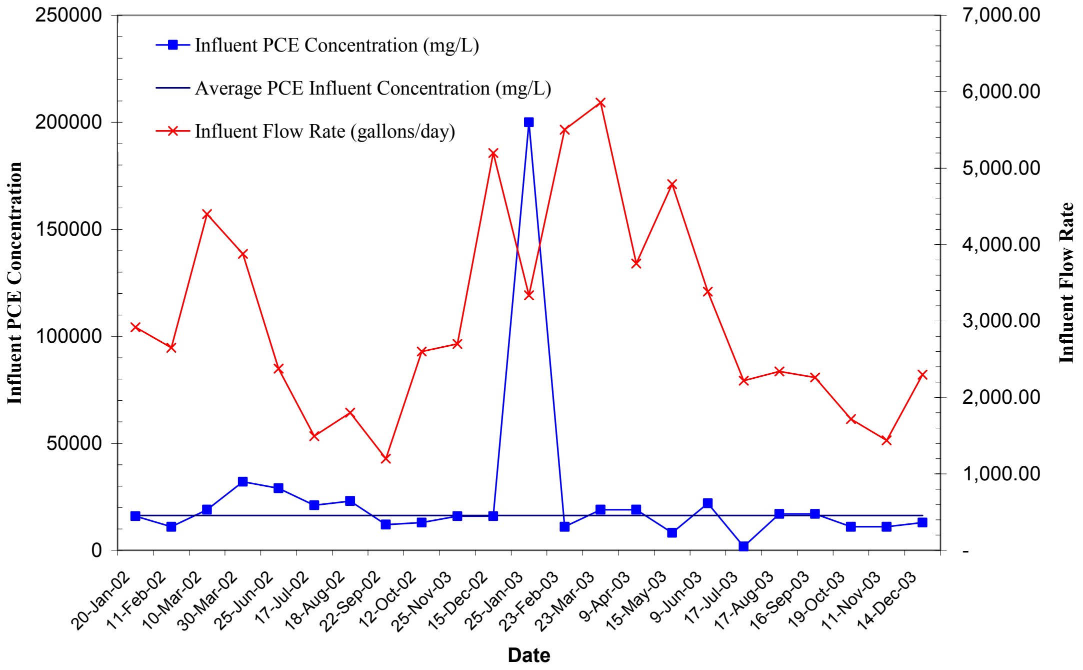

FIGURE 4: PCE Concentration and flow rate trends in the treatment system influent

(Note: January 2003 measurement is considered to be anomolous and was not included in average PCE concentration calculation.

## Free-Phase PCE in Bedrock

As discussed above, only a small percentage (less than 5%) of residual PCE in the subsurface is presently being removed by the treatment system. As illustrated in Figure 4, the influent concentrations have remained constant over the last two years. The average influent PCE concentration continues to be high (at approximately 8% of the PCE solubility limit) indicating the presence of a free-phase source in the containment area. However, no free phase product has been recovered over the last two years.

To determine if free-phase PCE was present in a discrete segment of the extraction system or if it was being recovered at all, the groundwater extraction wells and related groundwater extraction system tanks was evaluated by: 1) using a free product interface probe to gauge the extraction wells for free-phase PCE; 2) vacuum-extracting groundwater from the extraction wells and depressing the groundwater table below the level achieved by regular groundwater pumping; and, 3) using a free product interface probe to gauge the extracted groundwater in tanks for free-phase PCE.

No free-phase PCE was detected in any of the above three scenarios. However, as expected, the PCE concentrations in the extraction wells were high (PCE concentrations ranged from 3,500 μg/l to 310,000 μg/l). Since no free-phase PCE is detected in the wells, the free-phase PCE is likely contained within the weathered or fractured bedrock zone below the extraction well/trench invert elevations. Free-phase PCE, which has a higher density than water, naturally tends to flow downwards into the bedrock. The driving forces created by the groundwater pumping system or the vacuum extraction system appear to be insufficient to mobilize these residual materials from the matrix of the weathered/fractured sandstone. We theorize that the vertical, upward migration of groundwater into the Containment Area via pumping, which constituents 95% of the water inflow, is causing groundwater to flow through residual free-phase PCE below or surrounding the invert of the extraction wells. Consequently, the resultant groundwater concentration exceeds closure objective of 25 μg/L, but does not contain free-phase PCE.

These observations are in agreement with the phenomenon suggested by Parker et. al. (1994) where immiscible-phase organic liquids (such as the PCE) actually diffuse (i.e. disappear) into the matrix of the surrounding consolidated media. Parker et al.'s laboratory research and review of case histories suggest that the conceptual model where the fractured consolidated geologic media provides a pathway <u>only</u> for immiscible-phase flow and where no significant entry of the immiscible-phase liquid into the fractured consolidated geologic media is assumed is too simplistic. The paper further suggests that disappearance times for these liquids in weathered sandstone (such as that present at the subject site) are "generally less than several years for fracture apertures ranging from 10 to 200 microns typical for shales, siltstones, sandstones, and carbonate rocks". Their conclusions suggest that "Proposed methods for enhancing immiscible-phase mass removal using hydraulic manipulation, surfactants, or alcohols will be futile where the immiscible phase has disappeared into the clay or rock matrix, and reverse diffusion and desorption will control clean-up timeframes. Therefore, the prospects for permanent restoration of many DNAPL and LNAPL sites in fractured porous media are more limited than previously thought."

Presently, the groundwater extraction and treatment system is successfully controlling the migration of the PCE plume, however, it is not recovering free-phase PCE and consequently a significant reduction in dissolved-phase PCE concentrations is not expected to occur. Based solely on levels of residual dissolved-phase contaminant levels observed in the Containment Area and assuming no residual free-phase impacts, it is estimated that at the present rate it will take 760 years to achieve groundwater standards. Clearly, the existing groundwater containment/extraction and treatment system is not rapidly moving the site toward regulatory closure. This is consistent with the conclusions made by Parker et al. (1994). To achieve timely regulatory closure, a cost-benefit analysis of additional remedial actions or enhancing the present pump and treat method was performed as discussed next in this paper.

TABLE 1: Summary of Groundwater PCE Concentrations in June/July 2002.

| **Sample** | **Tetrachloroethene (PCE) in μg/L** |
|---|---|
| Objective | 25 |
| Solubility | 200,000 |
| MW-1 | <1.0 |
| MW-3S | <1 |
| MW-3D | <1 |
| MW-7 | <1 |
| MW-9D | <1 |
| MW-9S | <1 |
| MW-10 | <1 |
| MW-11 | <1 |
| MW-12 | <1 |
| MW-13 | <1 |
| MW-14 | <1 |
| MW-15D | <1 |
| MW-15S | <1 |
| MW-18D | <1 |
| MW-18S | <1 |
| PZ-1BWI | **29000** |
| PZ-2 | <1 |
| PZ-2BWO | 1.2 |
| PZ-3BWI | **290000** |
| PZ-4BWO | **20000** |
| PZ-5 | <1 |
| PZ-5BWO | **14000** |
| PZ-6BWI | **44000** |
| PZ-7BWO | **18000** |
| PZ-8 | <1 |
| PZ-8BWI | **11000** |
| PZ-9BWO | <1 |
| PZ-10BWI | **640** |
| PZ-11BWO | <1 |
| PZ-12BWI | 1.5 |
| PZ-13BWO | **330** |
| PZ-14BWI | **73000** |
| PZ-15BWI | <50 |
| PZ-16 | <1 |
| PZ-16BWO | <1 |
| PZ-17BWO | **1100** |
| PZ-18BWI | **4300** |
| PZ-19 | 3.8 |
| PZ-20 | **29** |

| **Sample** | **Tetrachloroethene (PCE) in μg/L** |
|---|---|
| Objective | 25 |
| Solubility | 200,000 |
| PZ-20BWO | **470** |
| PZ-21 | <1 |
| PZ-21BWO | <1 |
| PZ-22BWI | <1 |
| PZ-23BWI | **92000** |
| PZ-24BWO | 5.5 |
| PZ-25BWO | <1 |
| PZ-26BWO | <1 |
| PZ-27BWI | **58** |
| RT1 | **11000** |
| RT2 | **83000** |
| RT3 | **84000** |
| RT4 | **2700** |
| RT5 | **15000** |
| RT6 | **54000** |
| RT7 | **14000** |
| RT8 | **20000** |
| RT9 | **37000** |
| RT10 | **16000** |
| RT11 | **53000** |
| RT12 | **83000** |
| RT13 | **14000** |
| T100 | **29000** |
| T101 | **22000** |
| GC1 | **50000** |
| GC2 | **29000** |
| GC3 | **34000** |
| GTS201 | **49000** |
| GTS202 | **10000** |
| GTS203 | **5900** |
| GTS204 | **17000** |
| IT1 | **14000** |
| IT2 | **14000** |
| IT3 | **45000** |
| | |

Note:

Groundwater Remediation Objective Exceedances are indicated in **Bold**.

## Technology Limitations for Additional Remediation

The cost-benefit analysis of additional remediation at the site involved a two-step screening process. The essential purpose of the initial screening of the remedial action technology type or process was to eliminate those technologies from further consideration that may fall short of achieving remedial objectives (when compared with other options). The process of identifying a wide range of technology types at the start, and then screening those out that fall short of expectations, ensured the consideration of a wide range of process options. The technology types and process options for addressing groundwater contamination at the site were first evaluated based primarily on their technical implementability, considering site and chemical characteristics. Alternatives that remained after the initial screening for technical implementability were then screened using a qualitative comparison based on effectiveness, administrative implementability, and cost. The result was a manageable number of select technologies from which the preferred remedial alternatives could be identified and evaluated.

Six alternatives were identified in the initial screening. Table 2 provides a summary the preliminary identification and evaluation of the remedial options. The initial analysis indicated that aggressive remedial technologies exhibited a higher ability to remove PCE and therefore provided a better cost benefit. Accordingly, three in-situ remedial technologies were retained for further analysis and compared against continuing the existing system. The current system is considered more of a containment approach than a remediation approach.

The alternatives that were retained for further analysis included:

- In-situ Chemical Oxidation,
- Surfactant/Cosolvent Flushing and
- In-situ Thermal Treatment
- Continued Groundwater Containment/Collection with Existing System

These four remedial action technologies were further screened against the criteria of effectiveness (advantages/disadvantage), implementability and cost. Table 3 provides a summary of advantages and disadvantages of each in-situ remedial alternative along with the estimated cost per cubic yard of soil.

The implementability and effectiveness of the first three remediation technologies are comparable; however the cost difference is significant. We estimated that an in-situ, aggressive remedial approach will have a total life cycle cost on the order of three to four times that of continuing operation of the existing containment and recovery system. Among the alternatives, thermal in-situ remediation was the least expensive active treatment option, which was estimated to cost $14,200,000, where as continued remediation using the existing system for a period of 30 years was estimated to cost $3,200,000. The amount of soil/weathered bedrock to be remediated was estimated to be 160,000 cubic yards over an area of 5 acres.

In terms of their ability to achieve timely closure, thermal in-situ remediation was rated higher than the existing system. However, this technology, as was the case with other technologies, could not remediate the free-product PCE that appears to have diffused into the weathered bedrock matrix in a reasonable amount of time to levels that will achieve groundwater regulatory standards or allow for the current groundwater extraction treatment system to be shut down. None of the technologies that were evaluated have been demonstrated to be capable of effectively and efficiently addressing the bedrock matrix-diffused PCE. At best, the technologies had the potential to address the impacts immediately surrounding the point of injection, necessitating installation of an impracticable number of injection points and an unknown number of injection events or application time frame, potentially making the current estimated remediation cost even higher.

After evaluating the ability of the alternatives to achieve closure and the cost of implementation, the option of continuing operation of the current system and containment of the plume indefinitely was considered to be more cost-effective. The analysis indicated that in order to be cost-effective, any application of treatment technology must be able to result in discontinuation of the current groundwater system. Our evaluation concluded that none of the remedial technologies that were considered could remove PCE from the bedrock matrix with reasonable certainty, within reasonable time frame, and at a reasonable cost to levels that would allow shutting down the current groundwater extraction system and achieving groundwater cleanup objectives.

## Conclusions

An unusually large PCE release over a 5-acre area underlain by weathered/ fractured sandstone bedrock posed significant challenges. The immediate response actions recovered a significant volume of free-phase PCE and successfully contained the plume from further migration. Subsequently, a pump and treat system has been able to contain the PCE plume and treat impacted groundwater, albeit removing only small fractions of total PCE that is present at the site.

Although the extracted groundwater concentrations indicate the presence of free-phase PCE in the subsurface matrix, this PCE has not been readily available for removal. Monitoring data suggests that the PCE may have diffused into the matrix of the weathered bedrock and that reverse diffusion and desorption may be controlling the rate of PCE removal. At the present rate of removal, we estimate it will take an indefinite amount of time, in practical terms, to meet the regulatory cleanup objectives.

The identification and evaluation of existing remedial technologies to supplement or replace the existing pump and treat system revealed a clear lack of a proven, cost-effective technology to address the problem of remediating less-accessible PCE, as seen at this site. Our conclusion is that continuing operation of the current containment system is the most cost effective option until an alternative treatment technology that can reliably and cost-effectively treat the matrix-diffused PCE and achieve groundwater quality standards, is available.

Table 2: Summary of Initial Screening Process – A Comparison of Effectiveness, Implementability, and Cost

| Alternative | General Technology Description | Short Term Effectiveness | Long Term Effectiveness | Implementability | Benefit (B) and Drawbacks (D) | Cost |
|---|---|---|---|---|---|---|
| **Alternative 1- Natural Attenuation** | Natural attenuation by physical, chemical and biological processes reduces VOCs concentrations over time. | Compliance with groundwater standards will not be achieved. | Compliance with groundwater standards will not be achieved | Will not achieve site closure. | B – Lowest cost alternative<br>D – Appears incapable of addressing groundwater impacts | Low Capital Costs<br>Low to Moderate O & M Costs |
| **Alternative 2 - In Situ Enhanced Bioremediation (HRC Injection)** | Injection of materials such as HRC to promote biodegradation of contaminants. | VOC reduction in area of concern accelerated in short term. Reduction in PCE levels not expected to be significant because of the presence of PCE in the bedrock pores. | VOCs reduced over time by enhanced natural processes. | Technically feasible – could require repeated injections and additional testing to show effectiveness. Uncertain whether high PCE levels will allow for this approach. | B – Accelerated reduction of VOCs in area of concern.<br>D – May require multiple applications<br>D – Difficult to promote degradation of the PCE present within bedrock pores. | Moderate to High Capital Costs<br>Moderate O & M Costs |
| **Alternative 3 – Groundwater Containment/ Collection** | Continued operation of the existing site system or installation of a collection system that can be operated at a lower annual cost. | Regulatory compliance will be maintained. Reduction in PCE levels not expected to be significant because of the presence of PCE in the bedrock pores (limited to desorption and diffusion transport mechanisms from within the bedrock). | Significant reduction in PCE concentrations is not expected in the near long term. | Technically feasible – could continue to operate the current system until technology advances catch with the site remediation needs. | B – Low cost.<br>B – Allows for future remedial strategy implementation with technology advances.<br>D – Closure with this strategy alone unlikely in the near long term. | Low Capital Costs<br>Moderate to High O & M Costs |
| **Alternative 4 - In-Situ Chemical Oxidation (Ozone, Fenton's Reagent or Potassium Permanganate)** | Destruction of the residual contaminants by injecting oxidants to chemically change the PCE to innocuous compounds. Applied in conjunction with a containment/collection system. | Effective at contacting and destroying PCE present within preferential subsurface pathways. Not effective at contacting and destroying PCE present within the bedrock pores. | PCE concentration reduction/efficiency not expected to be immediately achieved to allow for site closure. | Technically feasible – could require repeated injections and additional testing to show effectiveness. | B – Accelerated reduction of VOCs in area of concern.<br>D – May require multiple applications<br>D – May not reduce overall site remediation system operation and groundwater monitoring timeframe. | Moderate-high to High Capital Costs<br>Moderate to High O & M Costs |
| **Alternative 5 - Surfactant/ Cosolvent Flushing** | Removal of the residual contaminants by injecting oxidants to chemically change the PCE to innocuous compounds. Applied in conjunction with a containment/collection system. | Effective at contacting and removing PCE present within preferential subsurface pathways. Not effective at contacting and destroying PCE present within the bedrock pores. | PCE concentration reduction/efficiency not expected to be immediately achieved to allow for site closure. | Technically feasible – could require repeated injections and additional testing to show effectiveness. | B – Accelerated reduction of VOCs in area of concern.<br>D – May require multiple applications<br>D – May not reduce overall site remediation system operation and groundwater monitoring timeframe. | Moderate-high to High Capital Costs<br>Moderate to High O & M Costs |
| **Alternative 6 – In-situ Thermal Treatment** | Removal of the residual contaminants by injecting steam or electrically heating the media to change the viscosity and boil the contaminant out. Applied in conjunction with a containment/collection system. | Effective at contacting and removing PCE present within preferential subsurface pathways and at contacting and removing PCE present within the bedrock pores (relative to other technologies). | PCE concentration reduction/efficiency not expected to be immediately achieved to allow for site closure. | Technically feasible – could require repeated injections and additional testing to show effectiveness. | B – Accelerated reduction of VOCs in area of concern.<br>D – May require multiple applications<br>D - Cost | High Capital Costs<br>Low to Moderate O & M Costs |

Table 3: Second Stage of Screening Process –In-Depth Comparison of Various Remedial Technologies.

| **Remediation Technology** | **Advantages** | **Disadvantages** | **Cost per cubic yard of Soil** |
|---|---|---|---|
| **Chemical Oxidation**<br>• Fenton's Reagent<br>• Potassium Permanganate<br>• Ozone Gas | • Rapid and complete reaction.<br>• Capable of achieving efficiencies greater than 90%.<br>• Short treatment duration.<br>• Best suited for homogeneous high permeability media. | • Requires handling of large quantity hazardous oxidizing chemicals.<br>• Regulatory issues related to injection of chemicals into the subsurface.<br>• Effectiveness is dependent on a good delivery system (horizontal or vertical wells).<br>• Low permeability and heterogeneous soils are difficult to treat.<br>• Can significantly decrease pH of the subsurface environment if not buffered effectively.<br>• Possible formation of toxic byproducts, evolution of heat and gas, and biological perturbation.<br>• Ability to remove free-phase product contained with in the matrix of weathered bedrock to efficiencies that will result in dissolved-phase groundwater impacts below regulatory levels is uncertain.<br>• Worker safety and training is critical. | $ 50 - $ 200 |
| **Thermal Treatment**<br>Six Phase Heating (Electrical Resistance Heating) | • Efficiencies greater than 70%.<br>• Short to medium term technology.<br>• Effective in low permeability conditions. | • Requires availability 3-phase electricity source.<br>• Needs to be coupled with a vapor extraction system.<br>• Worker safety and training critical.<br>• Precautions against accidental electrocution required.<br>• Ability to remove free-phase product contained with in the matrix of weathered bedrock to efficiencies that will result in dissolved-phase groundwater impacts below regulatory levels is uncertain. | $ 25 -$ 100 |
| Steam-Enhanced Extraction<br>*Uses vaporization of contaminants that can affect removal from within the matrix of weathered bedrock.* | • Capable of removing large portions of DNAPL and retarding downward and lateral migration.<br>• In Lab studies, efficiency greater that 99% reported in fractured plane of sandstone bedrock.<br>• Short to medium duration (lasting a few weeks to several months. | • Can potentially wash of contaminants away from the zone of treatment.<br>• Needs to be coupled with a vapor extraction system.<br>• Toxic vapors could be produced.<br>• Resulting air emissions may require treatment.<br>• Ability to remove free-phase product contained with in the matrix of weathered bedrock to efficiencies that will result in dissolved-phase groundwater impacts below regulatory levels is uncertain. | $ 50 - $ 300 based on 70% on-line efficiency |
| Surfactant/Cosolvent Flushing | • Mobilizes DNAPL that cannot be extracted by regular pump and treat systems.<br>• Short to medium term duration.<br>• Best suited for homogeneous high permeability media. | • Can potentially wash contaminants away from the zone of treatment.<br>• Low permeability and heterogeneous soils/media are difficult to treat.<br>• Resulting water and air emissions may require treatment.<br>• Surfactants can adhere to soil and reduce permeability.<br>• Ability to remove free-phase product contained with in the matrix of weathered bedrock to efficiencies that will result in dissolved-phase groundwater impacts below regulatory levels is uncertain. | $ 25- $ 250 |

## References

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