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EPA

SITE Technology Capsule

NoVOCs™ Evaluation at NAS North Island

Abstract

The MACTEC, Inc. (MACTEC), NoVOCs™ in-well volatile organic compound (VOC) stripping process is an *in situ* groundwater remediation technology designed for cleaning up groundwater contaminated with VOCs. In this process, air injected into a specially designed well simultaneously lifts groundwater, strips VOCs from the groundwater, and allows the groundwater to reinfiltrate into the aquifer.

The NoVOCs™ technology was evaluated under the Superfund Innovative Technology Evaluation (SITE) Program at Installation Restoration Site 9 of Naval Air Station (NAS) North Island in San Diego, CA to assess the technology's ability to treat groundwater contaminated with high levels of chlorinated and aromatic hydrocarbons. This project was performed in conjunction with EPA's Technology Innovation Office, Naval Facilities Engineering Command Southwest Division (SWDIV), Navy Environmental Leadership Program , and Clean Sites, Inc. This site was particularly challenging because the groundwater contained total dissolved solids (TDS) ranging from 18,000-41,000 milligrams per liter (mg/L), considerably higher concentrations of TDS than typical drinking water aquifers.

Operational difficulties associated with biofouling and precipitation of iron and other compounds on the NoVOCs™ well during the evaluation resulted in an incomplete evaluation of the performance and cost characteristics of the NoVOCs™ technology. The system was limited to four main operating periods and operated about 71% of the time, excluding system startup and shakedown. During system operation, valuable information was collected regarding (1) the operation and maintenance of the NoVOCs™ technology, and (2) site-specific factors that may influence the performance and cost of the system. This information may be useful to decision-makers when carrying out specific remedial actions using this technology or conducting further performance evaluations of the NoVOCs™ technology. Data from the SITE evaluation may require extrapolation to estimate the operating ranges in which the technology will perform satisfactorily. Since the evaluation was stopped as a result of operational difficulties, only limited conclusions can be drawn from the field evaluation of the NoVOCs™ technology.

VOC results for groundwater samples collected from the influent and effluent of the NoVOCs™ system indicated that 1,1-dichloroethene (1,1-DCE), cis-1,2-dichloroethene (cis-1,2-DCE), and trichloroethene (TCE) concentrations were reduced by greater than 98, 95, and 93%, respectively. The mean concentrations of 1,1-DCE, cis-1,2,-DCE, and TCE in the untreated water were approximately 3,530, 45,000, and 1,650 micrograms per liter (µg/L), respectively, and the mean concentrations of 1,1-DCE, cis-1,2-DCE, and TCE in the treated water discharged from the NoVOCs™ system were 27, 1,400, and 32 µg/L, respectively. The average total VOC mass removed by the NoVOCs™ system ranged from 0.01 to 0.14 pound per hour and averaged 0.10 pound per hour. Accounting for the intermittent operation of the NoVOCs™ system, the mass of total VOCs removed during the entire operation period from 4/20-6/19/98 was estimated to be approximately 92.5 pounds.

Because of the intermittent operation of the NoVOCs™ system, a direct evaluation of the radial extent of the NoVOCs™ treatment cell was not conducted. However, results from the dipole flow test show that measurable pressure changes occur at crossgradient locations 30 feet from the NoVOCs™ well and may be observed at farther

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distances. The resulting changes in pressure head provide an indication of the potential for flow in the surrounding aquifer and are used to provide an estimate of the radial extent of influence created by the NoVOCs™ well. However, the pressure head changes do not accurately represent flow patterns or contaminant transport, so no firm conclusions can be drawn about the radial extent of the NoVOCs™ treatment cell.

The NoVOCs™ technology was evaluated based on the nine criteria used for decision-making in the Superfund feasibility study process. Results of the evaluation are summarized in Table 1.

Introduction

The EPA SITE Program was established in 1986 to accelerate the development, evaluation, and use of innovative technologies that offer permanent cleanup alternatives for hazardous waste sites. One component of the SITE Program is the Demonstration Program, under which engineering, performance, and cost data are developed for innovative treatment technologies. Data developed under the SITE Demonstration Program enable potential users to evaluate each technology's applicability to specific waste sites. EPA SITE Technology Capsules summarize the latest information available on selected innovative treatment and site remediation technologies and related issues.

This Technology Capsule summarizes the findings of an evaluation of the MACTEC NoVOCs™ in-well VOC stripping system and provides information regarding lessons learned and recommendations for future evaluations of the technology. The NoVOCs™ system was evaluated under the EPA SITE Program at Installation Restoration Site 9 at NAS North Island in San Diego, CA over an 11-month period from 2/98-1/99. The NoVOCs™ system was designed to operate continuously; during the evaluation, however, the system experienced significant operational difficulties and was limited to four main operating periods. The evaluation focused on the ability of the NoVOCs™ system to treat groundwater contaminated with VOCs, specifically, chlorinated and aromatic hydrocarbons.

The evaluation was conducted in partnership with SWDIV, the Navy Environmental Leadership Program, the EPA Technology Innovation Office, and Clean Sites, Inc. MACTEC designed and provided technical support during installation and operation of the NoVOCs™ system, and the system was operated and monitored by SWDIV's support contractor, Bechtel National, Inc. (Bechtel).

This Technology Capsule presents the following information about the NoVOCs™ technology and the SITE Program evaluation:

- Technology Description
- Technology Applicability
- Technology Limitations
- Process Residuals
- Site Requirements
- Performance Data
- Summary of Results
- Economic Analysis
- Lessons Learned and Recommendations For Future Studies
- Technology Status
- SITE Program
- Sources of Additional Information
- References

Technology Description

MACTEC's NoVOCs™ system is a patented in-well stripping process for *in situ* removal of VOCs from groundwater. In this process, air injected into a specially designed well simultaneously lifts groundwater, strips VOCs from the groundwater, and allows the groundwater to reinfiltrate into the aquifer.

A schematic of the NoVOCs™ treatment process is shown in Figure 1. The NoVOCs™ well installed at NAS North Island consisted of a well casing installed into the contaminated saturated zone, with two screened intervals below the water table, and an air injection line extending into the groundwater within the well. Contaminated groundwater enters the well through the lower screen and is pumped upward within the well by pressurized air supplied through the air injection line, creating an air-lift pump effect. As the water is air-lifted within the well, dissolved VOCs in the water volatilize into the air space at the air-water interface. The treated water rises to a deflector plate and is forced out the upper screen to recharge the aquifer. The stripped VOC vapors are removed by a vacuum applied to the upper well casing. At NAS North Island, the stripped vapors were treated by the Thermatrix flameless oxidation process. Other offgas treatment systems can be used with the NoVOCs™ technology, and the Thermatrix system is not an integral part of the NoVOCs™ treatment system. The equipment used to operate the NoVOCs™ system, including blowers, a control panel, and air temperature, pressure, and flow rate gauges, is housed in an on-site control trailer.

The NoVOCs™ well configuration installed at NAS North Island incorporated recharge screens in the saturated zone; the recharge screens of most NoVOCs™ wells is located in the vadose zone. This modification is atypical because of concerns that a hydraulic barrier was present between the vadose zone and the intake screen, which could adversely affect the formation of the circulation cell.

Technology Applicability

The NoVOCs™ technology is applicable for the treatment of dissolved-phase VOCs in groundwater. In addition, the chemical and physical dynamics established by the recirculation of treated water make this technology suitable for remediation of contaminant source areas.

The technology is primarily applicable to sandy aquifers with moderate to high hydraulic conductivities and can

Table 1. Evaluation Criteria for the NoVOCs™ Technology

Evaluation Criteria	Performance
Overall Protection of Human Health and the Environment	The technology eliminates contaminants in the groundwater with minimal exposure to on-site workers and the community. Air emissions are reduced by using an offgas treatment system.
Compliance with Federal ARARS	Requires compliance with RCRA hazardous waste treatment, storage, and land disposal reguilations. Emission controls may be needed to ensure compliance with air quality standards.
Long-term Effectiveness and Permanence	Contaminants are permanently removed from the groundwater. Treatment residuals require proper off-site treatment and disposal.
Reduction of Toxicity, Mobility, or Volume through Treatment	Contaminant mobility is initially increased, which facilitates the long-term remediation of the groundwater within the system's treatment cell. The movement of contaminants toward the NoVOCs™ system prevents further migration of those contaminants and ultimately reduces the volume of contaminated media.
Short-term Effectiveness	During site preparation and installation of the treatment system, no adverse impacts to the community, workers, or the environment are anticipated. Short-term risks to workers, the community, and the environment are presented by increased mobility of contaminants during the initial start-up phase of the system and from the system's air stream. Adverse impacts from the air stream are mitigated by passing the emissions through an offgas treatment system before discharge to the ambient air. The time for treatment using the NoVOCs™ system is dependent on site conditions and may require several years.
Implementability	The site must be accessible to large trucks. The entire system requires about 500 square feet of space. Services and supplies may include a drill rig, carbon adsorption regeneration/disposal (or other off-gas treatment system), laboratory analysis, and electrical utilities.
Cost	Capital costs for installation are estimated at $190,000 and operation and maintenance costs for the first year are estimated to be $160,000 and $150,000 annually thereafter.
State Acceptance	State acceptance is anticipated because of the NoVOCs™ system uses well-documented and widely-accepted processes for the removal of VOCs from groundwater and for treatment of the process air emissions. State regulatory agencies may require permits to operate the treatment system, for air emissions, and to store contaminated soil cuttings and purge water for greater than 90 days.
Community Acceptance	The small risks presented to the community along with the permanent removal of the contaminants make public acceptance of the technology likely.

Figure 1. NoVOCs™ schematic.

readily be adapted to fit a variety of aquifer geometries. The technology employs readily available equipment and materials, and the material handling requirements and site support requirements are minimal.

The vendor claims that the technology can also be used as a groundwater interdiction system to prevent further migration of a contaminant plume, and can clean up aquifers contaminated with semivolatile organic compounds (SVOC) that are amenable to aerobic biodegradation. According to the vendor, the NoVOCs™ technology is also capable of simultaneous recovery of soil gas from the vadose zone and treatment of contaminated groundwater from the aquifer as a result of the *in situ* vacuum. For soil gas recovery, the upper screened portion of the NoVOCs™ well is completed within the vadose zone. The vendor further claims that the circulation cell established by the NoVOCs™ well can be used to distribute nutrients, catalysts, surfactants, and other compounds to enhance *in situ* remediation processes such as biodegradation.

At NAS North Island, one NoVOCs™ well was installed to remediate VOCs in a portion of the aquifer downgradient from a contaminant source area. The ability of the system to act as an interdiction system or to remove contaminants other than VOCs, in particular chlorinated and aromatic hydrocarbons, was not assessed during this field evaluation. Other vendor claims such as the ability of the NoVOCs™ technology to reduce VOCs from soil gas in the vadose zone and to act as a distribution system for other compounds also were not evaluated.

The NoVOCs™ system can be designed to work in a variety of hydrogeologic conditions. The recharge screen can be placed within the saturated or vadose zone, although placement of the recharge screen in the vadose zone is typical. Recharge into the vadose zone can be enhanced by using an infiltration gallery. The initial design for the NoVOCs™ well at NAS North Island included the extraction of groundwater from the lower portion of the aquifer and injection of treated water into the vadose zone through an infiltration gallery. Because of concerns that a hydraulic barrier may be present between the vadose zone and the intake screen, however, the well was redesigned to include the extraction of groundwater from the lower portion of the aquifer and injection of treated groundwater in the saturated zone, just below the hydraulic barrier.

The unique dual screen construction of a NoVOCs™ well in conjunction with *in situ* air stripping facilitates the stripping of VOCs and reinfiltration of the groundwater. As a result, remediation of the aquifer occurs without extracting groundwater, lowering the groundwater table, or generating wastewater, all of which are typical of traditional groundwater remediation systems. In addition, the vendor claims that the continuous flushing of the saturated zone with recirculated treated water and the increased horizontal and vertical groundwater flow within the saturated zone can facilitate the removal of adsorbed and nonaqueous-phase contaminants.

Technology Limitations

The NoVOCs™ technology has limitations in areas with very shallow groundwater (at or near the ground surface). In such areas, it may be difficult to establish a stripping zone long enough to remove contaminants from the aqueous phase. The technology has further limitations in thin aquifers; the saturated zone must be of sufficient thickness to allow installation of the system. In addition, the thickness of the saturated zone affects the size of the treatment cell; the smaller the aquifer thickness, the smaller the potential diameter of the treatment area. Furthermore, the technology may have difficulty performing at sites with low hydraulic conductivity or with highly variable hydraulic conductivity between the upper and lower screened intervals. Under variable hydraulic conductivity conditions, balancing the flow rate with optimum stripping conditions might prove difficult. This diffculty may be overcome by using an infiltration galley to increase the storage capacity and the infiltration area of the recharge zone.

High concentrations of VOCs typically require more than one pass through the system to achieve remediation goals. The number of passes depends on the initial contaminant concentration, amount of recirculation, and the removal efficiency of the system. Moreover, if recirculation is not well established, treated water containing contaminant concentrations greater than the remediation goal may be dispersed by the system and migrate downgradient. The effectiveness of the NoVOCs™ system's ability to remove contaminants is directly related to the volatility of the contaminants. Contaminants with high volatility and low water solubility are easier to remove than compounds with low volatility and high water solubility.

Based on the results of the SITE evaluation of the NoVOCs™ system at NAS North Island and other recirculating well evaluations, well fouling is a recognized problem that requires an appropriate design, as well as operation and maintenance activities, for successful management. Groundwater injection and extraction wells, including in-well stripping systems and recirculating wells such as the NoVOCs™ system, are subject to fouling from a variety of common causes. The three most common causes of fouling in recirculating wells and groundwater wells in general are (1) formation of chemical precipitates and insoluble mineral species (chemical fouling), (2) biofouling by colonizing microorganisms, and (3) accumulation of silt in the well structure. These issues may be controlled through groundwater pH control to manage formation of chemical precipitates and insoluble mineral species, injection of a suitable biocide, and appropriate design and construction of filter pack and well screens. However, any design that does not provide geochemical controls based on site-specific hydrogeologic and geochemical conditions is likely to experience significant operation and maintenance problems due to fouling.

Some of the geochemical effects may be easier to control in a closed-loop design than in a comparable open-loop design. In a closed-loop design, the stripping air is captured and used in subsequent stripping cycles. Carbon dioxide or an alternative type of gas such as nitrogen can be added to the stripping air to decrease the amount of carbon dioxide removed and the amount of oxygen added to the treated water. By reducing carbon dioxide removal from the groundwater, changes in pH in the treated water can be minimized. Additionally, by reducing the amount of oxygen added to the treated water, anaerobic conditions can be maintained and biological growth can be minimized. Geochemical and biological fouling caused by changes in pH and increased biological growth can also be managed by injecting acid and biocide into the treated water. The use of acid or biocide in recirculating wells may receive varying acceptance from the regulatory community, depending on the site-specific conditions and nearby water uses.

Process Residuals

The NoVOCs™ system generates a vapor offgas waste stream that can be treated by several different standard vapor treatment technologies applicable to VOCs, including activated granular carbon. During the SITE evaluation at NAS North Island, the Thermatrix flameless oxidation system was used to treat contaminants in the vapor waste stream. The Thermatrix system reduced contaminant concentrations in the vapor waste stream by greater than 99.99%. Use of the Thermatrix system resulted in the destruction of contaminants; therefore, no process residuals were generated that required disposal.

Soil cuttings, purge water, and decontamination wastes are generated during installation of the NoVOCs™ well and monitoring wells, and during well development and sampling activities. Disposal options for these wastes depend on local requirements and on the concentrations of contaminants.

Site Requirements

Space to set up the offgas treatment system and electricity are the only site support requirements for the NoVOCs™ system. The electrical power requirements for the NoVOCs™ system depend on several parameters that must be specified in the system design, including air flow rate and the pressure at which the air is injected into the aquifer. The space requirements for the aboveground components of the NoVOCs™ well, including the control trailer, aboveground piping, and offgas treatment system are approximately 500 square feet. A security fence to prevent unauthorized access to the NoVOCs™ well and control trailer is also recommended. Other requirements for installation and routine monitoring of the system include temporary storage of drilling cuttings, purge water, and decontamination wastes.

Performance Data

The NoVOCs™ technology was evaluated to determine its ability to remove VOCs from groundwater. The critical objectives of the evaluation were to (1) evaluate the removal efficiency of the NoVOCs™ well system for VOCs in groundwater, (2) determine the radial extent of the NoVOCs™ treatment cell, and (3) quantify the average monthly total VOC mass removed from groundwater. Because of operational difficulties with the NoVOCs™ system during the evaluation, objectives 2 and 3 could not be evaluated. In these cases, results and conclusions are presented based on the limited data available.

For this evaluation, groundwater samples were collected from the NoVOCs™ influent and effluent using two piezometers installed adjacent to the NoVOCs™ well and from 10 groundwater monitoring wells installed upgradient, crossgradient, and downgradient from the NoVOCs™ well. The groundwater monitoring wells were installed at different depths and radii from the NoVOCs™ well to evaluate changes in contaminant concentrations within the aquifer associated with operation of the NoVOCs™ system. Air samples were collected from four sampling locations to evaluate the concentration of contaminants in the influent and effluent of both the NoVOCs™ and Thermatrix systems. Groundwater and air samples were collected weekly for the first month of operation and monthly thereafter. However, only one monthly sampling event was conducted because of operational problems with the NoVOCs™ system. All samples were analyzed for the targeted VOCs.

Operation and maintenance of the NoVOCs™ system was conducted primarily by Bechtel with technical guidance from MACTEC. The NoVOCs™ system was designed to operate continuously, 24 hours per day, 7 days per week. During the evaluation, however, the system experienced significant operational difficulties and was limited to four main operating periods: System Startup and Shakedown (2/26-3/26/98), Early System Operation (4/20-6/19/98), Reconfiguration Operation (9/24-10/30/98), and Final Configuration Operation (12/4/98-1/4/99). Excluding system startup and shakedown, the system operated about 71% of the time during the remaining three operational periods.

Summary of Results

The site was particularly challenging because the groundwater contained TDS at concentrations ranging from 18,000 to 41,000 mg/L, which are considerably higher than concentrations of TDS in typical drinking water aquifers.

In early May 1998, the NoVOCs™ system began experiencing operating problems associated with high water levels in the NoVOCs™ well and low pumping rates. Evaluation participants initially thought that the flow sensor was not accurately measuring the pumping rate. As system operation progressed, however, the continued low pumping rate and increased frequency of high water levels in the NoVOCs™ well suggested that a more significant problem was occurring. By June 1998, the pumping rate had been reduced from the design rate of 25 gallons per minute (gpm) to approximately 5 gpm. Based on discussions between the Navy and MACTEC, the system was shut down on June 19, 1998 to evaluate the cause of the poor performance. Although iron fouling was confirmed in May 1999, other suspected causes for the poor performance included (1) biofouling or scaling of the screen intervals and formation near the NoVOCs™ well, (2) possible differences in hydraulic characteristics between the upper and lower portions of the aquifer, and (3) design problems with the NoVOCs™ well, in particular the length of the recharge screen.

To evaluate the recharge capacity of the NoVOCs™ system and provide information regarding the hydraulic characteristics of the aquifer in the vicinity of the NoVOCs™ system, a down-well video survey and a series of aquifer hydraulic tests were conducted. Based on the aquifer testing, it was concluded that the length of the screened intervals of the NoVOCs™ well should be able to sustain the design pumping rate of 25 gpm. During the video survey, fouling of the NoVOCs™ well screens by microbiological growth and iron precipitation was observed. This fouling appeared to have impaired the performance of the NoVOCs™ system by obstructing the well screen and filter pack. Microbiological testing of the groundwater confirmed the presence of biofouling organisms. Efforts to control fouling by addition of various acids, dispersants, and biocides met with varying degrees of success (only iron precipitation fouling was successfully controlled). Citric acid was added to sequester the iron but could have also increased biofouling. Failure to completely control the biofouling of the recharge screen eventually caused the termination of the evaluation in January 1999.

Because of operational difficulties with the NoVOCs™ system throughout the demonstration, only limited data were collected to evaluate the technology. The conclusions that may be drawn based on the limited data collected during the SITE evaluation are presented below. A detailed discussion of the evaluation results and conclusions is provided in the NoVOCs™ Technology Evaluation Report (Tetra Tech 2000).

1. Comparison of VOC results for groundwater samples taken adjacent to the influent and effluent of the NoVOCs™ well indicated that 1,1-DCE, cis-1,2-DCE, and TCE concentrations were reduced by greater than 98, 95, and 93%, respectively, in all the events except the first Bechtel sampling event, which was conducted during system shakedown activities. A summary of contaminant removal is presented in Table 2.

   Excluding the first sampling event, the mean concentrations of 1,1-DCE, cis-1,2,-DCE, and TCE in the untreated water were approximately 3,530, 45,000, and 1,650 µg/L, respectively, and the mean concentrations of 1,1-DCE, cis-1,2-DCE, and TCE in the treated water discharged from the NoVOCs™ system were approximately 27, 1,400, and 32 µg/L, respectively. The 95% upper confidence limits of the means for 1,1-DCE, cis-1,2-DCE, and TCE in the treated groundwater were calculated to be approximately 36, 1,740, and 45 µg/L, respectively. The maximum contaminant levels (MCL) for these compounds in groundwater are 6 µg/L for 1,1-DCE, 6 µg/L for cis-1,2-DCE, and 5 µg/L for TCE. MACTEC claims that the NoVOCs™ system can reduce effluent VOC concentrations to below MCLs if the contaminant source has been removed. Since dense nonaqueous-phase liquids may be present in the aquifer at the site and may act as a continuing source of groundwater contamination, MACTEC did not make any claims for reduction of VOC concentrations in groundwater at Site 9.

2. Because of the sporadic operation of the NoVOCs™ system, a direct evaluation of the radial extent of the NoVOCs™ treatment cell was not conducted. In lieu of a direct evaluation method, aquifer hydraulic tests were conducted to assess the hydrogeologic characteristics of the site and to indirectly evaluate the potential radial extent of the NoVOCs™ treatment cell. Although the aquifer pump tests cannot be directly applied to evaluate the radial extent of the NoVOCs™ treatment cell or even that groundwater recirculation was established, the test data do provide information on the radius of influence of the well under pumping (2-dimensional) and dipole (3-dimensional) flow conditions. The resulting changes in pressure head provide an indication of the potential for flow in the surrounding aquifer and are used to provide an estimate of the radial extent of influence created by the NoVOCs™ well. However, the pressure head changes do not accurately represent flow patterns or contaminant transport. Consequently, no firm conclusions can be drawn about the radial extent of the NoVOCs™ treatment cell.

   During the constant discharge rate (discharge = 20 gpm) pumping test, measurable drawdowns (+/- 0.01 feet) were observed at approximately 100 feet from the NoVOCs™ well in all directions and at different depths. This information indicates that the radius of resulting from extraction at 20 gpm could be as large as 100 feet. The dipole flow test data showed that measurable pressure responses occured at crossgradient locations 30 feet from the NoVOCs™ well and may be observed at greater distances. However, no drawdowns or water level rises could be positively measured in monitoring wells beyond the 30-foot distance.

3. Because of operational problems with the NoVOCs™ system, the mass of VOCs removed by the NoVOCs™ system was evaluated during five sampling events within a period of limited operation from April 28 to June 8, 1998. During this period, the average total VOC mass removed by the NoVOCs™ system ranged from 0.01 to 0.14 pound per hour and averaged 0.10 pound per hour. Accounting for the sporadic operation of the NoVOCs™ system, the mass of total VOCs removed during the entire operation period from April 20 through June 19, 1998 was estimated to be approximately 92.5 pounds. A summary of the total VOC mass removed is presented in Table 3.

Economic Analysis

An economic analysis for the NoVOCs™ technology to treat VOC-contaminated groundwater was conducted based on the SITE evaluation and cost information provided by the Navy and MACTEC. One-time capital costs for a NoVOCs™ system were estimated to be $190,000; annual operation and maintenance costs were estimated to be $160,000 per year for the first year and $150,000 per year thereafter. Since the time required to remediate an aquifer is site-specific, costs have been estimated for operation of a NoVOCs™ system over a range of time for comparison purposes. Based on these estimates and an annual inflation rate of 4%, the total cost for operating a single NoVOCs™ system was calculated to be $350,000 for 1 year; $670,000 for 3 years; $1,000,000 for 5 years; and $2,000,000 for 10 years. The cost of treatment per unit volume of water was not calculated because of the number of assumptions required to make such a calculation. Additionally, costs per unit volume of water were not calculated for this project because of the site-specific nature of treatment costs.

Costs for implementing a NoVOCs™ system at another site may vary substantially from this estimate for the SITE evaluation. A number of factors affect the cost of treatment using the NoVOCs™ system, including soil type, contaminant type and concentration, depth to groundwater, site geology and hydrogeology, groundwater geochemistry, site size and accessibility, required support facilities and available utilities, type of offgas treatment unit used, and treatment goals. It is important to (1) characterize the site thoroughly before implementing this technology to ensure that treatment is focused on contaminated areas, and (2) determine the redius of the circulation cell for the well and the resulting number of wells needed to remediate a particular site.

Lessons Learned and Recommendations for Future Studies

The evaluation of innovative technologies, especially *in situ* processes, poses significant technical difficulties even

Table 2. Treatment System Removal Summary

Well	Description	Bechtel 3/4/98	Bechtel 3/19/98	Tetra Tech Week 1 4/28/98	Bechtel 4/29/98	Tetra Tech Week 2 5/6/98	Tetra Tech Week 3 5/12/98	Tetra Tech Week 4 5/21/98*	Tetra Tech Month 1 6/8/98	Bechtel 6/8/98	Mean[2]	95% Confidence Interval
1,1-Dichloroethene (ug/L)												
PZ-02	System Intake	2,700 D	2,800	2,300	4,400 D	2,400	3,100	NA	4,300	5,400	3,425	950
PZ-01	System Recharge	270 D	50	25	30	16	26	NA	9.3	34	58	72
Percent Reduction[1]		90	98	99	99	99	99	NC	99	99	98	NC
Cis-1,2-Dichloroethene (ug/L)												
PZ-02	System Intake	13,000 D	40,000	45,000	52,000 D	39,000	40,000	NA	46,000	53,000 D	41,000	10,000
PZ-01	System Recharge	6,700 D	2,100	1,800	1,500 D	1,200	1,500	NA	580	1,100 D	2,060	1,600
Percent Reduction[1]		48	95	96	97	97	96	NC	99	98	95	NC
Trichloroethene (ug/L)												
PZ-02	System Intake	790 D	1,300	760	1,600 D	1,900	2,000	NA	2,300	1,700	1,540	460
PZ-01	System Recharge	190 D	65	50	25	26	27	NA	9.2	18	51	49
Percent Reduction[1]		76	95	93	98	99	99	NC	99	99	97	NC

Notes:

* Groundwater samples were not collected from PZ-01 and PZ-02 during fourth weekly sampling event.

D Laboratory qualifer identifies compounds in an analysis at a secondardy dilution.

(1) % Reduction = $[[C_{(w-1)} - D_{(w-2)}]/C_{(w-1)}] \times 100$; where $C_{(w-1)}$ = the concentration at PZ-02 and $C_{(w-2)}$ = the concentration at PZ-01.

(2) Arithmetic mean calculated using data from all eight sampling event.

(3) 95% confidence interval determined using a two-tailed Student's t-test.

Table 3. Summary of Total VOC Mass Removed

Effluent Sampling Event (Date	Effluent Total VOC Concentration per Event (ppb v/v)	Effluent Air Flow Rate During Event (scfm)	Effluent Total VOC Mass Removed Over 1-Hour Sampling Event** (lbs/hr)	System Operation (hr)	Total VOC Mass Removed (lbs)
1st Weekly (4/28/98)	15,060	50*	0.0145	261.5	3.8
2nd Weekly (5/6/98)	104,100	68	0.1134	126.75	14.4
3rd Weekly (5/12/98)	125,700	69	0.1391	101.25	14.1
4th Weekly (5/21/98)	136,000	63	0.1372	183.5	25.2
1st Monthly (6/8/98)	93,900	61	0.0914	383	35.0
Average	95,000	64.2	0.0991	NC	NC
Total	NC	NC	NC	1056	92.5

Notes:

* Flow meter not installed at sampling time; measurement obtained from NoVOCs™ trailer.

** Mass calculated using the Ideal Gas Law, assuming standard samle temperature (6°F) and pressure (1 atmosphere)

under ideal site conditions. Since these remediation processes occur in the subsurface and cannot readily be observed or easily measured, the evaluator must rely on a limited number of discrete measurements to provide an indication of changes in the subsurface caused by the technology. This task is further complicated by the typical lack of sufficient site characterization data to provide a thorough and detailed understanding of the hydrogeology and contaminant distribution at a site.

When applying an innovative *in situ* technology such as the NoVOCs™ system to a complex site such as NAS North Island Site 9, a team of experts with applied experience in recirculating well engineering, geology, hydrology, and geochemistry should be used. The NoVOCs™ system did not function without operational difficulties, partly because this site's groundwater, which contained TDS concentrations ranging from 18,000 to 41,000 mg/L, considerably higher concentrations of TDS than typical drinking water aquifers.

The NoVOCs™ system affects the groundwater geochemistry and subsurface environmental conditions through the removal of carbon dioxide from the groundwater, injection of air, and movement of contaminants to the well. In carbonate-rich groundwater, the removal of carbon dioxide affects the buffering capacity of groundwater and may result in increases in pH. These changes can affect chemical equilibria in the subsurface and cause the precipitation or dissolution of inorganic compounds. The oxygenation of the groundwater during air stripping and increased contaminant movement near the well may provide an environment for enhanced microbiological growth. The precipitation of inorganic compounds and increased microbiological growth can adversely affect the performance of the system by decreasing the ability of the well screens, filter pack, and adjacent formation to transmit water. Addressing the potential for these fouling issues and their proper management is critical during project planning and design.

Contaminant transport associated with the NoVOCs™ system is also complicated by the 3-dimensional groundwater flow induced within the aquifer surrounding the well and the lack of detailed site characterization information. When applying an induced flow to the subsurface, migration is typically confined to preferential pathways and is strongly controlled by the heterogeneity and anisotropy of the aquifer. Modeling of the contaminant transport during evaluation planning is recommended to provide an understanding of groundwater flow and to optimize placement of monitoring and measurement ports.

Even given a team of experienced professionals, problems may arise. To help minimize these problems, a summary of recommendations is provided to assist those involved in future evaluation of the NoVOCs™ system and groundwater circulation wells in general. Based on the NoVOCs™ evaluation at NAS North Island, Site 9, recommendations for (1) site specific characterization activities; (2) assessment of fouling potential (chemical precipitation, biological fouling, and siltation); and (3) integration of system controls are provided below.

Site-specific Characterization

A thorough site characterization is required to design a recirculating well system. Some of the characterization requirements are common geological practices, others are more specific to the technology being deployed. The recommended approaches are described below.

Geological Description

Discrete core samples (for example, samples collected every 5 feet) should not be considered until a sufficient number of continuous cores have been evaluated to develop a confident conceptual model of the site stratigraphy. At Site 9, the continuous coring performed specifically for the NoVOCs™ evaluation resulted in not only revision of the NoVOCs™ system conceptual design, but revision of the entire stratigraphic conceptual model of that portion of NAS North Island.

Aquifer Testing

A variety of aquifer testing approaches are applicable to recirculating well system design. These approaches include permeability testing of representative intact cores from the stratigraphic column. Grain size analysis of representative samples can provide some indication of formation permeability, but cannot provide assessment of the formation structure, which plays an important role in water conductivity. Site evaluation should include two aquifer tests at a minimum; one extraction pumping test to evaluate the productivity of the extraction zone and one injection test to evaluate the capacity of the recharge zone. A combined pumping and recharge test, known as a modified "dipole" test, can provide additional information regarding potential system performance. The dipole test can also provide information on site-specific anisotropy. Anisotropy is the ratio of the hydraulic conductivity in the horizontal direction to that in the vertical direction and strongly influences the extent of the groundwater circulation cell and capture zone. During all aquifer tests, pressure head changes should be monitored and recorded in all accessible monitoring locations.

Assessment of Fouling Potential

Site conditions should be evaluated for the three primary sources of fouling discussed below, and the system should be designed and operated to control the impacts of fouling.

Chemical Precipitation

Chemical precipitation may occur for both recirculating wells and extraction wells, and requires planning and careful implementation for successful control. During the design phase, system planners should perform the following tests:

- An aeration/titration test to identify the anticipated pH change with aeration, evaluate the potential for calcite precipitation, and estimate the water's demand for acidification to prevent calcite formation.

- Determination of total and dissolved iron and manganese concentrations in the water to assess the potential for fouling through precipitation of ferric hydroxide after aeration. Also evaluate the redox potential of the aquifer. Grossly polluted and saline aquifers may contain substantial reduced iron and manganese species that may become more soluble as the aquifer becomes more aerobic. The concentration of dissolved iron in the water can also indicate the potential for iron-related bacteria to develop in the system.

- An iron precipitation test can provide an estimate of the magnitude of iron precipitation that may occur in the system. The test can be conducted by determining the iron content of a water sample, then aerating the sample, allowing the ferric hydroxide to precipitate, and measuring the iron concentration in the remaining water again.

- Monitor pH and iron status in the aquifer regularly during system operation.

The results of the tests should be used to incorporate precipitation control features into the system design. For example, a closed-loop system might be chosen over an open-loop system, a stripping gas other than air might be selected, and injection of chemicals might be required. As with the control of biological growth, provisions should be made to inject chemicals to control precipitation into the well inlet filter pack as well as into the treated water being returned to the formation.

Biological Fouling

Biofouling is a demonstrated problem for recirculating and extraction wells. A recommended approach to minimizing biofouling problems is to evaluate the overall aquifer microbial ecology to assess both the fouling potential and potential control alternatives. A minimal evaluation of the microbial ecology of a candidate site includes the identification of the presence of natural and contaminant-related substrates within the aquifer (as measured by biological oxygen demand and chemical oxygen demand). The evaluation also should determine oxidation-reduction potential (aerobic versus anaerobic), temperature and pressure, and the presence of indigenous organisms (determined by culturing aquifer samples). System designers and operators must remain aware of aquifer ecology changes that may occur during system operation.

In the case of the NoVOCs™ technology, which vigorously aerates the groundwater coincidental with removal of dissolved VOCs, aerobic microbial communities can be expected to develop in previously anaerobic locations. Facultative anaerobes that were present as very minor fractions of the overall microbial community may become dominant. Specialized microbes, such as iron-related bacteria may also become established in locations where a constant supply of fresh substrate is available and physical conditions favor colonization (for example, in the well screens). If fouling microbes are present, provisions should be made to inject biocides into the well inlet filter pack as well as into the treated water being returned to the formation.

Siltation

Although siltation was not a problem at NAS North Island, recirculating wells are subject to fouling due to accumulation of aquifer solids, just as are any extraction or recharge well. The grain size and structure of the strata in which well screens will be placed must be thoroughly evaluated to ensure that the appropriate combination of screen and filter pack is designed for the well in each screened interval. After well construction, the screened intervals must be thoroughly and aggressively developed to achieve very low levels of suspended solids (less than 5 nephelometric turbidity units suspended solids). If the recirculating well uses an air lift action, like the NoVOCs™ technology, thorough development is essential. If not properly developed, the air lift action will develop the inlet screen and the resulting solids will be deposited in the recharge zone, effectively plugging the well.

Integration of System Controls

System designers should maximize the use of available electronic control technology. Recent development has produced dramatic increases in the capability and reduced associated costs for sophisticated supervisory, control, and data acquisition systems. The mechanical system, well, and offgas treatment system can be readily integrated with sensors for key parameters, automatic control for off-normal shutdowns, data recording, remote data acquisition, and remote control of the system. All aspects of the recirculating well design should be assessed as a system to identify critical control and monitoring functions, as well as supplemental control functions that will increase system efficiency and reduce downtime and on-site labor.

Technology Status

The concepts of the NoVOCs™ in-well VOC stripping system were initially proposed by researchers at Stanford University in the late 1980s (Gvirtzman and Gorelick 1992) and were further developed under a collaboration between Stanford University, EG&G Environmental, and the U.S. Department of Energy (DOE). An initial patent for the NoVOCs™ system (U.S. Patent No. 5,18,503) was granted to Stanford University; EG&G subsequently obtained an exclusive license to the technology.

In 1996, Stanford University and DOE carried out the first full-scale evaluation of the technology at Edwards Air Force Base, California. During this evaluation, TCE was removed from groundwater. In December 1997, MACTEC acquired the exclusive license to the NoVOCs™ system from EG&G. At the time of MACTEC's acquisition of the technology, there were more than 30 applications of the NoVOCs™ system at both private and government sites. According to the developer, the technology provides a viable alternative to traditional groundwater remediation systems, especially where pump-and-treat type systems have failed or are not removing significant contaminant mass. Like other groundwater remediation technologies, the NoVOCs™ system requires proper geologic and design considerations, and is not applicable to all types of contaminants or geologic settings.

SITE Program

In 1980, the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund. CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986. The SITE Program is a formal program established in response to SARA. The primary purpose of the SITE Program is to maximize the use of alternative technologies in cleaning up hazardous waste sites by encouraging the development and evaluation of new, innovative treatment and monitoring technologies. The NoVOCs™ technology was evaluated under the Demonstration Program. Other documentation resulting from this SITE evaluation include a Technology Evaluation Report that expands on results and conclusions presented in this Technology Capsule.

Sources of Additional Information

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