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aquifers cannot be restored through groundwater pumping and treating. Two lines of evidence support this assertion. First, extensive experience with groundwater transport models allows the prediction of the effectiveness of groundwater pumping. Leading groundwater scientists (7-9) have predicted that continuous pumping for as long as 100-200 years may be needed in order to lower concentrations by a factor of 100, assuming the ideal conditions of a totally dissolved contaminant in a homogeneous aquifer. Aquifer restoration is less reliable at sites involving nonaqueous-phase liquids (NAPLs) that either float on top of the water table or sink to the bottom of the aquifer. At best, even assuming restoration is possible, it is impossible to predict how long pumping and treating will take to restore an aquifer (7). In spite of this observation, aquifer restoration is the remedial objective at approximately 93% of the sites known to involve NAPLs (10). The director of EPA’s groundwater research laboratory in Ada, Oklahoma, has pointed out that restoration could take thousands of years at sites where water-insoluble constituents such as jet fuel are present (8). When large pools of dense NAPLs are present at the bottom of an aquifer, meeting drinking-water standards is unachievable at any cost (11).

The second source of proof of the ineffectiveness of pumping and treating for aquifer restoration comes from direct experience in pumping contaminated aquifers over the past 10 years. A recent EPA study (10) involving 19 sites where pumping and treating had been ongoing for up to 10 years concluded that although significant mass removal of contaminants has been achieved, there had been little success in reducing concentrations to the target levels. The typical experience is an initial drop in concentrations by a factor of 2-10, followed by a leveling with no further decline. To exacerbate the problem, once pumps are turned off, concentrations rise again.

Take, for example, the IBM Dayton hazardous waste site in New Jersey (10). Groundwater at the site was contaminated with approximately 400 gal of volatile organic compounds (VOCs), primarily 1,1,1-trichloroethane (TCA) and tetrachloroethene (PCE), with maximum groundwater concentrations up to 9590 ppb for TCA and 6132 ppb for PCE. Pumping with an average on-site extraction rate of 300 gpm between 1978 and 1984 lowered VOC concentrations to below 100 ppb. However, after shutdown of the operation in 1984, PCE concentrations rose to 12,558 ppb in 1988. Pumping was resumed in 1989, but the remedial objective was changed from restoration to containment. Thus, despite extensive groundwater pumping, this site is no closer to remediation than it was 12 years ago.

Other examples include the following. • Savannah River, SC. After four years of pumping to achieve aquifer restoration, TCE concentrations leveled of above 10,000 ppb. The system is being redesigned with the remedial objectives changed to containment and reduction of contaminant mass. • Verona Wellfield, MI. Substantial reduction of contaminant mass has been achieved. However, after six years of pumping, VOC concentrations have leveled off above 2500 ppb. • General Mills, MN. Substantial reduction of TCE concentrations has been achieved. However, after three years of pumping, aquifer concentrations have leveled off and remain as high as 460 ppb in one area. • Harris Corporation, FL. Five years of pumping has reduced the VOC plume. However, total VOC concentrations have leveled off above 500 ppb during the past year.

In spite of intense searching, we were unable to locate a single aquifer in the United States that has been confirmed to be successfully restored through pumping and treating. Although one Superfund site is claimed by the responsible party to be cleaned up, the claim has not yet been substantiated by EPA, and the extent of remediation is questionable because the site investigation did not identify the source of contamination or fully delineate the contaminant plume. Emerson Electric, a site in Florida involving low-level contamination, also is claimed to be cleaned up. However, the validity of this claim is also questionable because the plume was not fully delineated before extraction began, and no groundwater samples have been taken since the extraction wells were closed (10).

Why can’t aquifers be restored?

Contaminants in groundwater partition between the water and organic matter in soils. As groundwater is pumped, the chemicals are held back (retarded) by their adherence to the soil particles. At sites involving NAPLs or zones of low permeability, the restoration process is complicated further. Even highly soluble contaminants may become trapped in the finer pore structure because groundwater pumping causes preferential flow in high-permeability zones. Approximately 76% of Superfund sites for which pumping and treating is selected as the aquifer restoration method are contaminated by trichloroethylene (TCE), a contaminant denser than water (5). The geometric mean for the maximum concentration of TCE detected in groundwater at the 50 sites we reviewed (5) was 345 ppb with a range of...
2-4,100,000 ppb. The MCL for TCE is 5 ppb. Thus, for groundwater pumping to restore the average Superfund site, pumping must remove more than 99% of the mass of TCE in the dissolved and nonaqueous phases. It is well known that even with enhanced oil recovery methods, oil companies can only remove 30-50% of the oil from the subsurface. One wonders why Congress believes that EPA can remove organics from groundwater more effectively than oil companies which could make billions of dollars by improving oil recovery by 5-10%.

What is the next step?

To meet the challenge of aquifer restoration we recommend the following changes to Superfund policy.

Explicitly acknowledge that aquifer restoration is currently technically impossible. There is something terribly flawed about a process that authorizes the expenditure of billions of dollars to achieve an end (groundwater restoration) that is acknowledged by scientists (7-9), consulting companies, and the regulators themselves (10) to be currently unachievable. The unachievability of this end given the current state of technology needs to be widely and explicitly acknowledged before contaminated aquifers can be effectively managed.

Develop a more appropriate groundwater classification system. The current EPA groundwater classification system is not an adequate tool for prioritization at Superfund sites. It is based primarily on the preservation of groundwater quality and does not account for potential future uses. A more workable system has been proposed by the New Jersey Department of Environmental Protection (12). This system classifies groundwater not only according to water quality but also according to groundwater use. The system essentially consists of four groundwater classes. Class I aquifers are those needing special protection because they support sensitive ecological systems or high-quality surface watersheds. Class II and III aquifers are current and potential sources of drinking water, respectively. Class IV aquifers consist of groundwater that is not designated for potable water supply and is generally of poor quality. This last class contains several subclasses, one of which includes groundwater that may be used in the future but not for at least 50 years. The use of such a system for prioritization would reduce the use of indiscriminate groundwater remediation strategies.

Discontinue the use of Applicable or Relevant and Appropriate Requirements (ARARs) as cleanup goals for aquifer restoration. Current policy at Superfund sites is to select the most stringent ARAR as the cleanup goal for the site. This policy is unrealistic and misleading. Not only is restoration of contaminated aquifers to levels compatible with ARARs simply unachievable, but the continued pursuit of this objective creates false expectations on the part of Congress and the public. Reliance on ARARs simply postpones the necessary realization that the best that can be accomplished at contaminated sites today is plume containment and contaminant mass reduction.

Make plume containment and contaminant mass reduction primary remediation goals. Although pumping is ineffective for aquifer restoration, it has great value for plume containment and contaminant mass reduction. The record shows that a significant fraction (up to 50%) of the mass of contaminants can be recovered from contaminated groundwater either through pumping or in conjunction with vapor extraction. Action should be taken early to contain the contaminant plume (before the Remedial Investigation/Feasibility Study process is complete) because even small delays can exacerbate the problem. Plume containment should be the stated objective in the ROD, and remedial designs should reflect this objective.

Recognize that restoring aquifers to a pristine condition is not always necessary. Not all aquifers are created equal, either in terms of original water quality or their potential future uses. Therefore, a more flexible approach to remediation is needed. For contaminated aquifers that are near current sources of drinking water, every effort must be made to contain the plume indefinitely. However, for aquifers that are unlikely to be drinking-water sources, total restoration may not be necessary, and pumping for mass reduction for 3-5 years followed by natural attenuation (dilution) may be sufficient. Because natural attenuation is rarely considered as a remedial alternative for Superfund sites, guidelines for the selection of this alternative need to be developed.

Enhance efforts to protect groundwater. Once groundwater is contaminated, restoring it to a condition compatible with health-based standards is difficult if not impossible. Remedial efforts should, therefore, focus on developing and implementing permanent, cost-effective source control remedies. Efforts should be made to prevent future contamination and to assign a high priority to waste minimization efforts. Recycling should be encouraged by the federal government, and a realistic national policy on recycling needs to be developed. Prevention is the most critical element of a sound groundwater management strategy, and current policy at Superfund sites shifts attention and resources away from this strategic priority.

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(11) Freeze, R. A.; Cherry, J. A. Groundwater 1989; 27(4), 458-64.

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COMBINED STEAM INJECTION AND VACUUM EXTRACTION FOR IN SITU REMEDIATION

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pure trichloroethene, a mixture of benzene and toluene, and gasoline as separate liquid phases flowing ahead of the steam condensation front. Stewart and Udell (1988) developed three phase flow solutions to the problem of steam displacement of volatile contaminants and compared those results to experimental data with good agreement.

The research reported here adds to this body of literature through the presentation of new experimental data and further interpretation of previously reported data. The experimental data aid in defining the mechanisms which are responsible for the surprising success of combined steam injection and vacuum extraction for soil and groundwater decontamination.

2 MECHANISMS

When saturated steam is injected into an initially cool porous medium, the steam condenses, giving up the latent heat of vaporization to heat the porous solid and interstitial fluids. With continued injection three distinct zones will develop: an early isothermal steam zone, a variable temperature zone, and an isothermal zone at the initial medium temperature saturated with water and mobilized contaminant (see Figure 1). The rate of expansion of the steam zone is directly proportional to the injected steam enthalpy flux if the length of the variable temperature zone remains constant with time (Menegus and Udell, 1985, Hunt, Sitar and Udell, 1986, and Stewart and Udell, 1988). The interface between the steam zone and the variable temperature zone is essentially the location of steam condensation if the temperature gradient in the steam zone is not significant. For injection pressures near atmospheric and soil thermal properties and temperatures characteristic of field conditions, approximately 350 pore volumes of steam will be required to condense at the condensation front to expand the steam zone an additional unit volume. Thus, steam injection is characterized by high vapor volumetric flow rates in the steam zone. Within this thermal and fluid distribution context, contaminant removal mechanisms can be described.

2.1 Vaporization of low boiling point contaminants

For non-aqueous phase contaminants with boiling points lower than that of steam at pressures near atmospheric, vaporization will occur in the variable temperature zone ahead of the steam condensation front (point A in Figure 1). The resultant contaminant vapor would occupy a region extending to the left of point A into the steam zone. Yet, because of the high flux of steam in the steam zone, the contaminant vapor will be convected forward and displaced into the variable temperature zone ahead of point A where it must condense. Therefore, the low boiling point liquid will be mobilized ahead of the steam condensation front in spite of capillary forces which would otherwise trap the second phase liquid. As evidenced by the experimental observation of second phase contaminants flowing from the exit of the experiments reported by Hunt, Sitar and Udell (1988), it is expected that the contaminant vapor either condenses upon the second phase liquid or that any produced emulsions coalesce to the second phase liquid bank rather than flow as contaminant-in-water emulsions. Without doubt, pure separate liquid phase contaminants with boiling points less than that of water will be completely removed from the steam zone except for the small amount which is adsorbed to solid surfaces or is dissolved in liquid water which may be present in the steam zone.

With the accumulation of distributed, high volatility second phase contaminants into a coherent bank ahead of the steam condensation front, buoyancy forces reenter the displacement process. Hydrostatic forces in a connected contaminant bank can lead to percolation of the contaminant either upward or downward depending on whether the density is less than or greater than that of water, respectively.

2.2 Enhancement of contaminant evaporation rates

In most remediation projects, the contaminant will consist of many chemical components of varying thermodynamic properties. It is inevitable that the low vapor pressure components of the separate phase contaminant will remain in the pore spaces after the passage of the steam condensation front. However, these components will be contacted by the
limit. Second, the high pressure gradient is stabilizing with respect to displacement stability, as determined by the Saffman and Taylor (1958) stability criterion of a higher pressure gradient in the displacing phase than in the displaced phase. Indeed, Stewart and Udell (1988) showed that stable displacement of second phase liquids with viscosities greater than water can occur. Also, steam is capable of mobilizing any length of NAPL bank for a sufficiently low NAPL viscosity.

2.4 Dilution of initial pore water

The reduction of soil contaminant concentrations can occur through steam displacement of the contaminant in solution in the aqueous phase. As mentioned in the discussion of the displacement effectiveness of steam injection, all but the immobile water is removed from the pores. Therefore, if 80% of the contaminated water is displaced from the soil, the soil concentration, referenced to the mass of contaminant per dry mass of soil, would be expected to be reduced by at least 80% if all contaminant is in solution. However, a bank of distilled water representing the steam condensate is formed ahead of the steam condensation front. Through mixing, this steam condensate dilutes the initial water. Therefore, the water remaining in the steam zone would not necessarily contain the same contaminant concentration as the initial water.

To determine the reduction of aqueous phase contamination by steam displacement and dilution, experiments were performed in the same experimental apparatus as used in Hunt et al. (1988) and Stewart and Udell (1988). The solute chosen was sodium chloride, because of its low adsorption on quartz and zero vapor pressure. A dilute saline solution of 14.0 g/kg concentration was injected into a sandpack until the effluent fluid electrical resistivity matched that of the injected fluid. The 5.04-cm diameter sandpack was then subjected to a steam flowrate of 2 mg/min. A steady steam condensation front velocity was observed. The effluent was collected in a graduated cylinder. To maintain one-dimensional conditions in the sandpack, a series of heater tapes were sequentially turned on and adjusted in accordance with a predetermined calibration of heat loss versus sandpack/room temperature difference. After steam was observed in the outlet tubing, noted as time of steam breakthrough, injection continued until the effluent mass flux equaled the steam injection rate. The water remaining in the sandpack was thus considered to be immobile and at the irreducible saturation, which was determined from a mass balance to be 12.9%. A measured volume of distilled water was then injected into the steam zone as the column was allowed to cool. At the end of this procedure, the sandpack was completely saturated with water. The system was allowed to rest for 48 hours, allowing the salt remaining in the sandpack to diffuse into the injected water. The water was then allowed to drain from the sandpack through the injection port by gravity. All effluent solutes were analysed for salt concentrations by atomic adsorption spectroscopy.

Table 2 Water volumes and salt masses during various sequences of steam injection

<table>
<thead>
<tr>
<th>Water Volume in Solution (ml)</th>
<th>Salt Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State</td>
<td>724</td>
</tr>
<tr>
<td>Steam Injection (1.97 ml/min)</td>
<td></td>
</tr>
<tr>
<td>- before breakthrough</td>
<td>188</td>
</tr>
<tr>
<td>- after breakthrough</td>
<td>147</td>
</tr>
<tr>
<td>- total</td>
<td>335</td>
</tr>
<tr>
<td>Effluent</td>
<td></td>
</tr>
<tr>
<td>- before breakthrough</td>
<td>803</td>
</tr>
<tr>
<td>- after breakthrough</td>
<td>163</td>
</tr>
<tr>
<td>- total</td>
<td>966</td>
</tr>
<tr>
<td>Residual Water</td>
<td></td>
</tr>
<tr>
<td>- before breakthrough</td>
<td>109</td>
</tr>
<tr>
<td>- final</td>
<td>93</td>
</tr>
</tbody>
</table>
ceramic tape. Two tape heaters were then applied along the length of the holder and covered the entire radial surface area. The heater tapes were used to maintain adiabatic conditions at the surface during steaming. Finally, the apparatus was placed in a 2.5-cm thick ceramic blanket. The end plates were covered with additional insulation.

The steam generator consisted of copper tubing wound around electrical resistance heating plates and surrounded by an insulating blanket. A constant displacement pump supplied deionized, deaerated water at ambient temperature to the steam generator at a constant rate. During injection, the heater tapes were turned on sequentially as the steam front propagated through the core. A flexible 3-mm teflon exit line was run through an ice bath over a length of approximately 0.3 meters. The effluent was collected in 8- and 40-ml vials which were also held in an ice bath. After steam breakthrough, the steam injection was continued for varying lengths of time before termination.

The steam injection was followed by a period of vacuum extraction at 711 mm Hg. A vacuum pump was connected to the exit of the sample holder and the vacuum was applied for approximately five seconds to clear the exit line of steam injection condensate. The vacuum was then applied for some period of time and a sample of the condensate was collected. With the apparatus under vacuum, the samples cooled quickly due to the removal of energy from the hot matrix which was used to vaporize the remaining contaminated interstitial water.

A summary of the experimental conditions are given in Tables 3 and 4. The flow rate refers to the rate of steam injection into the sample, the maximum injection pressure is the pressure recorded at the steam generator at steam breakthrough, breakthrough corresponds to the time elapsed between the initiation of steam and the appearance of steam at the exit, steaming period refers to the time for which steam injection continued beyond breakthrough, and vacuum period refers to the elapsed time during which the sample was held under vacuum. The steam injection rate, the time periods of application of each phase and the soil type can be correlated to the levels of remediation achieved. The soil and water samples were analyzed for total extractable hydrocarbons (TEH) according to EPA Method 3530 for soils and EPA Method 3510 and 8015 for water. A summary of the results of the chemical analyses are presented in Table 5. As well as providing data on the importance of processing conditions and soil heterogeneities on decontamination rates, the data in Table 5 clearly illustrates the importance of the vacuum drying process on contaminant recovery rates. The solubility of diesel in water at room temperature is approximately 23 ppm and therefore the concentrations above 23 ppm observed in the condensed steam are evidence of

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**Table 3** Diesel contaminated soil samples used in experiments of combined steam injection/vacuum extraction

<table>
<thead>
<tr>
<th>Expt #</th>
<th>Description of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silty clay with gravel</td>
</tr>
<tr>
<td>2</td>
<td>Silty clay, uniform</td>
</tr>
<tr>
<td>3</td>
<td>Clayey gravel with sand</td>
</tr>
<tr>
<td>4</td>
<td>Clayey gravel, dry</td>
</tr>
<tr>
<td>5</td>
<td>Fine sand, dry</td>
</tr>
<tr>
<td>6</td>
<td>Fine sand, dry</td>
</tr>
</tbody>
</table>

**Table 4** Experimental conditions

<table>
<thead>
<tr>
<th>Expt #</th>
<th>Flow Rate</th>
<th>Pressure Breakthrough</th>
<th>Steam Period</th>
<th>Vacuum Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mL/min)</td>
<td>(kPa)</td>
<td>(min)</td>
<td>(min)</td>
</tr>
<tr>
<td>1</td>
<td>0.50</td>
<td>&lt;7</td>
<td>1.05</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
<td>34.5</td>
<td>1.00</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
<td>10</td>
<td>0.64</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.80</td>
<td>&lt;7</td>
<td>0.66</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>0.60</td>
<td>1.4</td>
<td>1.84</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>0.60</td>
<td>1.4</td>
<td>1.05</td>
<td>17</td>
</tr>
</tbody>
</table>

**Table 5** Summary of concentrations in soils and effluent liquids

<table>
<thead>
<tr>
<th>Expt #</th>
<th>Original Soil TPH</th>
<th>Promoted Soil TPH</th>
<th>TPH Concentration at 5 mm in Condensate</th>
<th>TPH Concentration in Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mg/kg)</td>
<td>(mg/kg)</td>
<td>(mg/L)</td>
<td>(mg/L)</td>
</tr>
<tr>
<td>1</td>
<td>1500</td>
<td>19</td>
<td>110</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>&lt;10</td>
<td>93</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>1100</td>
<td>45</td>
<td>93</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>640</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>178</td>
</tr>
<tr>
<td>5</td>
<td>710</td>
<td>120</td>
<td>23</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>5</td>
<td>230</td>
</tr>
</tbody>
</table>
The water pumped out of the recovery well prior to steam breakthrough was near the saturation limit for the various compounds found in the soil. Water samples taken from the well after breakthrough showed a sharp decrease in the contaminant concentrations. Contamination in the vapor removed from the steamed soil was initially high and did not drop until after 100 hours of steaming. Sharp drops in the concentration of individual components occurred at times inversely proportional to the vapor pressures of each compound.

The total soil concentrations of contaminant less acetone are plotted versus depth below the surface in Figure 4. The designations RW6, IW1, IW3 and IW5 refer to samples taken during the installation of the wells and used to characterize the pre-steaming distribution of contamination. These data show the large variability in soil concentrations with location. At the end of the 140-hour steam injection period, two continuously sampled borings, one inside the injection pattern and the other outside, were drilled. These two borings are designated as A1 and A2. At the time which these borings were recovered, temperature observation wells nearest these locations indicated an isothermal steam zone between 9 and 17 feet below the ground surface. This is indicated in Figure 4. A third boring was recovered after a short period of steam and vacuum cycling and is referred to as A3. Also plotted in Figure 4 is the vertical temperature profile at a location midway between the injection and recovery wells after 11 hours of steam injection. The temperature profile is shown to indicate evidence of a low permeability region at a depth of about 14.5 feet which apparently was not contacted by the injected steam. As evidenced by the results of this extensive soil analysis, the levels of soil contaminant concentrations decreased nearly two orders of magnitude in the steam zone. Also, apparent is the scatter of the soil concentration data which is presumed to be due to the heterogeneous nature of actual geologic media.

Vacuum cycling did produce contaminated vapors which were qualitatively observed to be of higher contaminant concentrations than those measured during active steam injection. The effectiveness of this phase of the steam injection/vacuum extraction process for recovering contaminants in the low permeability regions could not be adequately tested because of concerns regarding the possibility of drawing contaminants from outside the test pattern.

4 CONCLUSIONS

Several mechanisms have been identified which account for the observed removal of separate phase liquid contaminants from porous media by combined steam injection and vacuum extraction. These are:

1. Vaporization of low boiling point components.
3. Displacement of low viscosity liquids.
4. Dilution and displacement of the original contaminated water by steam and its condensate.
5. A possible decrease in the fraction of contaminant adsorbed to the solids.
6. Removal of residual contaminated water from the steam zone by drying using vacuum extraction alone.

ACKNOWLEDGMENTS

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IN SITU AERATION OF GROUNDWATER
A TECHNOLOGY OVERVIEW

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ABSTRACT

Remediation of chemicals in the saturated zone has historically been achieved by extracting groundwater and treating it ex situ. However, in many cases this method has been found to require a very long period of time and to have limited effectiveness. As an alternative, in situ groundwater aeration has been developed for permeable, water table aquifers containing relatively insoluble volatile organic compounds (VOCs). Air is injected directly into the saturated zone. It moves outward and upward by displacing water in the pore space and creating air pathways to the unsaturated zone. As it moves through the saturated zone, VOCs partition to the vapor phase which transports them to the unsaturated zone. A soil venting system in the unsaturated zone captures the evolving vapors containing the VOCs resulting in the VOCs coming out in the exhaust air which is treated, as necessary, and discharged. In appropriate situations, in situ groundwater aeration can be a very effective remedial process for VOCs.
the air moves through the saturated zone, volatile organic compounds (VOCs) will partition into the vapor phase from the water or saturated soil. The VOCs travel with the air upward to the unsaturated zone where they are captured by a soil venting system operating to remove the air.

Figure 1 is a schematic diagram of the overall process of *in situ* groundwater aeration. As depicted, compressed air is injected through a screen located beneath the water table. The air moves out and up through the saturated zone by various irregular pathways to the unsaturated zone. The air is then pulled into a soil venting system which is powered by a blower. The exhaust air from the blower is discharged directly or after treatment depending on the specific regulatory situation.

Figure 2 is a schematic diagram of the microsituation illustrating the movement of compressed air through pore spaces. As the compressed air moves through the screen into the saturated zone it displaces water in the pore spaces and moves in irregular pathways to the surface of the water table. It is important to note that the phenomenon is not analogous to a porous diffuser stone in a tank of water where bubbles form and move upward through the water. There is no standing water for bubbles to form in, since the water is contained in a porous media rather than an open tank. If anything, the phenomenon is more analogous to the situation within the porous diffuser stone submerged in the water.

The lateral movement of the air outward is normally favored because the horizontal permeability is typically higher than the vertical permeability. Hence, the pathway of the air can have a significant horizontal component.
Figure 3 is a typical layout of an *in situ* groundwater aeration system and the accompanying soil venting system. The soil venting system consists of a screened system connected to the blower by a vertical riser at the center. The dashed lines show the zone of influence of the soil venting system. Within this boundary, air is being captured by the soil venting system. In this illustration, six aeration points are located within the boundary of the soil venting system. The circles around each aeration point show the radius of effect of each point. The approach to design is to keep the radius of effect of the aeration points within the boundary of the soil venting system's zone of influence.

In operation of the system, the amount of air injected is controlled to be less than the amount of air withdrawn by the soil venting system. This is necessary to assure capture of the injected air and of the stripped VOCs. Proper balance of injected air with the removal capacity of the soil venting system is especially important for systems beneath buildings or in shallow groundwater. Inadequate removal of injected air can cause upward pressure on floors or an elevation of the water table. If these were to occur, buildings may be structurally damaged or groundwater may surface.

The performance of the air injection system can be monitored through the exhaust air VOC concentration. Figure 4 shows the typical variation of exhaust VOC concentration measured at the discharge side of the blower as a function of time. At start-up (time equals zero) of the soil venting system, the exhaust air VOC is at its initial concentration. As soil venting proceeds, the VOC concentration decreases usually very steeply at first as the saturated soil gas is removed. The solid line in Figure 4 depicts the exhaust VOC variation due to soil venting alone. The rate of decrease in concentration lessens as time progresses typically approaching some lower plateau.
it very rapidly. The irregular flow causes a wavefront among the free product, soil particles, water, and air which releases the small trapped pockets. If there is also a steep gradient and high velocities of groundwater flow, the mobilized material can move downgradient faster than it is air stripped. In this situation, downgradient wells can increase in VOC concentration, which is desirable because it means that VOCs have mobilized to a greater degree than before.

However, to design for this situation, sufficient site characterization must be performed in advance to determine the rate of groundwater movement and whether substantial amounts of free product are present in the saturated zone. Groundwater gradients and permeability estimates are required to estimate velocities. The presence of monitor wells with free product or VOCs concentrations near their solubilities indicates the potential presence of free product within the saturated zone.

Where rapid velocities and free product in the saturated zone occur together, then \textit{in situ} groundwater aeration should be combined with downgradient groundwater extraction and treatment if it appears that excessive free product movement will occur. This should assure that mobilized VOCs are captured.

**CASE HISTORIES**

Since 1985, \textit{in situ} groundwater aeration as described here has been used on over thirty sites in Europe and at least two in North America to remove VOCs from groundwater. In this section, three of these case histories will be reviewed in detail.

**Case History No. 1.** In the example described here, soil gas measurements inside a building revealed concentrations of more than 500 ppm for both trichloroethylene (TCE) and tetrachloroethylene (PCE). Peak
10 ft. of strongly sandy gravels, which constituted the aquifer. Underneath the aquifer followed a silt to slightly sandy clay. Initial analyses of groundwater samples showed TCE concentrations of 20,000 µg/L in Well B1 and 6,900 µg/L in Well B2.

From April 1985 to January 1986, pumping was carried out at Well B1. From April 1985 through January 1986, TCE concentrations decreased approximately an order-of-magnitude in B1 and B2 (i.e., 15,000 µg/L to 1,200 µg/L in B1 and 2,400 µg/L to 230 µg/L in B2). The clean-up goal was to attain 25 µg/L or less at B2. Since groundwater extraction and treatment was leading to a gradual decrease, it was decided to speed up remediation with in situ groundwater aeration. Five air injection points were installed within a 30 ft. radius of a soil venting point located at the source area. Air injection began in January 1986. Within 5 days, the TCE concentration in B1 decreased by a factor of ten from 12,000 µg/L to 120 µg/L. Within two months, the concentration decreased to 23 µg/L. Downgradient B2 responded similarly, decreasing from 200 µg/L to less than 10 µg/L.

Case History No. 3. Groundwater contamination was discovered on the site of a chemical manufacturer. Initial analyses revealed concentrations of more than 5,000 µg/L of solvents in the groundwater. Following the discovery, several wells were established up- and downgradient of the contamination sources which had been previously defined by soil gas investigations.

The geology of the site was characterized by uniform sandy gravels down to a depth of approximately 36 ft. The sandy gravels were underlain by marly clays, which form the base of the aquifer. The water table was at a depth of 8 ft. Soil venting was chosen as the process to clean-up the vadose zone, starting in June 1986. For the remediation of the contaminated groundwater eight air injection points were installed at the base of the aquifer.
FIGURE 1. Schematic Diagram Of The Profile Of An In Situ Groundwater Aeration System

Air Injection

Soil Venting

Unsaturated Zone

Water Table

Saturated Zone
FIGURE 3. Plan View Of Typical In Situ Groundwater Aeration System
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LIMITATIONS TO PUMP AND TREAT TECHNOLOGY FOR AQUIFER REMEDIATION

BY

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ABSTRACT

If one is charged with restoring a contaminated aquifer today, the procedure of pumping contaminated water to the surface for treatment and discharge is most often the state-of-practice technology. The perceived success of pump and treat technology can be misleading if the hydrology and contaminant characteristics at the site are not adequately understood. A failure to understand the processes controlling contaminant transport can result in extremely long pumping periods and, consequently, costly and inefficient remediation. Effects of tailing, sorption, and residual immiscible fluids on time required for pump and treat remediation of ground water are discussed.
size, geology, and contaminant type. For this purpose, assume that the area of ground-water contamination is ten acres; the aquifer has a thickness of about 55 feet; the water in storage amounts to 30 percent of the aquifer's volume; and the contaminant is salt water. Under these conditions, it would be possible to exchange the water in this ten-acre plume in about a year by pumping at a rate of 100 gallons per minute.

For example, 10 acres x 43560 ft²/acre x 55 ft x 0.3 water filled porosity x 7.5 gal/ft³ = 365 days/yr x 24 hrs/day x 60 min/hr x 103 gal/min x 1 yr.

Indeed, it appears that pumping would solve this problem, under these conditions, where the contaminant is very soluble and is not retained on the subsurface materials. In reality, it may be necessary to pump for two or three or more years to reach an acceptable salt concentration due to the "tailing" effect often observed in these types of remedial actions.

Tailing is the slow, nearly asymptotic decrease in contaminant concentration in water flushed through contaminated geologic material. Tailing may be caused by several phenomena. In the simplest case of a highly soluble non-retained contaminant, tailing is due to contaminant migration into the finer pore structure of the geologic material. These finer pores then contain water and contaminants that are only slowly exchanged with the bulk water present in larger pores, and tailing is a result. It is the water and contaminants in the larger pores that is mobilized during pumping.

The problem in trying to remove many of the man-made and natural organic compounds from ground water is that they tend to preferentially sorb to the organic and mineral components of the aquifer material. Therefore, when water is removed by pumping, the predominant amount of the contamination remains behind on the aquifer solids. Obviously, removing the aquifer material instead of
If we consider a similar scenario as above where the contaminated area is 10 acres (660 ft by 660 ft), the aquifer is 55 feet thick and flow is from one vertical face to the opposite vertical face with a volume discharge of 100 gpm and a porosity of 0.3, the interstitial velocity of the water would be approximately 660 ft/year and it would take water approximately one year to pass from one end of the contaminated area to the other. If the bulk density of the soil is 100 lb/ft$^3$, the density of water is 62.4 lb/ft$^3$, and the soil partition coefficient is 0.75 (unitless), then it would take 5 years for the pollutant to traverse the length of the plume, and pump and treat might still be quite feasible.

The problem of site remediation is complicated exponentially, however, if the contaminants are themselves constituents of a water-insoluble oily phase such as gasoline, heating oil or jet fuel. In this case, the oily phase will become trapped in the finer pore spaces by capillary forces and cannot readily be pumped out. This residual saturation can result in a significant hidden source of contamination. It is invisible to a monitoring well as only the dissolved fraction will be present in the water that is withdrawn. Its benzene, toluene, and xylene components then partition or "bleed" into the passing ground water at a rate and to a concentration which is characteristic of the contaminants of concern.

To properly appreciate the time required to remove the constituents of an oily phase such as gasoline by pumping, it is only necessary to return to the scenario conditions developed above for salt water. However, it is necessary to include terms for the partitioning of the compounds of concern to the residual oil. The relative velocity of the contaminant now follows the equation

$$\frac{V_w}{V_c} = 1 + \frac{\rho_s}{\rho_a \phi} k_d + \frac{\rho_s}{\rho_a \phi} k_p$$
In any event, if the pumps are stopped for some period of time, the water soluble gasoline components will again dissolve into the ground water and one will find that the contaminant concentrations have returned to their previous levels.

There is little doubt that pumping and treating ground water is a viable approach to aquifer restoration in some instances, particularly when the aquifer is hydrologically homogeneous and the contaminant or contaminants are highly soluble and have little affinity for sorbing to the aquifer material. It may also have utility when it is necessary to remove the more highly concentrated portions of a contaminant plume, or perhaps even a separate phase
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Introduction

The extraction and injection wells used in ground-water contamination remediations produce complex flow patterns, where previously there were comparatively simple flow patterns. Historical trends at local monitoring wells are thereby rendered useless. Further, the complex flow patterns generated by remediation wellfields present great challenges in terms of characterization of the altered transport pathways. Hence, there is often a need for more data to be generated during the remediation than were generated during the entire RI/FS process at a site, and for those data to require much more sophisticated interpretations.

The Remediation Performance Project is a multi-phase effort, with the funding of subsequent phases dependent on the conclusions and productivity of Phase 1. The Phase 1 efforts are focused on collecting information about the adequacy of monitoring networks and compliance criteria now in use at Superfund sites, and about the manner in which the resulting data are interpreted and presented for decision making. Special emphasis is placed on transport-process data needs in the use of assessment models for decision making.

Phase 2 of the project will focus on development of a methodology by which appropriate monitoring well network designs and compliance criteria can be selected and used effectively, so that the ongoing performance of a remediation can be tracked accurately. The potential power of the methodology developed in Phase 2 will be illustrated by applying it to existing Chem-Dyne and United Chrome Products Superfund sites' data. Complete field validation of the methodology will require enhanced characterization of these or other sites to provide the optimal level of transport process data recommended by the methodology, and is reserved for Phase 3 of the project.
Tasks

In order to meet the stated objectives, specific tasks have been outlined for Phase 1 and a brief summary of Phase 2 activities has been prepared. A complete Phase 2 Work Plan will be prepared during Phase 1 (Task 4). The Phase 2 Work Plan will likewise include a brief discussion of Phase 3 activities, and a schedule for developing the Phase 3 Work Plan.

The Phase 1 tasks have been broken down into subtasks and the responsibility of each participant has been indicated for the subtasks. A schedule for Phase 1 activities is provided, which shows the dates for completion of major milestones and reports.

Task 1: Examine Site Characterization and Compliance Datasets

Survey RI/FS and compliance monitoring documents from several sites; visit the sites to ascertain the adequacy of existing information and to document current compliance oversight/performance evaluation activities.

subtask 1.1: survey existing datasets

Use the information acquired from site visits and review of RI/FS and compliance documents to discuss the types and adequacy of chemical and hydrogeologic data typically acquired. Provide examples of the data acquired (both tables and graphs) and characterize their occurrence statistically. Qualify the value of the data in the decision making process, by describing the data collection methods and their inherent limitations.

[KEELY & VALENTER]

subtask 1.2: analyze current data handling

Review RI/FS and compliance documents to determine the uses to which the data are put. In particular, study the completeness of possible interpretations. Discuss the averaging and grouping of data (esp. total VOC's versus individual plots of volatile contaminants) and the effects that this can have on the decision-making process. Identify chronically under-utilized data (e.g., inorganics and metals), and discuss the reasons for their inadequate use.

[KEELY, PALMER, & VALENTER]

subtask 1.3: investigate transport-process data needs for models

Use the information acquired from site visits and review of RI/FS and compliance documents, to discuss the need for additional transport-process parameter data, as related to their use in assessment models. Provide examples illustrated with mathematical model simulations, where [better] definition of TP parameters would reduce uncertainty in health risks, and uncertainties in the performance of remediations. Describe the sophistication level of the models that are needed to make use of the recommended TP parameters; include updated summaries of the availability and support for appropriate models (esp., as available through the International Ground Water Modeling Center).

[KEELY, PALMER, & WITTBRÖDT]
subtask 3.3: assess the value of under-utilized DP methods

Describe, discuss, and demonstrate the use of statistical analyses for data interpretation, such as Analysis of Variance (ANOVA), regression analyses, and correlation analyses. Describe, discuss, and demonstrate the potential use of traditional chemical data presentation methods that are under-utilized; place special emphasis on graphical techniques such as Stiff and Piper diagrams, species distribution diagrams, and phase diagrams.

[KEELY, PALMER & VALENTER]

subtask 3.4: study the potential utility of emerging DP methods

Describe and provide examples of chemical time-series sampling; discuss the value of the results. Describe the principles and limitations of geostatistical methods (e.g., kriging). Examine the potential utility of adapting data presentation methods from other disciplines (e.g., wind roses, cumulative mass curves) to the display and analysis of technical information from hazardous waste sites.

[KEELY]

Task 4: Prepare for Phase 2

Prepare for the field activities and model calibrations to be undertaken in Remediation Performance Phase 2.

subtask 4.1: select Phase 1 tasks to expand

Based on the site visits and document reviews, discuss the addition of other sites to the overall project. Based on the Phase 1 examinations of common, under-utilized, and emerging data presentation methods, select those that will be further investigated for their use in the Remediation Performance Evaluation Methodology.

[KEELY]

subtask 4.2: plan acquisition of additional data at key study sites

Estimate the resources required to use SOS & SOS methods of site characterization for contaminant transport and fate analyses. Identify key collaborators and contributors (e.g., RSKERL, NCGWR, IGWMC, other projects w/EPA), and their roles in future work.

[KEELY]

subtask 4.3: ensure that equipment and software are tested and ready

Test the SUN computer and modeling software that were acquired for simulations. Obtain OSHA/EPA safety training for all field personnel. Obtain and test safety equipment and supplies.

[KEELY, PALMER, WITTBRORD & VALENTER]

subtask 4.4: prepare a Phase 2 work plan

The Phase 2 Work Plan will describe the tasks to be completed with the funds made available, and will demonstrate continuity with Phase 1 and the overall objectives of the Remediation Performance Project.

[KEELY]
NARRATIVE STATEMENT
Revised 9 February 1988

INNOVATIONS IN DELIVERY AND RECOVERY TECHNIQUES FOR IN-SITU REMEDIATIONS
(THE PULSED PUMPING METHOD)

A Proposal for Cooperative Research

submitted to

Hazardous Waste Engineering Research Laboratory
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by

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9 February 1988
OPTIMIZING RECOVERY OF CONTAMINANT RESIDUALS
BY PULSED OPERATION OF HYDRAULICALLY DEPENDENT REMEDIATIONS

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Introduction

Conventional remediations of ground-water contamination typically involve continuous operation of an extraction-injection wellfield. The level of contamination measured at monitoring wells may be dramatically reduced in a moderate period of time, but some contamination usually persists. Both theoretical considerations and field observations indicate that the contaminant load discharged by extraction wells under steady-state operational conditions declines over time and asymptotically approaches a residual level in the latter stages (Figure 1). At that point, large volumes of water are being treated to remove small quantities of contaminants. Depending on the reserve of contaminants within the aquifer, this may cause a remediation to be continued indefinitely, or it may lead to premature cessation of the remediation and closure of the site. The latter is particularly troublesome because an increase in the level of ground-water contamination may follow (Figure 2) if the remediation is discontinued prior to removal of all residual contaminants.

Driving Mechanisms

There are several mechanisms potentially responsible for the persistence of residual contamination and the kind of post-closure effect depicted in Figure 2. In order to generate such effects, the release of contaminant residuals must be slow relative to pumpage-induced water movement through the subsurface. Phenomena that generate this kind of behavior during continuous operation of an extraction-injection wellfield include (i) diffusive mass transport within spatially variable sediments, (ii) hydrodynamic isolation, (iii) sorption-desorption, and (iv) liquid-liquid partitioning.
Figure 1. Effluent concentration pattern for continuous wellhead operations.
Figure 2. Potential ground-water contamination response to cessation of continuous pumpage. The three year window is a typical regulatory criterion for maintenance of minimum remediation concentrations for site closures.
Variations in rates of advection caused by spatial variability of hydraulic conductivity result in rapid clean-up of higher permeability zones by extraction wellfields, but only diffusion-controlled cleansing of low permeability zones (Figure 3). The situation is similar, though reversed, for in-situ remediations that require the injection and delivery of nutrients or reactants to the zone of intended action; access to contaminants in low permeability sediments is diffusively restricted. The orders-of-magnitude greater surface area of the low-permeability sediments allows significantly greater amounts of contaminants to accumulate on them during the pollution event/activity, in contrast to much lower accumulations of contaminants in high permeability sediments. Hence, the majority of contaminant reserves may be available only under diffusion-controlled conditions in many heterogeneous settings.

The operation of any wellfield in a moving aquifer results in the formation of stagnation zones downgradient of extraction wells and upgradient of injection wells. The stagnation zones are hydrodynamically isolated from the remainder of the aquifer, so mass transport within the isolated water will take place only by diffusion. If remedial action wells are located within the bounds of a contaminant plume, such as for the removal of 'hot-spots', the portion of the plume lying within their associated stagnation zones will not be effectively remediated.

For sorbing compounds, the number of pore volumes to be removed depends not only on the sorptive tendencies of the contaminant but also on whether flow rates during remediation are too rapid to allow contaminant levels to build up to equilibrium concentrations locally (Figure 4). If insufficient contact time is allowed, the affected water is advected away from sorbed contaminant residuals prior to reaching equilibrium and is replaced by fresh water from upgradient. This process generates large volumes of mildly contaminated water where small volumes of highly contaminated water would otherwise result.

When non-aqueous phase residuals are trapped in pores by surface tension, diffusive liquid-liquid partitioning controls dissolution into the ground water. Similar to the process with sorbing compounds, flow rates during remediation may not be sufficiently slow to allow aqueous saturation levels of the partitioned contaminant to be reached locally (Figure 5). If insufficient contact time is allowed, the affected water is advected away from the liquid phase contaminant residuals prior to equilibration and is replaced by fresh water from upgradient. Again, this process generates large volumes of mildly contaminated water where small volumes of highly contaminated water would otherwise result.

Pulsed Pumping Remediations

Pulsed operation of hydraulic systems is the cycling of extraction or injection wells on and off in 'active' and 'resting' phases (Figure 6). The resting mode of operation can allow sufficient time for contaminants to diffuse out of low permeability zones and into adjacent high permeability zones, until maximum concentrations are achieved in the higher permeability zones; or, for sorbed contaminants and non-aqueous phase residuals, sufficient time can be allowed for equilibrium-
Figure 3. Diffusive release of contaminants from low permeability sediments to adjacent high permeability sediments.
ADVECTION

ORGANIC CARBON OR MINERAL OXIDE COATING

EQUILIBRIUM CONCENTRATION

CONCENTRATION

TIME

SLOW DESORPTION

INITIAL RAPID DESORPTION

Figure 4. Concentration of ground-water contaminants controlled by de-sorption kinetics
Figure 5. Dependence of ground-water contamination level on partitioning of non-aqueous phase (P) residuals as a function of increasing ground-water velocity.
Figure 6. Effluent concentrations for a pulsed pumping remediation. Residual and maximum contaminant levels decline with each cycle.
concentrations to be reached in local ground water. Subsequent to each rest cycle, the active cycle of pulsed operations removes the minimum volume of contaminated ground water, at the maximum possible concentrations, for the most efficient treatment. By occasionally cycling only select wells, their stagnation zones may be brought into active flowpaths and remediated.

Pulsed operation of remedial action wellfields incurs certain additional costs and concerns that must be compared with its advantages for site-specific applications. During the rest cycle, peripheral gradient control may be needed to ensure adequate hydrodynamic control of the plume. In an ideal situation, peripheral gradient control would be unnecessary. Such might be the case where there are no active wells, major streams, or other significant hydraulic stresses nearby to influence the contaminant plume while the remedial action wellfield is in the resting phase. The plume would migrate only a few feet during the tens to hundreds of hours that the system was at rest, and that movement would be rapidly recovered by the much higher flow velocities back toward the extraction wells during the active phase.

Plume movement during the resting phase when significant hydraulic stresses are nearby, however, may be unacceptable. Irrigation or water-supply pumpage, for example, might cause plume movement on the order of several tens of feet per day. It might then be impossible to recover the lost portion of the plume when the active phase of the pulsed pumping cycle commences. In such cases, peripheral gradient control during the resting phase would be essential. If adequate storage capacity is available, it may be possible to provide gradient control by downgradient re-injection of treated waters.

Regardless of the mechanics of the compensating actions, their capital and operating expenses must be added to those of the primary remedial action wellfield to obtain the complete cost of pulsed pumping. In addition to the obvious costs, ancillary costs must be considered. The fact that transient flowpaths are created means that special considerations attend the establishment of performance evaluation criteria and compliance points for pulsed operations, and there will be cost increases as a result. The benefits of pulsed pumping must also be tabulated and costed to provide a basis on which to compare the overall operation with conventional pump-and-treat remediations (or other remedial action alternative chosen for consideration at a given contamination site).

Oregon Graduate Center is currently undertaking a major study of the pulsed pumping remediation technique with funding from the U.S. Environmental Protection Agency. The authors are seeking input to this study; any reader having suggestions or comments should contact the project participants at the address in the notice that follows the biosketches at the end of this article. The objectives and products of the OGC/EPA project are outlined in the next sections of this article.
Objectives

The overall purpose of the proposed research is to investigate the benefits, costs, and complications of pulsed pumping in delivery and recovery operations associated with conventional (e.g., pump-and-treat) and in-situ remediation of ground-water contamination. It is expected that the results of the proposed research will also be of direct application to other hydrodynamically dependent remedial action technologies, such as conventional pump-and-treat systems. Development of a detailed methodology for design of optimally efficient, cost-effective hydrodynamic delivery and recovery systems is central to the project.

The elements of theories that are necessary for optimal design of delivery and recovery systems are available, but much remains to be done to bring these elements together for practical applications. Fortunately, much of what needs to be accomplished can be done inexpensively by computer simulation studies. Accordingly, we propose to conduct sensitivity analyses on various design and operation scenarios involving in-situ remediations (e.g., examining combinations of extraction wells, injection wells, and treatment and storage units).

The theories used for computer simulations are based on ideal assumptions, such as instantaneous contact of injected reactants with all waters of a certain stratum. Hence, clean-up efficiencies predicted by computer simulations may exceed what is achievable in reality. Laboratory experiments and field data comparisons are proposed, therefore, to provide a minimal basis on which to qualify cost estimates and preliminary design recommendations that are generated by computer simulations. For the same reason, a proposal will be developed and submitted to the co-sponsors for a complete validation of pulsed pumping in a separate field demonstration project; the design elements for such a demonstration project will be developed in this project.

We find it useful to break out four specific objectives for the current project:

Objective #1
To examine factors that influence the operational characteristics of hydrodynamically dependent in-situ remediations. Beyond a thorough literature survey, the proposed research includes examination of design and performance data at existing hydrodynamically dependent remediation sites, an Invited Expert's Project Review Workshop, sensitivity analyses by computer simulation, and laboratory experimentation.

Objective #2
To determine the theoretical and practical potentials for improved delivery and recovery by pulsed pumping. Computer simulation of typical scenarios of hydrodynamically dependent in-situ remediations will be performed to determine optimal design and operation parameter ranges. Theoretical predictions of operating efficiencies will be partially validated by laboratory experiments. Completion of validation efforts by field demonstration(s) will be proposed for funding as a separate project.
Objective #3
To characterize the efficiency of conventional hydrodynamically dependent remediations, relative to pulsed pumping simulations of remediations at select sites. The value that pulsed pumping may have for improvement of conventional remediations will be studied by comparing simulations with field data at two sites where pump-and-treat remediations are in progress. The constraints in pulsed pumping are similar to those of continuous pumping, so realistic comparisons should be possible.

Objective #4
To provide decision support information needed by the co-sponsors to determine the feasibility and desirability of a field demonstration project. In addition to technical reports, a briefing document is to be developed for the co-sponsors that appraises the technical feasibility, costs, and peripheral issues associated with conducting a field demonstration of pulsed pumping.

Research Approach

It is our opinion that the stated objectives can be achieved most effectively by a combination of computer simulations, laboratory experiments, and on-site demonstrations. Simulations alone may provide great insights, but lack the credibility gained by acquiring data in performance tests. Laboratory experiments provide performance test data on controlled scale models of real-world systems, thereby allowing for partial validation of results from computer simulations. Demonstrations at actual sites provide performance data on non-ideal systems, requiring no scale-up factors or extrapolations of results, but are the most costly and difficult to control.

Therefore, we propose a cost-effective combination of computer simulations, laboratory experiments, and preparations for a field demonstration: our emphasis in the first year of the project is on the computer simulations. Design of the laboratory experiments will also occur in the first project year, based on insights drawn from the simulations. The experiments will be performed using small physical aquifer models ( "sand tanks"). Injection and extraction of fluorescein dyes and volatile organic contaminants will be used to study flowlines and mass transfer rates under various conditions in the sand tank models.

Together with the literature review, and telephone and mail surveys of existing hydrodynamically dependent remediations, the first year simulations and laboratory experiment designs will be critiqued by invited experts in a project review workshop during the fourth quarter of the first project year. The Invited Expert's Project Review Workshop will be coordinated with the co-sponsors; the list of invitees, agenda, dates, and location will be jointly developed.

Laboratory experiments will be in full swing during the second project year, and will be completed by the midpoint of the third project year. During the same period, design and operational data will be examined from two conventional pump-and-treat remediations (identified in the telephone and mail surveys) and compared with simulations of pulsed
pumping for those sites. Results from the laboratory experiments and field data comparisons will be evaluated along with ongoing simulation efforts to provide the basis for design of a field demonstration. Final evaluations for a field demonstration will be completed in the third/final project year.

This project does not presently include funds to perform the field demonstration. We believe that a field demonstration is essential, in the long term, to establishing the viability and cost-effectiveness of pulsed pumping. We also believe, however, that a field demonstration is a major enterprise that will require careful preparations and substantial funding (upwards of $500,000 per year). Our understanding is that the cosponsors are not yet poised to commit to such a level of funding in this research area. Rather, they are interested in first sponsoring a limited investigation (this project) to establish the potential of pulsed pumping. The decision to fund a field demonstration project will be predicated, in part, on the outputs of this project. Accordingly, we will prepare a decision-support document and a field demonstration project proposal in the final project year.

Products

The major deliverables of the project are three camera-ready reports that are suitable for publication as EPA/USAF Technology Transfer documents or guidance documents. The most comprehensive of the three, the Project Technical Report, will serve as a complete record of all computer simulations, laboratory experiments, and field surveys conducted during the project; it is likely to be several hundred pages in length, and will be submitted 90 days prior to the end of the project. At appropriate points during the project, completed sections will be submitted to the co-sponsors for comment/feedback.

The second major deliverable is a Design and Operation Manual for pulsed pumping operations. The Manual will be approximately one hundred pages in length and will be written in handbook form; e.g., there will be minimal discussion of theory, but numerous graphs, illustrations, tables, etc. The focus throughout the Manual will be a step-by-step methodology by which one determines the optimum configuration and operation of a hydrodynamically dependent remediation for a real-world situation. Preliminary sections of this document will be reviewed during an Invited Expert's Project Review Workshop in the fourth quarter of the first project year. A complete draft will be submitted for peer-review and administrative review at the end of the second project year. The document will be improved subsequently, per review comments, and the final version will be submitted within 60 days of receipt of the review comments.

The third of the primary deliverables is a briefing document that summarizes the benefits, costs, and complications of pulsed pumping as determined by this project, and lays out the options for a field demonstration project. Tentatively titled "Decision Support Analysis for Field Demonstration of Pulsed Pumping Remediation", this document will be submitted to the cosponsors six months prior to the end of the project.
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Notice: Call for Comments

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GUIDANCE ON
REMEDIAL ACTIONS FOR
CONTAMINATED GROUND WATER
AT SUPERFUND SITES

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Chapter 7
EVALUATING PERFORMANCE AND MODIFYING REMEDIAL ACTIONS

7.1 INTRODUCTION

Even when a detailed hydrogeologic investigation has been performed, the complex behavior of contaminants in ground water, combined with the heterogeneity of hydrogeologic systems, make predicting the effectiveness of remediation difficult. This chapter presents a conceptual discussion of evaluating performance and modifying remedial actions. Administrative requirements associated with changes in a remedial action and elements of a performance evaluation program are identified and discussed.

Performance evaluations of the full-scale remedial action, based on the monitoring data discussed in Section 7.4, are conducted periodically to compare actual performance to expected performance. The frequency of performance evaluations should be determined by site-specific conditions. Conducting performance evaluations and modifying remedial actions is part of a flexible approach to attaining remedial action objectives. Decisions can be verified or modified during remediation to improve a remedy's performance and ensure protection of human health and the environment.

7.2 MODIFYING DECISIONS

Figure 7-1 represents a decrease in contaminant concentration over time for three ground-water remedial actions of varying effectiveness. Line A represents a remedial action that is meeting design expectations, and the desired cleanup levels are predicted to be reached within the anticipated time. Line B represents a remedial action that is predicted to achieve the cleanup levels, but the action will have to be operated longer than anticipated. Line C represents a remedial action that will not achieve the desired cleanup levels for a long time, if ever, without modifying the remedial action. Performance evaluations provide information about whether remedial action objectives can be met using the selected alternative.

Performance evaluations should be conducted 1 to 2 years after startup to fine-tune the process. More extensive performance evaluations should be conducted at least every 5 years. After evaluating whether cleanup levels have been, or will be, achieved in the desired time frame, the following options should be considered:

- Discontinue operation
- Upgrade or replace the remedial action to achieve the original remedial action objectives or modified remedial action objectives
Modify the remedial action objectives and continue remediation, if appropriate

The performance evaluation program may indicate that the remedial action objectives have been met and the remedy is complete. In other cases, operational results (e.g., contaminant mass removal has reached insignificant levels) will demonstrate that it is technically impracticable to achieve cleanup levels in a reasonable time, and a waiver to meeting ARARs may be required. Additional information, onsite conditions, or other factors may indicate that cleanup levels can be adjusted to less stringent levels and still protect human health and the environment.

These options provide the decision-maker with flexibility to respond to new information and changing conditions during the remedial action. Figure 7-2 illustrates this flexible decision process.

7.3 MODIFICATIONS TO RECORDS OF DECISION

Three types of changes can occur in a remedy following ROD signature: minor changes, significant changes, and fundamental changes. Minor changes, such as the decision to move the location of a well or minor cost or time changes, are those technical or engineering changes that do not significantly affect the overall scope, performance, or cost of the alternative and fall within the normal scope of changes occurring during the remedial design/remedial action engineering process. Such changes should simply be documented in the post-decision document file and, optionally, can be mentioned in a remedial design fact sheet, which is often issued as part of the community relations effort.

Significant changes to the remedy in terms of scope, performance, or cost are explained in an Explanation of Significant Differences provided for under CERCLA Section 117(c). This document describes the differences and what prompted them and is announced in a newspaper notice. This is placed in the administrative record for the site, along with the information that prompted the change. Significant changes involve a component of the remedy, such as a change in the volume of contaminated ground water that must be addressed, or a switch from air stripping to carbon adsorption in a ground-water pump and treat remedy, but do not fundamentally alter the hazardous waste management strategy represented by the selected remedy.

Fundamental changes are changes in the overall waste management strategy for the site; they require amendments to the original ROD. A change from active restoration to passive restoration would be considered a fundamental change. Procedures for amending a ROD are the same as for issuing a ROD. They include the following:
7.4 PERFORMANCE MONITORING

This section provides guidelines for using ground-water monitoring data to evaluate performance. It does not provide detailed information on technical aspects of ground-water monitoring, such as well installation techniques or sampling procedures. The TEGD (U.S. EPA, 1986e) is one resource for this information.

The monitoring system should be designed to provide information that can be used to evaluate the effectiveness of the remedial action with respect to the following:

- Horizontal and vertical extent of the plume and contaminant concentration gradients, including a mass balance calculation, if possible
- Rate and direction of contaminant migration
- Changes in contaminant concentrations or distribution over time
- Effects of any modifications to the original remedial action
- Other environmental effects of remedial action, such as saltwater intrusion, land subsidence, and effects on wetlands or other sensitive habitats

7.4.1 Well Locations

Because ground-water contamination problems are site specific, the number and locations of monitoring wells must suit site conditions and the remedial action selected. In general, wells should be located upgradient (to detect contamination from other sources), within the plume (to track
the response of plume movement to the remedial action), and
downgradient (either to verify anticipated responses or to
detect unanticipated plume movement). Also, monitoring
should reflect both horizontal and vertical ground-water
flow. If a containment system is used, wells or other de-
tection devices should also be located where contaminant
releases are most likely to occur.

7.4.2 Sampling Duration and Frequency

A determination that the remedial action is complete
may require a statistical analysis of contaminant levels.
The Office of Policy, Planning, and Evaluation is preparing
guidance for using statistics to assess ground-water moni-
toring data. Also, OSW has prepared guidance for using sta-
tistics to evaluate ground-water monitoring data at RCRA
sites (U.S. EPA, 1987m). This guidance may provide useful
information for Superfund sites as well.

The intervals between sampling events should be short-
est at the beginning of the remedial action. In many cases,
monthly sampling intervals may be reasonable during the first
year. Data collected during the first year may be used to
assess gaps in the data, further characterize the aquifer,
identity locations for additional monitoring, and evaluate
sources of uncertainty, such as sampling, analysis, and site
conditions.

The recommended long-term frequency for sampling depends
in part on the effectiveness of the remedial action as deter-
mined through the ongoing monitoring program. If monitoring
shows a steady, predictable decrease in contaminant concentra-
tions in the aquifer, reducing the sampling frequency may be
reasonable. The determination of long-term sampling fre-
quency may also depend on the rate of plume migration, the
proximity of downgradient receptors, and the variability of
the ground-water data and the degree of confidence needed
for achieving the cleanup level at a specific location.
Quarterly sampling may be reasonable for long-term monitor-
ing at some sites.

Monitoring data provide the basis for determining when
remedial action objectives have been met and when the reme-
dial action is complete. Special analytical services may be
needed in some cases to confirm cleanup levels that are
lower than the standard detection limit. Operation should
continue for a limited time after cleanup levels have been
achieved. In many instances, contaminant levels in the
aquifer increase when pumping is terminated because
contaminants are allowed to re-equilibrate in the ground
water. This phenomenon would be observed if the rate at
which ground water was removed through pumping is greater
than the rate of desorption of contaminants. Monitoring
programs should therefore ensure that ground water is sampled until any residual contaminants could have desorbed from the aquifer material.

7.4.3 Source Control Monitoring

Another goal of performance monitoring is to ensure that any source control action completed at the site effectively prevents further degradation of ground water. To achieve this goal, it may be necessary to monitor the unsaturated zone using techniques such as soil-gas monitoring to detect contaminants before they reach the ground water.
IN-SITU AERATION FOR STRIPPING VOLATILE ORGANIC CONTAMINANTS FROM SHALLOW GROUND WATER SYSTEMS

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ABSTRACT

A permeable barrier system for in situ ground-water treatment has been developed using relationships based on conventional bubble aeration technology. Specifications for aeration requirements and excavation design are developed using the interactive computer program ISAAC. Input parameters include desired removal efficiency, volumetric dimensions for an aeration trench, average linear ground-water flow-rate, average diameter of gravel backfill, porosity of the packing, and maximum bubble size. The database consists of the physical and thermodynamic properties of the solutes for more than 30 halogenated hydrocarbons, aromatic organics, and trihalomethanes.

Decontamination of the aquifer is achievable using moderately sized air compressor systems. Predicted removal rates may vary between 90% and 99% depending on the compounds present. In comparison to traditional air-stripping technology, the benefits of this system include reduced capital cost of equipment, lower installation costs, minimal visibility, less disruption of business in urban areas, and more flexibility for remote application.

INTRODUCTION

Conventional groundwater remedial alternatives most frequently include a combination of contaminant containment, removal of soluble pollutants, surface treatment of the contaminated water and subsequent disposal or reuse, and in situ stabilization of groundwater contaminants. Reviews of the existing technologies for containment, removal, and stabilization are contained in Amdur et al. (1986), Canter and Knox (1986), Guswa et al. (1987), Keely (1984), and Wagner et al. (1987). A permeable barrier system offer the potential for in situ treatment using microbiological, chemical, and physical methods (Hanson and Shelton, 1988). This paper discusses a conceptual design for an in situ treatment system to remove a wide variety of volatile organic priority pollutants from shallow ground-water aquifers. The projected costs for construction, operation, and maintenance of this system appear to be competitive with conventional treatment systems.

SYSTEM CONFIGURATION AND CONCEPTUAL MODEL

In the configuration of barrier system consists of three components: an aeration trench, an air distribution system, and a vapor extraction and recovery manifold. Construction materials include PVC piping, slotted pipe for air distribution, and gravel for backfill. The air is supplied by one or more air compressors. Other features that...
support the design include a vacuum pump/GAC system for recovery of waste gases, ground-water monitoring wells, fencing, and shelters.

The major feature of the design is an aeration trench that is constructed perpendicular to ground-water flow directions along the leading edge of the contaminant plume. Air distribution piping is placed at the bottom of the excavation, plumbed to the air compressors, and covered by backfill consisting of gravel or cobbles. A vapor extraction manifold system for recovery of stripped gases is incorporated into the upper zones of the unsaturated backfill. The trench surface can be repaved or covered with an iron grill at existing grade. All piping for the aeration and vapor extraction system are located below grade and lead to a small building which houses the air compressors, vacuum pumps, and GAC adsorption units. Figure 1 is a schematic showing the major features of the system.

As groundwater flows through the aerated trench, volatile organic compounds are stripped from the water. The efficiency of removal is controlled by detention time, airflow rate, concentration gradients, temperature, the physical properties of the ground water and physical and thermodynamic properties of the individual contaminants. Waste gases stripped from the ground water are collected by the vapor extraction manifold and are adsorbed on GAC in containment vessels which are connected in series.

\[
C_{LE}/C_{Li} = \left(1 + \exp(-K_L a V_L/H Q_L)\right)^{-1},
\]

where

- \( H \) = dimensionless Henry's Law constant
- \( K_L \) = mass transfer coefficient (cm^2/s)
- \( Q_L \) = volumetric gas flow rate (m^3/hr)
- \( Q_V \) = volumetric liquid flow rate (m^3/hr)
- \( V_L \) = volume of liquid in trench system (m^3).

The mass transfer coefficient can be estimated from the equations presented in Akita and Yoshida (1974):

\[
K_L = 0.5 \frac{g}{\rho_L} D_a 1/2 \rho_L 3/8 \sigma -3/8 \ \text{db}
\]

\[
a = 6 \ \frac{\epsilon}{\rho_L}, \ \text{and} \ \epsilon/(1-\epsilon)^4 = 0.0268 \ \nu \ -1/6 \ \rho \ / \ \rho_L \ -1/8.
\]

where

- \( K_L \) = mass transfer coefficient (cm^2/s)
- \( g \) = gravitational constant (cm/s^2)
- \( D_a \) = bulk diffusivity of the gas in water (cm^2/s)
- \( \rho_L \) = fluid density (g/cm^3)
- \( \sigma \) = surface tension of the solution (g/cm)
- \( \epsilon \) = bubble diameter (cm)
- \( \rho \) = interfacial bubble surface area (cm^2)
- \( \nu \) = kinematic viscosity (cm^2/s), and
- \( U_G \) = superficial gas velocity (cm/s).

The bulk diffusivity of each solute is calculated from empirical equations reported by Othmer and Thakar, the values of molal volume used in the Othmer and Thakar equations are estimated using Benson's method (Reid et al., 1977).

\[
D_a = (140 X 10^{-5}) \rho_w^{-1.1} \nu M^{-0.6}
\]
\[ \frac{V_c}{V_M} = 0.422 P_c + 1.981 \]

where

- \( \mu_w \) = absolute viscosity of water (centipoise),
- \( V_M \) = molal volume of the solute (cm\(^3\)/g-mole),
- \( V_c \) = critical volume of the solute (cm\(^3\)/g-mole),
- \( P_c \) = critical pressure of the solute (atm).

**DESIGN ANALYSIS**

Solutions to the design equations are calculated by the computer program ISAAC (In Situ Aeration Analytical Code). ISAAC's database is a compilation of physical and thermodynamic properties for more than 30 volatile organic compounds commonly associated with ground-water contamination. The thermodynamic database includes values to compute design requirements for operational temperatures of 10\(^\circ\) and 15\(^\circ\) Celsius. The organic compounds include petroleum derivatives (for example, benzene, toluene, ethylbenzene); industrial solvents (for example, chlorinated hydrocarbons, carbon tetrachloride, decalin); and trihalomethane compounds (for example, chloroform). Twenty-two compounds in the database are EPA priority pollutants.

The program is menu driven. Input parameters are desired removal efficiency, volumetric dimensions of the trench, average linear ground-water flow velocity, average diameter of backfill materials, porosity of the packing material, and maximum anticipated bubble size. ISAAC calculates aeration requirements, generates a data report listing final design specifications, and estimates costs for construction. Data output is easily transferred to commercially available software for report presentation.

**PERFORMANCE LIMITATIONS**

The application of the system is limited by hydrogeologic considerations, the physical properties of the contaminants present in the groundwater, and the plume configuration. For maximum treatment efficiency, the bottom of the aeration trench must intercept the base of the contaminant plume. In some cases, the applicability of ISAAC may be limited by the excavation capabilities of the trenching equipment. In most applications, the average linear ground-water flow rate should not exceed 10\(^{-3}\) centimeters per second (3 feet per day).

The effectiveness of stripping for individual contaminants is governed by the Henry's Law Constant, mass transfer coefficient, detention time, and air to water ratio. The relationship between these variables can be graphically represented by a plot of mass transfer rate versus hydraulic dilution rate. The degree of stripping as calculated by ISAAC for six volatile organics with varying thermodynamic characteristics is depicted in Figure 2. The volumetric airflow necessary...
to achieve a desired level of contaminant removal can be determined from the plot presented in figure 3. The properties of the six compounds used in developing the figures are summarized in Table I.

Mixtures of different contaminants do not inhibit or reduce the efficiency of the treatment system. The system is sized to achieve a desired effluent quality for the least strippable compound present in the ground water. The most effective removal rates will be exhibited for soluble compounds with large Henry’s Law constants, high vapor pressures, and low solubility.

COST COMPARISONS WITH AIR-STRIPPING TREATMENT TECHNOLOGY

Physical treatment systems incorporating carbon adsorption or air-stripping are most commonly utilized in cases involving gasoline contamination. Of the two, air-stripping usually proves to be the more cost-effective especially in situations where the water contains high concentrations of organics.

The cost of an in situ aeration system to clean a hypothetical aquifer of the six test volatile organics to 99% of influent concentration is approximately $65,000. These projected costs are based on a 1400 m² trench, an airflow of 85 m³ per minute (3050 cfm), an air-to-water ratio of 1500, and a trench detention time of 3 minutes. This estimate includes excavation, dewatering, piping, backfilling, and repaving. Other capital expenditures for two air compressors, vacuum pumps, and protective buildings and fencing are also included. The unit costs are largely based on estimates reported by EPA (1985).

A packed tower air stripper could cost in excess of $100,000 to purchase and assemble the tower, blowers, recharge pumps, and flow controls (EPA, 1985). In a typical air stripping treatment system, the costs of drilling, installing, and operating collection wells would be an additional expense that has not been calculated. In contrast to the aeration barrier, the packed tower air stripper is capable of treating a much larger volume of water.

CONCLUSIONS

Aeration barriers possess several major attributes which make them attractive alternatives for ground water decontamination.

- The design can be applied to cleanup of a wide variety of contaminants and hydrogeologic conditions.
- Large volumes of treated water do not have to be reinjected or disposed.
- Wastes produced by the stripping processes are easily collected and managed.
- The operation of the aeration barrier causes minimal impact on the system surrounding environment.
- The system can be easily constructed and installed by local subcontractors at a cost that is competitive with conventional treatment systems.

Limitations of in situ aeration barriers include the need to fully intercept the full vertical profile of contaminant plumes, the requirement for low rates of hydraulic loading, and reduced accessibility for maintenance. In spite of these limitations, in situ aeration technology promises to be an innovative and cost-effective alternative to aquifer cleanup.

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by
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Appendix J

In Situ Vacuum Extraction and Air Stripping of Volatile Organic Compounds

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Process Description

Hannover Umwelttechnik (HUT) has developed an inexpensive and relatively effective in situ treatment technology for vacuum extraction of volatile organic compounds from soil vadose zones and groundwater. A diagram of a typical HUT installation is shown in Figure J-1.

The equipment used by HUT is fairly simple and commonly available. PVC slotted piping, 2 inches in diameter with 0.5 mm wide slots, is placed into the ground where the contamination is the highest as an extraction well. A small pump, attached to the top of the pipe via flexible plastic tubing, draws the volatile contamination along with soil moisture through a condensation drum for water removal. The air stream is then passed through an activated carbon canister to remove the volatile organic compounds. One extraction well under ideal conditions will affect an area up to 100 m (90 yds) in diameter. As many pipes and pumps may be used as are necessary for the contamination at a given site.

When the ground water is contaminated, cleanup by air stripping is practiced in coordination with the vacuum extraction. Compressed air is pulsed into the aquifer through injection wells. The compressed air strips the contaminants in the ground water and they are then drawn to the extraction wells. A diagram of this technique is shown in Figure J-2. The compressed air is introduced in a pulsed manner, not continuously, to prevent channeling or short circuiting.

Process Limitations/Performance Data

The HUT vacuum extraction technology is most effective on sandy soils, typically reaching background levels of 200 ppb hydrocarbons in the soil gas. Where there is a large clay fraction, the slotted pipes may become clogged or filled with silt. To try to avoid these problems, HUT has devised a double pipe extraction well. A second, larger slotted pipe (3 inches in diameter, 1 mm slot width) is placed concentric to the typical 2-inch extraction well, with gravel pack in between, to act as filters to the silt and clay particles. This extraction well configuration has shown some success in the field.

The vacuum extraction and air stripping technologies are only effective on volatile contaminants. Contaminants not treated by this method include, for example, extractable organics and PCBs. Figure J-3 shows the range and effectiveness of one extraction well after 2 months of operation. Figure J-4 shows the effects of vacuum extraction on hydrocarbon concentration followed by extraction with in situ air stripping of the ground water.

Cost

In carrying out a remediation project, HUT sells their equipment to the customer. After the treatment is completed, HUT may buy back the equipment at a depreciated price. Typical treatment costs by this method are < 10 DM/tonne (< $5 ton). The initial investigations for a typical installation cost about 2,500 DM ($1,500). The cost of a pumping installation is typically 2,500 DM ($1,500) also, bringing the total price of a treatment to 5,000 DM ($3,000). If the scale of the project is large, an automatic activated carbon filter and regenerator made by Prouter may be leased for 7,000 DM/month (about $4,000/month).

Process Status

A large insurance company developed HUT as a service arm to remediate dumped spills and storage tank leak problems at their clients' sites. The vacuum extraction equipment developed by HUT differs from
that found in the United States market by virtue of its simplicity and lower cost.

The key advantage to a vacuum extraction system is that it achieves cleanup of soils with minimal waste byproducts and is adaptable to contamination beneath buildings. When used in combination with on-site carbon regeneration, the by-product generation is minimized to an even greater extent.

HUT has had over 300 vacuum extraction installations throughout Germany. Two research projects recently being carried out by HUT are an ozone-enhanced biological treatment study and the in situ use of a non-toxic surfactant to leach oils from the soil. HUT does not yet have serious intentions for licensing their technology abroad and they hold no patents. If they did become interested in transferring their technology to the United States' markets, they would probably start a U.S. affiliate and have the necessary equipment produced in the U.S.
Figure J-2. Volatilization of organics in ground water by pulsing with compressed air.

Figure J-3. Performance and range of an HUT vacuum extraction installation.

![Graph showing performance and range of HUT vacuum extraction installation.]


Figure J-4. Soil gas hydrocarbon concentration over time with HUT in situ vacuum extraction and air stripping.

![Diagram showing soil gas hydrocarbon concentration over time with HUT in situ vacuum extraction and air stripping.]

IN SITU AERATION OF GROUNDWATER
A TECHNOLOGY OVERVIEW

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ABSTRACT

Remediation of chemicals in the saturated zone has historically been achieved by extracting groundwater and treating it ex situ. However, in many cases this method has been found to require a very long period of time and to have limited effectiveness. As an alternative, in situ groundwater aeration has been developed for permeable, water table aquifers containing relatively insoluble volatile organic compounds (VOCs). Air is injected directly into the saturated zone. It moves outward and upward by displacing water in the pore space and creating air pathways to the unsaturated zone. As it moves through the saturated zone, VOCs partition to the vapor phase which transports them to the unsaturated zone. A soil venting system in the unsaturated zone captures the evolving vapors containing the VOCs resulting in the VOCs coming out in the exhaust air which is treated, as necessary, and discharged. In appropriate situations, in situ groundwater aeration can be a very effective remedial process for VOCs.
the air moves through the saturated zone, volatile organic compounds (VOCs) will partition into the vapor phase from the water or saturated soil. The VOCs travel with the air upward to the unsaturated zone where they are captured by a soil venting system operating to remove the air.

Figure 1 is a schematic diagram of the overall process of *in situ* groundwater aeration. As depicted, compressed air is injected through a screen located beneath the water table. The air moves out and up through the saturated zone by various irregular pathways to the unsaturated zone. The air is then pulled into a soil venting system which is powered by a blower. The exhaust air from the blower is discharged directly or after treatment depending on the specific regulatory situation.

Figure 2 is a schematic diagram of the microsituation illustrating the movement of compressed air through pore spaces. As the compressed air moves through the screen into the saturated zone it displaces water in the pore spaces and moves in irregular pathways to the surface of the water table. It is important to note that the phenomenon is not analogous to a porous diffuser stone in a tank of water where bubbles form and move upward through the water. There is no standing water for bubbles to form in, since the water is contained in a porous media rather than an open tank. If anything, the phenomenon is more analogous to the situation within the porous diffuser stone submerged in the water.

The lateral movement of the air outward is normally favored because the horizontal permeability is typically higher than the vertical permeability. Hence, the pathway of the air can have a significant horizontal component.
Figure 3 is a typical layout of an *in situ* groundwater aeration system and the accompanying soil venting system. The soil venting system consists of a screened system connected to the blower by a vertical riser at the center. The dashed lines show the zone of influence of the soil venting system. Within this boundary, air is being captured by the soil venting system. In this illustration, six aeration points are located within the boundary of the soil venting system. The circles around each aeration point show the radius of effect of each point. The approach to design is to keep the radius of effect of the aeration points within the boundary of the soil venting system's zone of influence.

In operation of the system, the amount of air injected is controlled to be less than the amount of air withdrawn by the soil venting system. This is necessary to assure capture of the injected air and of the stripped VOCs. Proper balance of injected air with the removal capacity of the soil venting system is especially important for systems beneath buildings or in shallow groundwater. Inadequate removal of injected air can cause upward pressure on floors or an elevation of the water table. If these were to occur, buildings may be structurally damaged or groundwater may surface.

The performance of the air injection system can be monitored through the exhaust air VOC concentration. Figure 4 shows the typical variation of exhaust VOC concentration measured at the discharge side of the blower as a function of time. At start-up (time equals zero) of the soil venting system, the exhaust air VOC is at its initial concentration. As soil venting proceeds, the VOC concentration decreases usually very steeply at first as the saturated soil gas is removed. The solid line in Figure 4 depicts the exhaust VOC variation due to soil venting alone. The rate of decrease in concentration lessens as time progresses typically approaching some lower plateau.
it very rapidly. The irregular flow causes a wavefront among the free product, soil particles, water, and air which releases the small trapped pockets. If there is also a steep gradient and high velocities of groundwater flow, the mobilized material can move downgradient faster than it is air stripped. In this situation, downgradient wells can increase in VOC concentration, which is desirable because it means that VOCs have mobilized to a greater degree than before.

However, to design for this situation, sufficient site characterization must be performed in advance to determine the rate of groundwater movement and whether substantial amounts of free product are present in the saturated zone. Groundwater gradients and permeability estimates are required to estimate velocities. The presence of monitor wells with free product or VOCs concentrations near their solubilities indicates the potential presence of free product within the saturated zone.

Where rapid velocities and free product in the saturated zone occur together, then in situ groundwater aeration should be combined with downgradient groundwater extraction and treatment if it appears that excessive free product movement will occur. This should assure that mobilized VOCs are captured.

CASE HISTORIES

Since 1985, in situ groundwater aeration as described here has been used on over thirty sites in Europe and at least two in North America to remove VOCs from groundwater. In this section, three of these case histories will be reviewed in detail.

Case History No. 1. In the example described here, soil gas measurements inside a building revealed concentrations of more than 500 ppm for both trichloroethylene (TCE) and tetrachloroethylene (PCE). Peak
13.8

10 ft. of strongly sandy gravels, which constituted the aquifer. Underneath the aquifer followed a silty to slightly sandy clay. Initial analyses of groundwater samples showed TCE concentrations of 20,000 µg/L in Well B1 and 6,900 µg/L in Well B2.

From April 1985 to January 1986, pumping was carried out at Well B1. From April 1985 through January 1986, TCE concentrations decreased approximately an order-of-magnitude in B1 and B2 (i.e., 15,000 µg/L to 1,200 µg/L in B1 and 2,400 µg/L to 230 µg/L in B2). The clean-up goal was to attain 25 µg/L or less at B2. Since groundwater extraction and treatment was leading to a gradual decrease, it was decided to speed up remediation with in situ groundwater aeration. Five air injection points were installed within a 30 ft. radius of a soil venting point located at the source area. Air injection began in January 1986. Within 5 days, the TCE concentration in B1 decreased by a factor of ten from 12,000 µg/L to 120 µg/L. Within two months, the concentration decreased to 23 µg/L. Downgradient B2 responded similarly, decreasing from 200 µg/L to less than 10 µg/L.

**Case History No. 3.** Groundwater contamination was discovered on the site of a chemical manufacturer. Initial analyses revealed concentrations of more than 5,000 µg/L of solvents in the groundwater. Following the discovery, several wells were established up- and downgradient of the contamination sources which had been previously defined by soil gas investigations.

The geology of the site was characterized by uniform sandy gravels down to a depth of approximately 36 ft. The sandy gravels were underlain by marly clays, which form the base of the aquifer. The water table was at a depth of 8 ft. Soil venting was chosen as the process to clean-up the vadose zone, starting in June 1986. For the remediation of the contaminated groundwater eight air injection points were installed at the base of the aquifer.
FIGURE 1. Schematic Diagram Of The Profile Of An In Situ Groundwater Aeration System
FIGURE 3. Plan View Of Typical In Situ Groundwater Aeration System

Radius Of Effect Of Air Injection

Air Injection

Soil Venting Screen

Zone Of Influence Of Soil Venting

Compressor

Exhaust Air

Blower
AUTHORS

Andrew C. Middleton, Ph.D.: Dr. Middleton holds a Ph.D. in environmental engineering and has over 19 years of experience in the environmental area. Prior to joining ReTeC, he was president of Haniel Environmental Services, Inc., the U.S. branch of a West German company specializing in site remediation. While in this position, his activities included managing soil gas surveys and in situ clean up of VOCs with soil venting and groundwater aeration systems. He has published over 15 articles, made over 25 presentations, and served as an expert witness in the fields of environmental engineering and environmental management.

Dieter H. Hiller, Ph.D.: Dr. Hiller holds a Ph.D. in geophysics from Stuttgart University and has over ten years of experience in geology, hydrogeology, and geophysics in the area of site remediation. He is currently Director of International Projects for Harress Pickel Consult. Prior to this, Dr. Hiller was President of Harress' U.S. operations for two years. During this time he directed soil gas surveys and the design and installation of soil venting and groundwater aeration systems on U.S. projects, including two Superfund sites. Prior to this position, he was in charge of Harress' remediation projects in Bavaria. He is one of the leading experts in the world in remediation of sites contaminated with volatile organic compounds.