INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0577

Well Injection Depth Extraction (WIDE) Soil Flushing

Industry Programs

Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

May 2001

Innovative Technology
Summary Report

Well Injection Depth Extraction (WIDE) Soil Flushing

OST/TMS ID 2172

Industry Programs

Demonstrated at
DOE Ohio Field Office
Ashtabula Environmental Management Project (AEMP)
Ashtabula, Ohio

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

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SUMMARY

Technology Summary

Problem:

Contamination in low-permeability, high-clay-fraction soils poses a significant technical challenge to *in situ* remediation efforts. Conventional technologies such as pump and treat groundwater remediation, and vapor extraction using conventional well fields, are typically ineffective when applied to sites with low permeability soils.

Solution:

An innovative subsurface remediation technology, termed Well Injection Depth Extraction (WIDE), has been developed by researchers from North Carolina State University (NCSU). The WIDE system is a hybrid soil flushing/soil gas extraction system that uses Prefabricated Vertical Wells (PVWs) for the *in situ* remediation of contaminated fine-grained soils with hydraulic conductivities ranging from 10^{-3} to 10^{-8} cm/s. The WIDE system has been field demonstrated as suitable for removal of dissolved-phase contaminants, dense non-aqueous phase liquids (DNAPLs), and light non-aqueous phase liquids (LNAPLs). A photograph of the demonstration system at DOE's Ashtabula Environmental Management Project (AEMP) is presented in Figure 1 below.

Figure 1. WIDE™ demonstration system.

How it Works

The WIDE system utilizes PVWs in lieu of conventional wells or sumps to extract groundwater and inject liquid flushing agents. PVWs are constructed of a geosynthetic composite system consisting of an inner core, and an outer filter jacket. A typical PVW measures 4 inches (100mm) in width by 0.15 inches (4mm) in thickness. The PVWs are used for extraction of groundwater and soil gase and injection of flushing liquids. Installed at relatively close spacing (< 3 ft), the PVWs shorten groundwater drainage paths and accelerate the soil flushing process. The PVWs are installed using direct push technology (e.g. hydraulically driven mandrel) at fast rates of 10 ft/s into firm clay soils. After installation, the PVWs are connected at the surface with manifold piping, and a vacuum is applied to extract the groundwater and volatilize contaminants. Appropriate surface treatment trains are utilized to treat extracted groundwater and soil gas.

Potential Markets

- Remediation of low permeability soils (clays/silts) by removal of contaminated groundwater and gases
- Delivery of various flushing/treatment agents (e.g. surfactant, oxidation agents, and biological nutrients)
- Leaking Underground Storage Tank (UST) sites

Advantages over baseline

The WIDE technology has the following advantages over the baseline technology (conventional pump and treat remediation):

- Applicable to soils with low hydraulic conductivities (k: 10^{-3} to 10^{-8} cm/s)
- PVWs can be utilized for soil gas extraction, air injection, liquid extraction, and liquid injection
- Installation of PVWs is rapid and inexpensive with no drilling required
- PVWs can be economically installed at relatively close spacings (< 3 ft), thereby shortening contaminant transport pathways
- Shorten typical pump and treat remediation duration
- Depth specific injection and extraction capability
- Targets the source points of a plume, thereby minimizing the volume of liquids being extracted
- Expedited contaminant recovery with reduced long-term operating costs

Demonstration Summary

The WIDE system was demonstrated at DOE's AEMP, which is located at a former uranium manufacturing site owned by RMI Environmental Services (RMIES). The site's groundwater and soils are contaminated with trichloroethylene (TCE), uranium (U), and technetium-99 (^{99}Tc) as a result of long-term uranium manufacturing operations for the DOE's weapons complex. Subsurface remediation at AEMP is technically challenging due to the site's glacial till soil exhibiting low hydraulic conductivity and having a high clay fraction. The proposed corrective action to address the site's soil and groundwater contamination is ex situ vapor stripping for source control combined with a groundwater interceptor trench with traditional pump and treat for migration control. The overall remediation time frame for this option is estimated between 18 to 87 years.

The field-scale demonstration of the WIDE system measured 70 ft by 70 ft and included a grid of over 480 PVWs installed to a depth of 15 ft. The system utilized a vacuum extraction unit to remove the groundwater and simultaneously volatilize the TCE. An above-ground treatment system was constructed to treat TCE-contaminated groundwater and soil gas. The site's existing wastewater treatment plant (WTP) was utilized to treat the radioactive constituents.

The WIDE system successfully extracted TCE, U, and ^{99}Tc from the subsurface, thereby reducing the concentration of these contaminants in the groundwater. Under extraction only operation, TCE removal was enhanced by volatilizing TCE from the soil. The system was able to exchange one pore volume of groundwater through the sites low permeability soils in 258 hours of operation. Injection of liquids through PVWs with concurrent extraction was found to increase groundwater extraction flowrates and enhance the removal of dissolved contaminants.

The WIDE system is ready for deployment and commercial application.

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All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for Well Injection Depth Extraction (WIDE) Soil Flushing is 2172.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

WIDE was developed for *in situ* remediation of low-permeability and high clay-fraction subsurface soils and groundwater. The goals of the demonstration project were to:

- Design, construct, and operate a full-scale WIDE system in a low permeability, high clay-fraction, glacial till soil.
- Evaluate the capabilities of WIDE to remediate soil and groundwater contaminated with trichloroethylene (TCE), uranium (U), and technetium (^{99}Tc).
- Investigate the WIDE system's capabilities to reduce contaminant concentrations to desired levels

Major elements of the WIDE technology include:

- PVWs
- Groundwater and soil gas vacuum extraction system
- Liquid injection system
- Above-ground treatment system

PVWs

The development of PVWs was based on the existing technology of prefabricated vertical drains (PVD), or known more commonly as wick or strip drains. The prefabricated vertical drain is a geotechnical engineering technology that has been routinely used since the mid-50's for soil (silt and clay) improvement and dewatering of mine tailings.

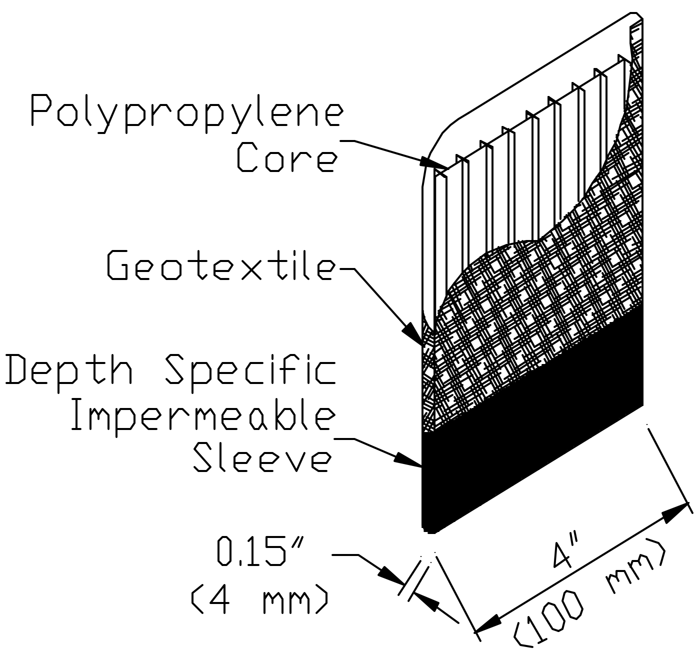

Figure 2. PVW cross-section.

The PVW is manufactured as a composite system of an inner core, an outer permeable filter jacket, and at specified positions, an impermeable barrier sleeve. This geosynthetic composite is illustrated in Figure 2. The PVW typically measures 4 inches (100 mm) wide by 0.15 inches (4 mm) thick. The core is constructed of extruded polypropylene and the filter jacket is a durable, non-woven polypropylene geotextile. The impermeable sleeving is a reinforced high-density polyethylene, and is a unique distinction of the PVW. This design feature enables depth specific extraction and injection capability.

The WIDE system utilizes PVWs as the conduit for vacuum extraction of the contaminated liquids and gasses, concurrent with pressurized injection of a flushing solution. The PVWs shorten the groundwater drainage path, promoting subsurface liquid/gas movement and thus expediting the soil flushing process (illustrated in Figure 3).

The WIDE system offers advantages over conventional well galleries and deep excavation cut-off trenches. The PVWs are designed for depth-specific extraction of contaminated plumes with or without concurrent liquid injection. The WIDE technology has been designed to target the areal and depth source points of a plume, thereby controlling and minimizing the volumes of liquids being extracted.

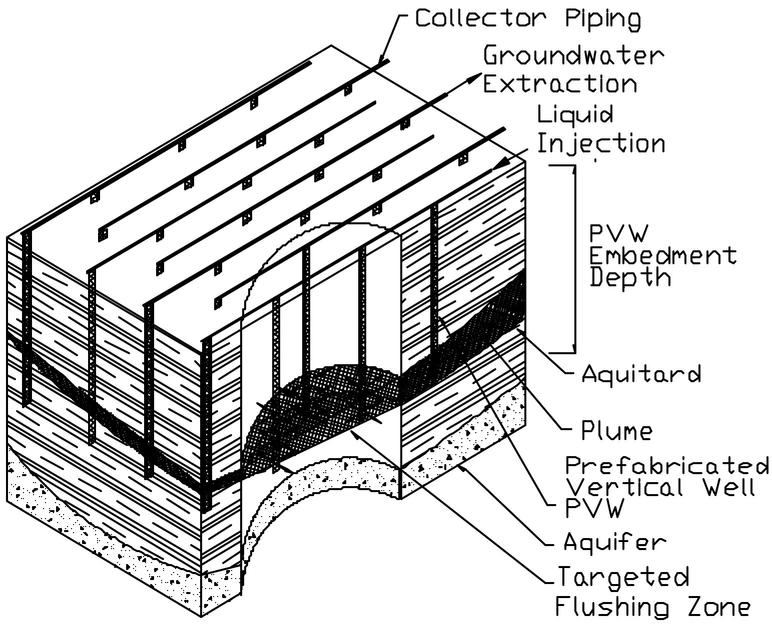

Figure 3. WIDE™ soil flushing system.

The PVWs are installed using a device patented by the Nilex Corporation of Denver, Colorado, which is illustrated in Figure 4. The Nilex process uses a hollow steel mandrel which typically measures approximately 4.6 in wide by 1.17 in deep with lengths exceeding 98 ft. The PVWs are positioned within the hollow core of the mandrel. Then, the steel mandrel is pushed into the soil under hydraulic or vibratory forces at rates of greater than 10 ft/s in firm clay. Typically, a 23 ft deep PVW installation can be accomplished in approximately 4 seconds.

Field construction typically entails a grid of PVWs in offset rows of injection/extraction lines at relatively close spacing (< 3 ft). The interval spacing and offset between the injection/extraction dedicated PVWs are based on engineering design and modeling. The PVWs are connected to a surface network of piping that is used for distributing the air vacuum, receiving the extracted groundwater, and introducing the injection liquids.

Figure 4. PVW mandrel installation system.

Groundwater and Soil Gas Vacuum Extraction System

The primary components of this system are a vacuum compressor and cyclone air/water separator. The vacuum extraction system simultaneously removes groundwater and soil gas, promoting volatilization of contaminants. The vacuum extraction system and the PVW field are pictured in Figure 5.

Liquid Injection System

The injection system uses a liquid storage tank and a positive displacement pump to inject liquids into the subsurface through the PVWs. At the AEMP project, water was used as the flushing agent, but other flushing solutions, such as surfactant, or reagents may be injected.

Above-Ground treatment system

Treatment train design is contaminant-specific and site-specific. The WIDE technology demonstration at the AEMP utilized vapor-phase granular activated carbon (GAC) to remove TCE from the air phase. Liquid-phase GAC was used to remove the non-volatilized trace concentrations of TCE from the groundwater. The on-site WTP was employed to remove any remaining U and ^{99}Tc from the liquid phase.

Figure 5. PVW field with extraction piping.

System Operation

The WIDE system may function under the following operational approaches:

<u>Concurrent injection/extraction</u>: This mode is for an aggressive soil flushing scheme. Injection of liquids to the subsurface through the PVWs maintains saturated conditions and develops pressure gradients in the aquifer, promoting advective and diffusive transport of contaminants to the extraction PVWs.

<u>Extraction Only:</u> All of the PVWs operate under air vacuum, specifically to lower the groundwater table and promote soil gas extraction. This technique has proven to be effective for removing volatile contaminants.

<u>Injection Only:</u> This technique addresses aquifer recharge and saturation of the vadose zone promoting contaminant diffusion.

Operational Issues

Parameters affecting operation of the WIDE system deal mostly with developing adequate vacuum on the PVWs required for groundwater extraction. A major physical limitation to the WIDE technology is extraction depth. The PVWs are limited to extracting groundwater from a maximum depth of 33 ft (assuming a liquid specific gravity of 1, at 1 atmosphere). In practice, the actual depth for groundwater extraction is approximately 31 to 32 ft, accounting for hydraulic head losses within the PVWs, vacuum compressor, and surface piping system (Quaranta and Gabr, 2000).

Cold temperatures impact operation. Low ambient air temperatures (<30 degrees F.) cause icing of the extracted groundwater within the PVWs and surface piping. This problem may be addressed by a number of engineering controls, such as insulation/heat tracing, or heated enclosures.

SECTION 3
PERFORMANCE

Demonstration Plan

The DOE's AEMP is located at RMI Titanium Plant, a former uranium metals processing facility which supplied extruded and milled uranium products for use within the DOE's weapons complex. As a result of long-term uranium manufacturing operations, the site's groundwater and soils were contaminated with TCE, U, and ^{99}Tc.

A former evaporation pond at the site is credited as the source of the TCE and U contamination. The pond measured approximately 30 ft in length and 20 ft in width. The WIDE demonstration test area is positioned over the former pond. The TCE concentration gradients in the groundwater below the 70 ft by 70 ft demonstration pad are illustrated in Figure 6. The demonstration pad was divided into four equal quadrants (measuring 35 ft by 35 ft), each of which was capable of operating independently. Maximum U and TCE concentrations in the groundwater below that demonstration area were measured during the baseline sampling (December 1998) and showed concentrations as high as 13,000 ppb U and 632,000 ppb TCE.

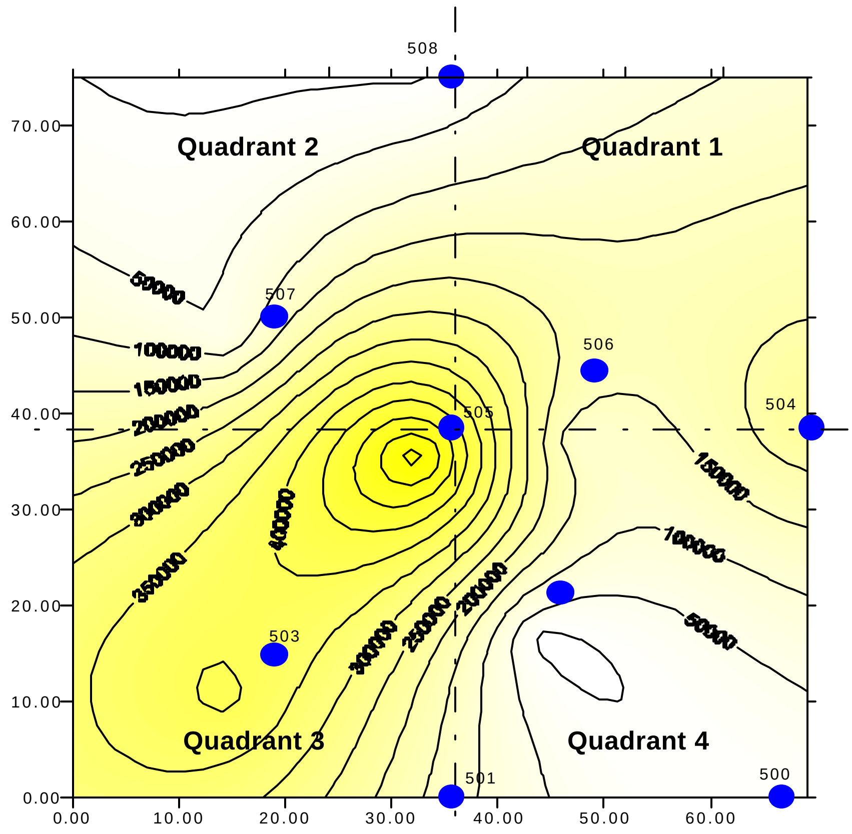

Figure 6. TCE concentrations (ppb) in groundwater.

The site soil is a low permeability glacial till, classified as Ashtabula Till, and is underlain by Devonian Chagrin shale bedrock (Dames & Moore, 1985). The till is composed of approximately 82 percent clay/silt with an average specific gravity of 2.73 (Eckenfelder, 1996). Shale fragments, pebbles, silt, and sand are found in differing degrees within the clay matrix (Dames & Moore, 1985). The piezometric surface is 2 to 3 feet below the ground surface, depending upon seasonal changes. Groundwater moves in three zones: the till zone, the till/bedrock zone, and the bedrock zone (Eckenfelder, 1996).

A subsurface investigation was performed to determine the characteristics of the soil matrix. Key characteristics are provided in Table 1.

Table 1: Subsurface and soil characteristics

Parameter	Value
Soil Classification	CL
Clay Content	42 to 78 %
Moisture Content	20 %
Hydraulic Conductivity	10^{-6} cm/s
Cation Exchange Capacity	30 - 60 meq/100g
Total Organic Carbon Content	5 %
Depth to groundwater	2-3 ft

Demonstration Objectives and Approach

The objectives of the technology demonstration were to design, construct, operate, and monitor the performance of the WIDE system. The performance of the WIDE system was evaluated under the following modes of operation:

1) Extraction only: Under the extraction only mode, a 42 kPa vacuum was applied to all 15- ft deep PVWs in a single quadrant. For the demonstration, the system was typically operated for 6 hours per day and shutdown overnight. The operation schedule during the demonstration was constrained by the site operations schedule and environmental discharge permit restrictions. A full-scale system would be expected to operate 24 hours a day and 7 days a week.

2) Injection only: Under the injection only operation, water was injected through selected PVWs in a specific quadrant to raise the groundwater table and saturate the previously unsaturated (vadose) zone. This was performed to assess the groundwater recharge capacity and to observe the TCE diffusion response.

3) Injection/Extraction: Under injection/extraction operation, selected PVWs within a quadrant operated in either a concurrent injection/extraction mode, or in an extraction mode with pulsed injection. The total volume of liquid injected and extracted was balanced under this operational scheme.

During demonstration, groundwater and air extraction rates were measured. Groundwater elevations and contaminant concentrations where monitored at the groundwater monitoring wells. Contaminant removal rates where calculated based on TCE and U concentrations of grab samples collected from extracted soil gas and groundwater.

Results

The results presented in this report are based on operation of the WIDE system from January through August of 1999. The demonstration was scheduled to continue through December of 1999. During the first eight-month operating period, the WIDE system was brought on-line, and tested under the modes of operation noted above.

The performance data presented in the following section was generated from operation of Quadrant 4. This particular quadrant exhibited the lowest range of TCE and U concentrations and was therefore operated the longest to assess the performance of the WIDE system at relatively low contaminant concentrations. The groundwater extraction rates, air flowrates, and contaminant removal rates presented below are based on the performance of the system in Quadrant 4, which measures 35 ft by 35 ft. The results of groundwater monitoring for all four quadrants are presented later in this section.

Extraction Only Operation

Observations of system performance indicated the following:

- The groundwater extraction flowrate ranged from 25 gal/hr to 150 gal/hr. Typically, the flowrate would decrease over a six hour operation period as the groundwater level was lowered.

- As the groundwater extraction flowrate decreased, the air flow rate increased from an initial rate of 120 cfm to 350 cfm over the 6 hr operation.

- The local groundwater elevation was lowered during the 6 hr operation period with subsequent recovery occurring over night while the system was shut down.

- At a flowrate of 125 gal/hr, the WIDE system was able to exchange one pore volume of groundwater in 258 hours of non-continuous operation (6 hours per day for 43 days).

Under the extraction only mode, TCE was removed first with the extracted groundwater in the soluble phase, then as the groundwater elevation was lowered, TCE was volatilized from the soil surface, and was removed in the gas phase. TCE recovery from Quadrant 4 produced removal rates as high as 6,975 mg/hr of TCE (gas and liquid phase). Over a 50 hour operation period, a total of 140,000 mg of TCE was extracted from the quadrant (2,800 mg/hr). A graph presenting cumulative TCE removal versus cumulative operation time for extraction only operation is presented as Figure B-1 in Appendix B.

Remediation of the uranium constituent occurred as a result of groundwater extraction. Uranium recovery increased with increasing groundwater extraction rates. Uranium removal rates as high as 600 mg/hr were observed.

Injection Only Operation

Injection only testing indicated that a total of 4,000 gallons could be injected into the ground during a 6 hour period. Injection rates between 300 to 500 gal/hr were readily sustainable and rates as high as 1,100 gal/hr were achieved.

Injection/Extraction Operation

Under injection/extraction operation, groundwater extraction rates were greater than observed during the extraction only scenario. Groundwater injection and extraction rates were balanced at approximately 120 gal/hr from Quadrant 4. A total of 6,000 gallons of groundwater was extracted from the quadrant, over a cumulative operation time of 50 hours.

Over 50 hours of operation, approximately 65,450 mg of TCE was recovered from the subsurface. Observed TCE removal rates ranged from 1,200 to 1,800 mg/hr. Most of the TCE removed was volatilized by the extraction process. A total of 64,000 mg of TCE was measured in the gas phase, and 1,450 g was measured in the dissolved liquid phase. Typically, greater than 95 percent of the TCE was volatilized by the vacuum process. A graph presenting cumulative TCE removal, versus cumulative operation time for injection/extraction operation is presented as Figure B-2 in Appendix B. The uranium recovery rates for the same quadrant were approximately 640 mg/hr.

The results of the testing in Quadrant 4 are summarized in Table 2.

For remediation of the TCE plume, the extraction only mode achieved the best results. TCE removal decreased when shifting from extraction only operation to concurrent injection/extraction mode. A maximum removal rate of 6,935 mg/hr was achieved under the extraction only mode, while only 1,800 mg/hr was observed under the injection/extraction mode. Based on these findings, the primary removal mechanism for the TCE contamination was determined to be soil gas extraction.

Table 2. Summary of Demonstration Results, Quadrant 4

Parameter	Extraction Only Operation	Injection/Extraction Operation
Groundwater extraction flow-rate range (gal/hr)	25-120	100-1,100
Operation period for exchange of 1 pore volume of groundwater exchange (cumulative hours)	258	96
TCE recovery rate range (mg/hr)	787 - 6,935	1,200 - 1800
Uranium recovery rate range (mg/hr)	386 - 428	642

For remediation of the uranium contamination in the groundwater, concurrent injection/extraction was the preferred mode of operation. The uranium removal rate increased from 420 mg/hr under extraction only to 640 mg/hr under concurrent injection/extraction, a 33 percent increase in uranium removal. The increased U removal was attributed to the greater volume of groundwater extracted under the injection/extraction mode and advective transport of the U towards the extraction PWVs. Therefore, the primary removal mechanism for the U removal was groundwater flushing.

Results of Groundwater Monitoring

The TCE concentrations in the groundwater were monitored over the course of the demonstration through several monitoring wells installed throughout the demonstration area. The groundwater well locations are illustrated in Figure 4. The results of groundwater monitoring for the first eight month operating period for all four quadrants are summarized in Table 3.

Table 3. Groundwater monitoring results

Quadrant #	Groundwater Monitoring Well #	Vacuum System Operating Time (hours)	TCE Contaminant Reduction Range - Groundwater	TCE Percent Reduction
1	506	54	Initial: 105,000 pp Final: 45,000 ppb	57%
2	507	89	Initial: 70,000 ppb Final: 38,000 ppb	46%
3	503	31	Initial: 400,000 ppb Final: 160,000 ppb	60%
4	502	380	Initial: 2,800 ppb Final: 1,200 ppb	57%

ppb=µg/l

Significant reductions in the TCE groundwater concentrations were observed in all quadrants. The results from Quadrant 4 are significant because Quadrant 4 has a relatively low initial TCE concentration. Lower concentrations are typically more difficult to remediate. The WIDE technology was able to reduce the TCE concentration in Quadrant 4 by 57 percent, but notably these reductions took longer to achieve.

Figure 7 presents the results of the groundwater monitoring for Quadrant 3. Figure 7 is presented to illustrate the fluctuations in TCE concentration resulting from operation of the WIDE system. The figure contains a plot of the TCE concentration measured from well 503 within the quadrant and a plot of the TCE concentration measured in monitoring well 501 located outside of the quadrant. The x-axis represents the monitoring period in days. A note is provided on the graph indicating the cumulative hours of operation in that quadrant during the monitoring period (31 hrs). Graphs of the groundwater monitoring results for the Quadrants 1, 2, and 4 are included in Appendix B.

The TCE concentration in monitoring well 503 prior to operation of the WIDE system was 400,000 ppb (µg/L). After 31 hours of operation (over a 261 day period) the groundwater contaminant level was reduced to 160,000 ppb, a net reduction of 60%. As evident in Figure 6, the TCE concentration in the groundwater would rebound after decreasing. This effect was observed in all four quadrants and is attributed to the continued desorption of TCE from the clay soil and is a result of the soil's relatively high cation exchange capacity (CEC). Increases in TCE concentration may also be attributed to mobilization of TCE from the vadose zone due to the injection of liquid.

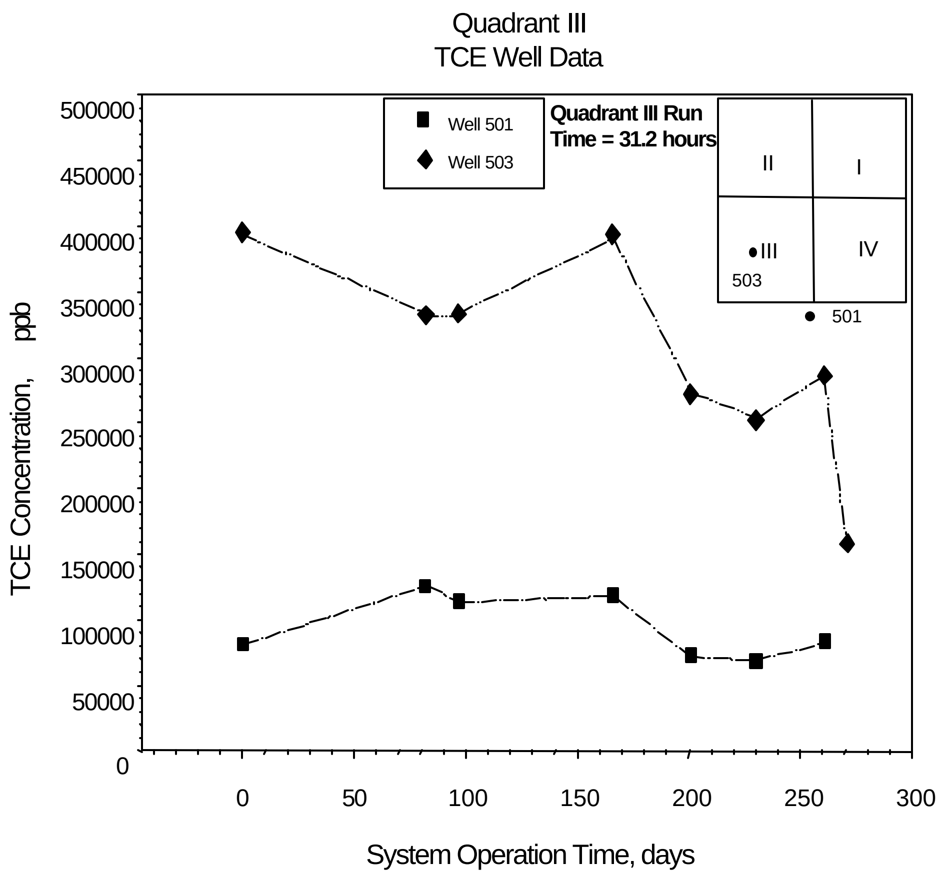

Figure 7. Quadrant 3 monitoring well results.

Conclusions

Demonstration of the WIDE system in the glacial till soil showed that this innovative system did remove subsurface TCE and U contamination by extracting groundwater and soil gas from the low-permeability, high clay fraction soil. The WIDE technology has demonstrated its effectiveness and success in reducing the source of the contamination by achieving large contaminant concentration reductions within relatively short operational times. The WIDE system also proved capable of injecting liquids into the subsurface to enhance the soil flushing process.

Other notable findings are:

- Groundwater extraction rates were higher under concurrent and pulsed injection/extraction operating modes.
- TCE removal rates were highest under the extraction only mode where gas extraction enhanced the removal of TCE contamination from the moist soil particle surface.
- Groundwater extraction was the optimum removal mechanism for U contamination
- TCE concentrations in the groundwater would rebound after decreasing, suggesting that TCE was continually desorbing from the soil.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

The baseline method for remediation of TCE contaminated groundwater is pump and treat remediation. Competing innovative technologies addressed in this section include Lasagna™ and *In Situ* Chemical Oxidation With Deep Soil Mixing.

Pump and Treat

Pump and treat refers to pumping contaminated groundwater from an aquifer followed by above-ground treatment of the groundwater. Conventional pump and treat remediation utilizes groundwater wells or interceptor trenches to access the groundwater. This is the baseline method for controlling groundwater and removing dissolved-phase contaminants. Various surface treatment trains can be utilized to treat the groundwater depending on the contaminants present. For groundwater contaminated with TCE, air stripping and granular activated carbon are typically used. Uranium can be removed by adsorption methods (e.g. ion exchange) or precipitation methods.

Lasagna™

Lasagna™ is an integrated, *in situ* technology which remediates soils and soil pore water contaminated with soluble organic compounds. Lasagna™ is especially suited to sites with low permeability soils where electroosmosis can move water faster and more uniformly than conventional hydraulic methods. The Lasagna™ process combines electrokinetics with treatment zones that are installed directly in the contaminated soils to form an integrated *in situ* remedial process. The process uses electrokinetics to transport contaminants in soil pore water into treatment zones where they can be captured or decomposed. Lasagna™ is designed to treat soil and groundwater contaminants completely in situ, without the use of injection or extraction wells. It has proven to be effective for the in-situ remediation of fine-grained soils contaminated with organics, inorganics, and mixed wastes.

In Situ Chemical Oxidation with Deep Soil Mixing

In situ chemical oxidation delivers oxidants to the subsurface to rapidly degrade organic contaminants. Deep soil mixing is an *in situ* remediation technology that utilizes large diameter augers to inject and aggressively mix reactants with subsurface soil.

In situ chemical oxidation can be applied to the subsurface with relatively stable oxidants such as potassium permanganate ($KMnO_4$). Chemical oxidation using $KMnO_4$ has been widely used for treatment of pollutants in drinking water and wastewater applications for over 50 years. *In situ* chemical oxidation has more recently been used to remediate hazardous waste sites with soils and groundwater contaminated with organics. Delivery processes that have been demonstrated include: deep soil mixing, hydraulic fracturing, multi-point vertical lancing, horizontal well recirculation, and vertical well recirculation.

Deep soil mixing is attractive for contaminated sites that contain low permeability soils. Contaminants are either removed from the soils or stabilized in place. The mixing process allows good access for reagent delivery to all soil particles and the interstices between particles. However, this technology requires surface access at all locations where soils are contaminated.

A comparison of the baseline technology (pump and treat), WIDE, LASAGNA™, and in situ chemical oxidation with deep soil mixing is provided in Table 4.

Table 4. Comparison of technologies

Technology	Advantages	Disadvantages
Pump and Treat	- Established technology which is accepted by regulators	- Slow (remediation times often projected for 20-30 years) - Dependent on hydraulic conductivity of soil - Process often limited by slow contaminant diffusion rates
WIDE	- Applicable to low permeability soils - Installation is relatively simple and inexpensive with no drilling required - Expedites contaminant recovery and reduce long-term operating costs - Targets the source points of a plume, thereby controlling and minimizing the volumes of liquids being extracted	- Direct push installation of PVWs is dependent on subsurface geology and is not applicable to sites where subsurface rock, boulders, or cemented layers exist (pre-drilling is required at these sites) - limited to depths less than 33 ft - experiences freezing problems at ambient temperatures below 30 - 35EF
Lasagna™	- Applicable to low permeability soils - Reduces time required for remediation compared to baseline - Use of treatment zones eliminates the need for above ground waste handling - Treatment zones are more cost effective than other electrokinetic methods	- Process is energy (electric) intensive - Process is complex
In-situ chemical oxidation with deep soil mixing	- Applicable to low permeability soils - Reduces time required for remediation compared to baseline - The reagent ($KMnO_4$) is readily available, inexpensive, and results in generation of innocuous materials such as carbon dioxide, manganese dioxide solids, potassium and chloride (when treating chlorinated compounds) -No secondary waste steam produced	- Not as effective at sites containing saturated organic compounds (e.g., TCA) or media with a high natural oxidant demand - Oxidation chemicals can cause formation of particulate MNO_2 in soil pores, thus reducing soil permeability - Deep soil mixing requires surface access at all locations where soils are contaminated - Technology is limited to oxidizable contaminants

Technology Applicability

The WIDE technology is applicable for the *in situ* remediation of contaminated fine-grain fraction soils (clay/silts) with hydraulic conductivities ranging from 10^{-3} to 10^{-8} cm/s. Its soil flushing capabilities are suitable for removal of dissolved-phase contaminants, DNAPLs, and LNAPLs. The technology has demonstrated the capability of segregating the hazardous and radioactive constituents of a subsurface mixed waste (e.g. separation of TCE from U and ^{99}Tc). The WIDE system is also effective for vapor extraction of volatile contaminants from the vadose zone.

The PVW is the heart of the WIDE technology and has potential application in a number of environmental remediation schemes. Potential applications include:

- injection of nutrients for bio-remediation
- injection/extraction of chemical reagents for *in situ* treatment (.e.g. oxidation agents)
- injection of surfactant to mobilize contaminants
- injection of air (i.e. air sparging)

Patents/Commercialization/Sponsor

Patents

Patent disclosures and applications are in process with the US Patent and Trademark Office. A Disclosure Document (No. 422400) has been filed for “Prefabricated Well Injection Depth Extraction (WIDE) System for Enhanced Soil Flushing” under 37 CFR Section 1.21(c) , 1997.

Commercialization

The project has industry commercialization support from the Nilex Corporation. The Nilex Corporation is the manufacturer of the PVWs and has worked with NCSU throughout development of the WIDE system.

Sponsors

Research and development on the WIDE system was sponsored by the US DOE’s NETL, through a cooperative agreement with West Virginia University (WVU) and subcontracts to NCSU, RMI Environmental Services (RMIES), and The Nilex Corporation. This project has involved ongoing laboratory research and field-scale development under the direction of principal investigators Dr. J. Quaranta and Dr. M. Gabr of NCSU’s Civil Engineering Department and formerly of WVU. The DOE's AEMP was the host for the technology demonstration. RMIES of Ashtabula, OH, the site owner and prime contractor was contracted for site support services, including construction, O&M, analytical sampling, QA/QC oversight, engineering support, regulatory interface, and cost documentation.

SECTION 5
COST

Methodology

The cost analysis includes the following components:

- Summary of WIDE demonstration costs
- Projected costs for 1.25-acre WIDE system for the remediation of TCE contamination at the Corrective Action Management Unit (CAMU) at the AEMP
- Cost comparison between a full-scale WIDE system, the baseline technology (pump and treat), and a competing innovative technology (LASAGNA™) for remediation of TCE contamination at AEMP

Cost information for the WIDE system is based on the field demonstration conducted at the AEMP in 1999, and was provided by the principal investigators. The demonstration costs are categorized according to the *Hazardous, Toxic, and Radioactive Waste Work Breakdown Structure* (HTRW WBS, 1998) developed by the Interagency Cost Estimating Group (ICEG). Cost information for the baseline technology is based on the Groundwater Remediation Technology Review for the CAMU at the RMI Extrusion Plant, prepared Eckenfelder, Inc. (Eckenfelder 1997). Cost information for the LASAGNA™ technology was based on information provided by Monsanto Company, which leads a consortium of companies contributing to development of LASAGNA™.

Remediation of the CAMU at AEMP will be the basis for a cost comparison between the WIDE system, the baseline technology (pump and treat), and Lasagna™.

Description of CAMU

The CAMU is identified in the Corrective Measures Study (CMS) completed by Eckenfelder, Inc. in 1996. The CAMU includes a TCE contaminated groundwater plume that covers an area of approximately 1.25 acres. The TCE concentration in the groundwater ranges from approximately 5 Fg/l to 630,000 Fg/l. The depth to groundwater is approximately 0 to 5 ft and contamination extends to a depth of 20 ft. The remediation goal for TCE in groundwater is 5 Fg/l , which is the Safe Drinking Water, Maximum Contaminant Level (MCL). The proposed target for soil has not yet been established.

Cost Analysis

Summary of WIDE Demonstration Costs

The field-scale demonstration of the WIDE system consisted of a grid of approximately 480 PVWs installed to a depth of 15 ft over a 70 ft by 70 ft area (approximately one-tenth acre). The system was located in the area of the Former Evaporation Pond. The system utilized a 980 cfm vacuum compressor to extract the groundwater and simultaneously volatilize the TCE. The system also had the capability to inject liquids into the subsurface via an injection tank and pump. The above-ground treatment system consisted of an air/water, cyclone separator, and vapor phase granular activated carbon filter for TCE removal. The water from the air/water separator was collected in a holding tank and treated with granular activated carbon for TCE removal prior to transfer to the site's existing WTP. The site's wastewater treatment plant was utilized to remove the radioactive constituents prior to the water's release through the approved point source discharge.

The demonstration system was scheduled to operate from January 1999 through December 1999 (one year). The cost information provided here is based on the first 8 months of operation. The demonstration costs and projected full-scale costs are presented in Table 5 for the Remedial Action (construction) and Table 6 for Operation and Maintenance (O&M). These projected costs for the full-scale WIDE system are described in the following sub-section.

The total core cost to construct the WIDE demonstration system was approximately $386,458. O&M core costs for the one year demonstration were projected to be $199,798 based on extension of the costs for the first six months of operation. For the purposes of cost comparison with other technologies, only core costs are included in this report. Non-core costs such as project management, permitting support, quality assurance, cost accounting, technical reporting, and health and safety are not included.

Estimated Full-Scale WIDE Remediation Costs

The proposed full-scale WIDE system for remediation of the CAMU's 1.25 acre TCE plume will be similar in design to the demonstration-scale system. The costs for the full-scale WIDE system presented in Tables 5 and 6 are conceptual in nature and are based on input from the technology developer and extension of the demonstration costs. A detailed engineering design and cost estimate for the full-scale system has not been completed. The full-scale cost projections are based on the assumption that an economy of scale will be gained in certain areas for the larger application. The following additional assumptions will apply to the full-scale system:

- 6,000 PVWs will be utilized
- PVWs will be installed at 3 ft spacing and at an average depth of 20 ft
- The PVW field will be divided into 20 zones
- Each zone will be comprised of 300 PVWs
- Four vacuum extraction units will be utilized
- Treatment equipment will include air/water separation, and vapor-phase granular activated carbon
- Effluent will be piped to site WTP for treatment prior to discharge

Table 5. Remedial action (construction) costs: demonstration and full-scale

WBS Number		Description	Demo Cost ($)	Full-Scale Cost ($)
331		**REMEDIAL ACTION**		
331	01	MOBILIZATION AND PREPARATORY WORK		
		Mobilization of PVW installation subcontractor	$10,000	$10,000
331	02	MONITORING AND SAMPLING		
		Pre-construction sampling and analysis	$35,000	$35,000
		Soil borings, monitoring well installation, sediment sampling	$13,400	$25,000
331	03	SITE WORK		
		Grading and crushed stone pad	$4,558	NA
331	06	GROUNDWATER COLLECTION AND CONTROL		
		Vacuum extraction units	$129,187	$516,748
		Piping materials (pvc, gauges, sampling ports, fittings)	$15,107	$181,824
		PVW installation subcontract (materials, labor, equipment)	$60,000	$170,000
331	13	PHYSICAL TREATMENT		
		Piping, trenching, electrical, instrumentation (labor and materials)	$36,414	$218,484
		Groundwater treatment (materials and labor)	$30,724	$61,488
331	22	GENERAL REQUIREMENTS		
		Engineering (design and construction oversight)	$52,068	$109,070

		Total	$386,458	$1,327,614

Based on the assumptions above, the total estimated core cost to construct a full-scale WIDE system for the remediation of the 1.25 acre TCE plume is $1,327,614.

Full-Scale O&M Costs

O&M costs for the full-scale system were also projected based on the demonstration costs. Full-scale operation procedures would be similar to those employed during the demonstration. A primary difference will be in regard to sampling frequency. Extensive performance sampling was required during the demonstration phase for modeling purposes due to the R&D nature of the project. Performance sampling frequencies for the full scale system will be significantly less.

The following assumptions will apply to the O&M costs for the full-scale system:

- System will operate 24 hours per day, 7 days per week, and 10 months per year
- Four vacuum extraction units will service five zones each (operating one zone at a time in a rotational scheme)
- The system will operate in an “extraction only” mode for TCE removal
- One full-time operating technician will be utilized
- Non-core costs such as project management, health and safety, permitting and QA/QC are excluded

Table 6. Annual operation and maintenance costs for WIDE system

WBS Number		Description	Demo Cost	Full-Scale Cost
342		**OPERATION AND MAINTENANCE**		
342	02	SAMPLING AND MONITORING		
		Sampling and analysis	$90,000	$25,000
342	06	GROUNDWATER COLLECTION AND CONTROL		
		O&M of PVW and vacuum extraction units	$63,493	$114,968
		Equipment maintenance (compressor oil)	$4,000	-
342	13	PHYSICAL TREATMENT		
		O&M of groundwater treatment	$22,855	$40,000
342	22	GENERAL REQUIREMENTS		
		Engineering oversight	$19,450	$25,000
		O&M Total	$199,798	$204,968

Cost Comparison

Remediation of the CAMU at AEMP is the basis for a cost comparison between the WIDE system, the baseline technology (pump and treat), and Lasagna^{TM}.

Each technology will be operated and maintained for a period of time after construction. The cleanup duration is dependent on the performance of the technology with respect to achieving prescribed clean-up goals. The cleanup duration greatly affects the life cycle cost. Accurate prediction of cleanup duration is difficult and many environmental cleanups take longer than predicted. In the Groundwater Remediation Technology Review, the baseline technology has an estimated cleanup duration of 18-87 years, with a footnote that the remediation time frame could increase significantly if remediation is diffusion limited

(Eckenfelder 1997). The cleanup duration for the LASAGNA™ technology, based on other applications, has been predicted to be approximately 2 years. The reader should note that the costs for LASAGNA™ are based on reducing the TCE soil concentration to a level of 1 ppm, and not the 5 ppb groundwater cleanup goal. In-depth modeling for the application of LASAGNA™ to the Ashtabula site has not been performed. Preliminary estimates of the cleanup duration for the WIDE system are approximately 5 years to reach a concentration of 5 ppb. This estimate is based on parametric modeling from Phase I research that predicted the TCE concentration in the groundwater could be reduced from 10,000 ppb to 5ppb in 3 years .

For the purposes of the cost comparison, regulatory sampling and analysis costs for each technology were assumed to be $25,000 annually .

Baseline Technology Costs

The baseline technology for remediation of TCE contaminated groundwater in the area near the former evaporation pond is pump and treat remediation. This alternative has an ex situ vapor stripping component to treat 3,500 cy of TCE-impacted soils excavated from the vadose zone. This baseline is the preferred remediation alternative outlined in the CMS. The alternative includes:

- Excavation of TCE contaminated soils near the former evaporation pond and ex situ vapor extraction
- Replacement of treated soil in the original excavation and site restoration
- Installation of a groundwater extraction trench
- Installation of a groundwater treatment system for TCE removal
- Long-term operation and maintenance (18-87 years)

The groundwater collection trench would be approximately 500 ft in length and 30 ft in depth, installed just above the shale bedrock. The anticipated extraction rate would be a maximum of 5 gpm. The extracted groundwater would then be treated to remove TCE prior to discharge into the existing wastewater treatment system. TCE removal would be accomplished using an air stripper. The direct capital costs associated with implementation of the baseline corrective measure alternative are summarized in Table 7 (Eckenfelder, 1997). The costs in Table 7 have been indexed to October 1999 from 1997 by 5.0% based on Engineering New Record's Construction Cost Index History (ENR, 1999).

Table 7 . Summary of baseline costs.

Description	**Cost**[1]
Excavation and treatment TCE contaminated soil (non-LLW soil)[2]	$619,500
Direct capital cost for groundwater treatment system [2]	$71,400
Engineering [2]	$66,675
Annual O&M of groundwater treatment system	$52,500
Annual regulatory sampling and analysis	$25,000
Present Value Life Cycle Cost[3] (2.9%, **18** years)	$1,832,539
Present Value Life Cycle Cost[3] (2.9%, **87** years)	$3,207,777

[1] Cost reported in 1999 Constant Dollars
[2] Instantaneous Cost, 1999 Constant Dollars
[3] Present value life cycle cost was determined by discounting O&M costs (equal series, constant dollars) by a real interest rate of 2.9 percent per Office of Management and Budget (OMB) Circular, Appendix C (OMB 1999).

LASAGNA™

The LASAGNA system, presented as a competing technology, would be implemented in the vertical configuration to address both soil and groundwater contamination. The Lasagna system would be applied to the TCE contaminant plume which is 1.25 acres in area and 20 ft in depth (approximately 40,741cy). The cost estimates are for core costs only, such as pretreatment sampling, design, site preparation, electrodes, treatment zones, equipment installation, O&M, and site restoration. The following assumptions apply to the LASAGNA™ system:

- Electrode depth: 20 ft
- Degradation Zones: Zero-valent Iron
- Pore Volumes Required for Remediation: 1
- Remediation Period: 2 years
- TCE cleanup to less than 1 ppm (soil concentration)
- Electricity Cost $ 0.08/kwh

Table 8. Summary of Lasagna™ costs

Description	Cost
Installation cost	$1,566,037
Annual system O&M cost	$677,234
Annual regulatory sampling and analysis	$25,000
Present Value Life Cycle Cost (2.9%, 2 years)	$2,901,690

[1] Cost reported in 1999 Constant Dollars
[2] Instantaneous Cost, 1999 Constant Dollars
[2] Present value life cycle cost was determined by discounting O&M costs (equal series, constant dollars) by a real interest rate of 2.9 percent per OMB Circular, Appendix C (OMB 1999).

Table 9 presents a side by side cost comparison of the capital, annual O&M, and present value life cycle costs for the baseline technology, WIDE and LASAGNA™.

Table 9. Life Cycle Cost Comparison of Remedial Alternatives[1]

Technology	Baseline Technology	WIDE	LASAGNA™
Construction/Installation Capital Cost[2]	$757,575	$1,472,614	$1,566,037
Annual O&M Cost	$77,500	$204,698	$702,234
Present Value Life Cycle Costs[3]			
2 years	--	--	$2,901,690
5 years	--	$2,268,993	--
18 years	$1,832,539	--	--
87 years	$3,207,777	--	--

[1]Cost reported in 1999 Constant Dollars
[2]Instantaneous Cost, 1999 Constant Dollars
[3]Present value life cycle cost was determined by discounting O&M costs (equal series, constant dollars) by a real interest rate of 2.9 percent per OMB Circular, Appendix C (OMB 1999).

Cost Conclusions

Based on the cost analysis presented here, WIDE has a 5 year life-cycle present value of approximately $2.26 million. Although, the baseline alternative has the lowest cost when calculated for an 18 year life-cycle, it is unlikely that the clean up goals would be achieved in this time period . When considering an 87 year life-cycle, the baseline alternative is the most expensive at cost of over $3.2 million.

LASAGNA^{TM} offers the most rapid remediation at an estimated 2 years, at a cost of approximately $2.9 million. The reader should note that the costs for LASAGNA^{TM} are based on reducing the TCE soil concentration to a level of 1 ppm, and not the 5 ppb groundwater cleanup goal. Therefore, a longer period of time may be required to achieve the 5 ppb groundwater cleanup goal.

The innovative technologies, WIDE and LASAGNA^{TM}, aggressively target the source of the contamination and have much faster remediation times compared to the baseline option. Faster remediation results in additional indirect cost savings that are not captured in the above cost comparison. Indirect cost savings that result from faster remediation include project management, project overhead, and site management and support. Further, faster remediation results in decreased liability and allows the sites to be put back into beneficial use more rapidly.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

Communication with regulators should be established early in the development process for new remediation technologies. Permits depend on the specific application and state/federal requirements. Early and continuous discussions with the regulators encourages more rapid permitting.

- At federal facilities a National Environmental Policy Act (NEPA) review is required.

- Comprehensive Environmental Recovery, Compensation, and Liability Act (CERCLA) or Resource Conservation and Recovery Act (RCRA) corrective action permitting may be required.

- A National Pollution Discharge Elimination System (NPDES) permit for the installation of the groundwater treatment system will be required if extracted groundwater is treated and discharged to surface water.

- An air permit may be required to govern emissions from the groundwater treatment system.

- An Underground Injection Permit may be required if flushing agents, surfactant, or other chemicals are introduced into the groundwater.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

Potential worker safety risks include those associated with standard construction operations as well as those associated with work at a contaminated site and with potentially hazardous chemicals as regulated by the Occupational Safety and Health Administration (OSHA)

Community Safety

- No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with WIDE.
- The WIDE technology has the potential to decrease the clean-up duration, thus reducing long-term risks to the nearby community.

Environmental Impact

- WIDE targets the areal and depth source of a plume, thereby minimizing the volumes of extracted liquids and minimizing remediation time, thereby freeing land for beneficial reuse.

Socioeconomic Impacts and Community Perception

- The general public has limited familiarity with the WIDE technology; however, the concept can be easily explained to the public.
- The technology should receive positive public support as it is an improvement over the baseline
- WIDE has a minimal impact on the economy and labor

SECTION 7
LESSONS LEARNED

Implementation Considerations

Prior to implementation of the WIDE system at a particular site, the mode of operation (i.e. extraction only or concurrent injection/extraction) should be determined. The mode of operation is established based on the contaminants being targeted and the subsurface conditions. Extraction only operation was demonstrated to be more effective for targeting volatile contaminants and the injection/extraction mode was more effective for non-volatile, dissolved contaminants.

Design of the vacuum system and surface treatment system is based on the mode of operation, subsurface conditions, and contaminants present. The WIDE system is primarily made up of off-the-shelf components, allowing rapid construction and deployment.

The WIDE technology was effective in dewatering a saturated subsurface under extraction only operation, as well as saturating the vadose zone under and injection only mode. The system may be readily deployed in various soil types, (sands, silts, and clays), as well as in the vadose or saturated zone. Adjusting the PVW geotextile apparent opening size (AOS) will permit extraction of various low viscosity, free-product liquids, i.e., oils, sludges, fuel products (Gabr et. al. 1999).. The WIDE system may be installed on sloped surfaces, within existing facilities, or directionally to extend under buildings.

Technology Limitations

The primary limitation of the WIDE technology is related to depth of contamination. Though PVWs can be installed to depths of greater than 90 ft, vacuum extraction of liquids is limited in practice to depths of approximately 30 ft. The WIDE technology is predominantly a shallow depth (<30 ft) remediation system.

Needs for Future Limitation

One area for future development is in the “winterizing” the WIDE technology. At the Ashtabula site, the PVWs were connected above ground with PVC piping. This setup experienced icing problems at temperatures below 30 degrees F. For the WIDE system to be capable of operating in cold temperatures, this limitation needs to be addressed. This could be in the form of heat traced insulation, a heated enclosure, or burying the piping.

Design and performance modeling is needed to further the development of the technology. Currently, long-term performance data for continuous operation is not available.

Technology Selection Considerations

The WIDE system is an effective shallow-depth soil flushing tool. For short-term source reduction, WIDE has demonstrated its ability to significantly reduce contaminant concentrations in short time frames. The system has also proven to be capable of free-product recovery. As a long-term remediation system, WIDE is proving its effectiveness for reducing contamination to low clean-up limits. The WIDE technology may be used to augment other existing technologies, i.e. bioremediation, surfactant flushing, soil vapor extraction, where subsurface soil discontinuities would benefit from the close spacing and redundancy of PVWs.

APPENDIX A
REFERENCES

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APPENDIX B
PERFORMANCE FIGURES

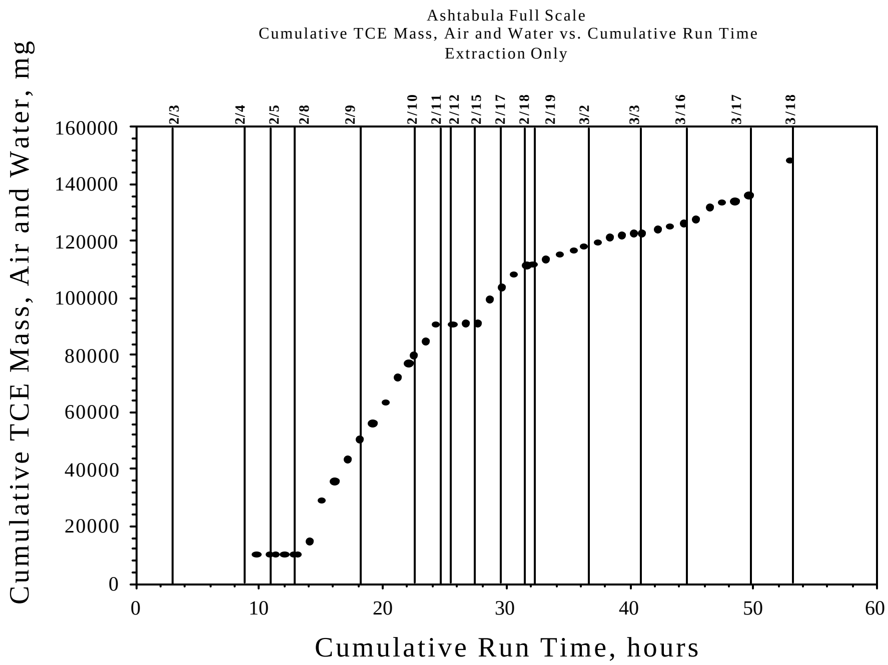

Figure B1. Mass TCE removed vs. time (extraction only).

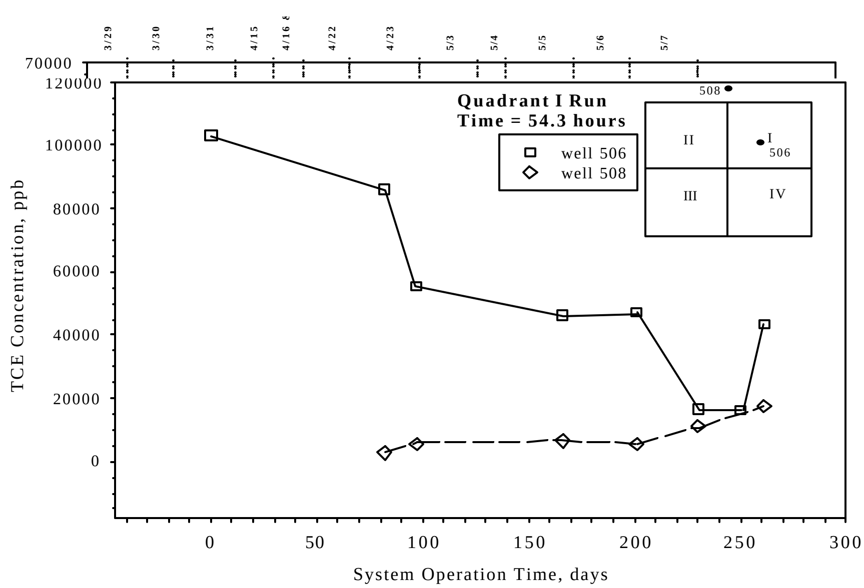

Figure B3. Quadrant 1 monitoring well results.

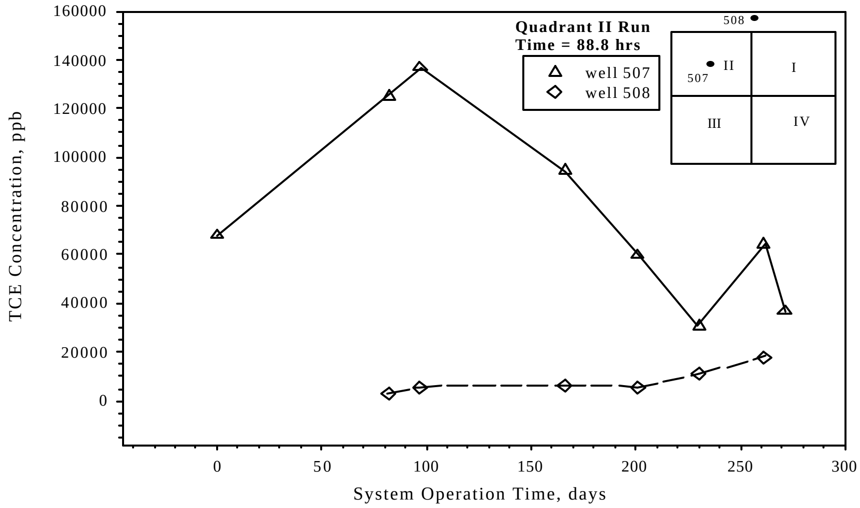

Figure B4. Quadrant 2 monitoring well results.

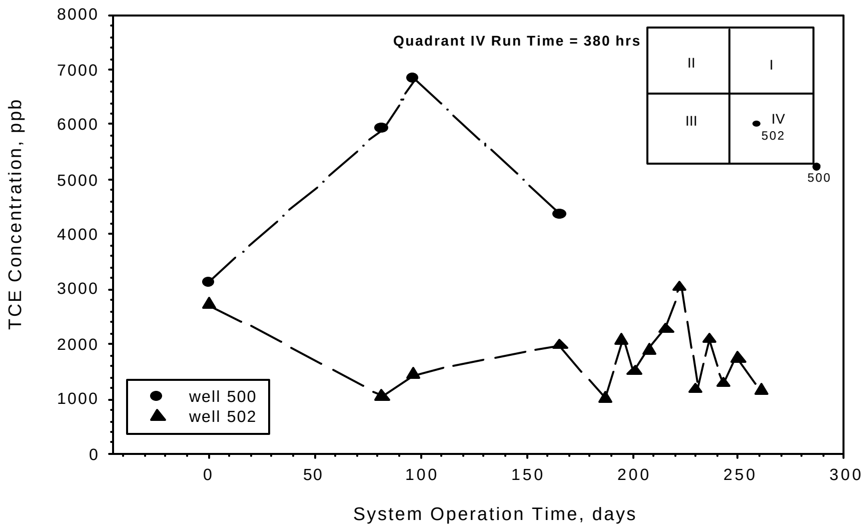

Figure B5. Quadrant 4 monitoring well results.

APPENDIX C
ACRONYMS AND ABBREVIATIONS

AEMP	Ashtabula Environmental Management Project
CAMU	Corrective Action Management Unit
CERCLA	Comprehensive Environmental Recovery, Compensation and Liability Act (CERCLA)
DNAPL	Dense Non-Aqueous Phase Liquid
DOE	Department of Energy
ENR	Engineering News Record
GAC	Granular Activated Carbon
HTRW WBS	Hazardous , Toxic, and Radioactive Waste Work Breakdown Structure
ICEG	Interagency Cost Estimating Group
LNAPL	Light Non-Aqueous Phase Liquid
MCL	Maximum Contaminant Level
NCSU	North Carolina State University
NEPA	National Environmental Policy Act
NETL	National Environmental Technology Laboratory
NPDES	National Pollution Discharge Elimination System
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Administration
OST	Office of Science and Technology
OMB	Office of Management and Budget
PVD	Prefabricated Vertical Drain
PVW	Prefabricated Vertical Well
PCE	Perchloroethylene
RMIES	RMI Environmental Services
TCE	Trichloroethylene
TMS	Technology Management System
UST	Underground Storage Tank
WIDE™	Well Injection Depth Extraction