Acoustically Enhanced Remediation,
Phase II - Technology Scaling

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Introduction

Weiss Associates is conducting a three phase program investigating the *in-situ* application of acoustically enhanced remediation (AER) of contaminated unconsolidated soil and ground water under both saturated and unsaturated conditions.

- Phase I - Laboratory Scale Parametric Investigation
- Phase II - Technology Scaling
- Phase III - Large Scale Field Tests

The Phase I project was introduced in Iovenitti et al. (1994). The details of the work conducted under that project were reported in Weiss Associates (1995) and summarized by Iovenitti et al. (1995). Phase I consisted of (1) an one-dimensional "proof-of-principle" bench-scale investigation using unconsolidated soil samples approximately 1.5" x 3.5", and (2) an analysis of the field deployment and engineering viability of the AER technology. The salient features of Phase I are summarized below.

Phase I was originally designed to test acoustical enhanced non-aqueous phase liquid (NAPL) remediation in low permeability soils. However, given the difficulty and time-consuming nature of testing low permeability soil, Phase I focused on ground water NAPL remediation in well-sorted and poorly-sorted sand, and hydraulic conductivity changes in low permeability clay and silt. With modest optimization testing, a greater than 70% increase in NAPL recovery from the poorly sorted sand was established with acoustic excitation relative to a baseline ground water pump and treat. A uniform and homogeneous clay with a hydraulic conductivity of 10^{-8} cm/sec was also tested. This clay most likely represents a worst case low permeability field condition. With acoustic excitation the hydraulic conductivity of this clay was increased four-fold relative to a baseline ground water pump and treat. This four-fold increase represents a 90% decrease in the time required to remediate this soil. Naturally occurring low permeability zones will generally have a much more variable grain size distribution than the clay tested, and consequently, the AER induced hydraulic conductivity increases are expected to be greater.

Figure 1 presents the results of an engineering analysis of the expected frequency, power level, and acoustical intensity regime where AER could be field deployable. Beneficial acoustical excitation effects were observed for strain amplitudes of 10^{-5} to 10^{-4}, or acoustical intensities on the order of 100 - 10,000 watts per square meter (W/m^2).

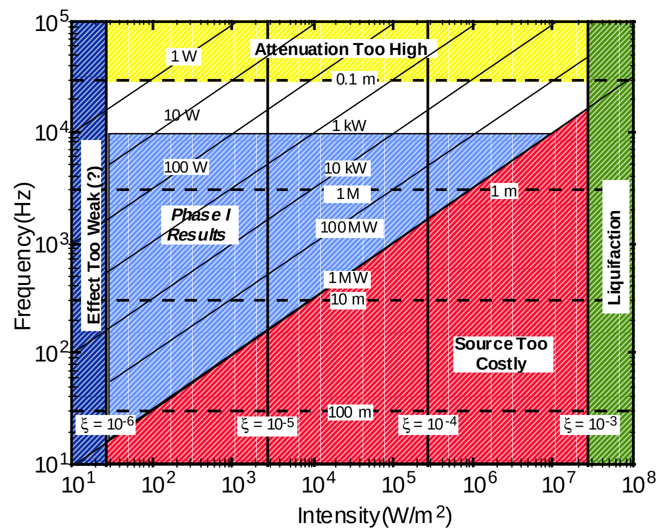


Figure 1. Frequency, Power Level, and Field Intensity Compared Against the Phase I Experimental Regime

Two-dimensional, computer modeling of the Phase I results showed that a phase-tuned acoustical source deployment methodology could generate the acoustical intensities required in the field. With phase tuned arrays, the maximum local intensity is proportional to the power of the individual sources, proportional to the square of the number of sources, and inversely proportional to the square of the distance from the sources in the array. Figure 2 shows a variable gray scale for interpreting the modeling results in Figures 3 and 4.

Figure 3 shows the acoustical intensity distribution generated by 8 x 10 kilowatt (kW) sources incoherently summed in a two-dimensional domain 100 m x 100 m. Under such conditions the intensity at the center of the domain is only 10 W/m^2. Figure 4 shows the acoustical intensity field generated by 8 x 10 kW sources that are phase tuned and sweeping the zone of constructive interference through the volume of interest by beam steering. Under these conditions, intensities on the order of 100 W/m^2 can be established across most of the volume. This theoretical modeling analysis conservatively suggests that a plume 50 m - 70 m in diameter could be readily remediated by a single wellfield deployment. A conceptual illustration of the AER field deployment is shown in Figure 5.

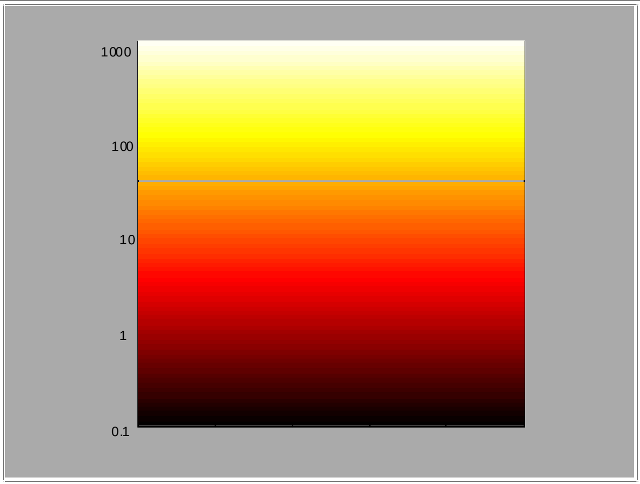


Figure 2. Acoustic Intensity (watts per square meter) Gary Scale Used in Figures 3 and 4

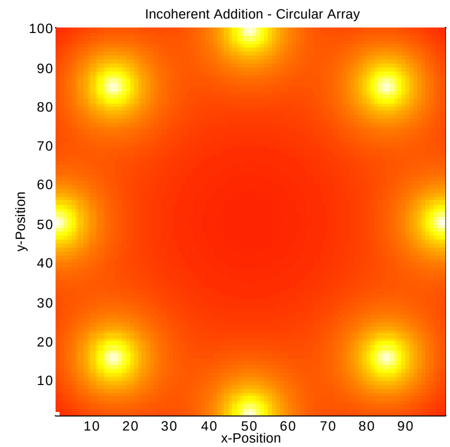


Figure 3. Acoustic Maximum Intensity Versus Location Produced by Eight Sources that Incoherently Sum; domain in meters

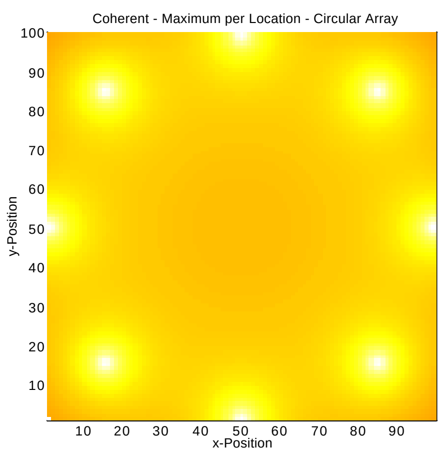


Figure 4. Acoustic Maximum Intensity Versus Location Produced by Sweeping (or Beam Steering) Eight Phase Tuned Sources Across the Volume; domain in meters

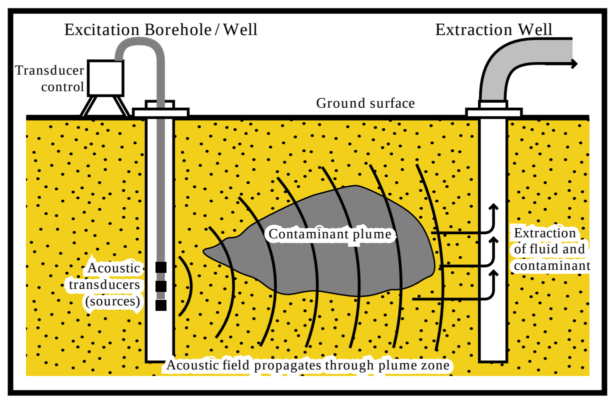


Figure 5. The Acoustically Enhanced Remediation Field Deployment Concept

Phase II - Technology Scaling, the subject of this paper, was designed to bridge the gap between Phase I which involved laboratory "proof-of-principle" one-dimensional bench-scale testing on samples on the order of inches and two-dimensional computer modeling of acoustic remediation deployment strategy using phase tuned arrays, and Phase III which will involve large-scale field tests on the order of 100s of feet.

Phase III is a field scale "proof-of-principle". It will consist of development of acoustical sources and their associated computer adaptive controls, "clean" site testing at a non-industrialized, non-contaminated site, followed by pilot scale field treatability tests at contaminated sites.

AER addresses the need for NAPL (either lighter or denser than water: LNAPL or DNAPL, respectively) in high and low permeability sediments, and the remediation of other types of subsurface contaminants (e.g., metals, radionuclides) in low permeability soils. This program has been placed in the U.S. Department of Energy's (DOE's) DNAPL product line.

The primary subcontractors in this Phase II effort were Scientific Applications and Research Associates (SARA), Inc., and University of Colorado at Boulder, Department of Civil Environmental, and Architectural Engineering Porous Media Laboratory (CU-PML). Lawrence Berkeley National Laboratory (LBNL) also participated in the project.

Objectives

Current technologies to remediate NAPL in either high or low permeability soils may not be timely or cost-effective. The removal of NAPL from high permeability soils is limited by the physical forces (e.g., capillary forces) that hold in NAPL within the pore, and by the soil micro-heterogeneities. NAPL remediation in low permeability soils is limited by the significantly reduced capability of the soil to transmit fluid and its high sorptive capacity. DNAPLs have been found to be especially difficult to remediate because (1) their presence in the field are difficult to confirm, and (2) they tend to sink deeper into the aquifer upon mobilization.

Phase I indicated that AER could be used to effectively remediate NAPL in high permeability soil, and that removal of NAPL from low permeability soil could be increased since the water flux through these soils was significantly increased. Phase II, Technology Scaling, focused on (1) evaluating the characteristics of an AER field deployment system, (2) developing DNAPL flow and transport performance data under acoustic excitation, (3) predicting the effect of acoustic remediation in three-dimensional unconsolidated hydrogeologic conditions, (4) conducting an engineering analysis of acoustical sources, and (5) identifying candidate field site(s) for large-scale field testing of the technology.

Approach

The Phase II laboratory test data required to meet the objectives of this project were attempted to be obtained by conducting large scale, two-dimensional laboratory tests primarily in tanks, 72" x 48" x 2". The length of the tank cell, 72", was dictated by the need to avoid standing acoustical waves in the cell. The width of the tank, 2", was dictated by the two-dimensional nature of the laboratory tests, and the possible use of a transmission gamma-ray spectrometer at the CU-PML. Off-the-shelf piezoelectric sources were determined to be inadequate for our test purposes. Ten 7.5 kHz custom-built, wafer-composite piezoelectric sources were built for this test program.

Two tank cells were designed, built, and utilized: a "clean" tank where no contaminants were used, and a "contaminated" tank where the soil-water-DNAPL system was tested under acoustic excitation (excited) and baseline (no acoustic excitation) conditions. 1,1,1-trichloroethane (TCA) was used as the representative DNAPL in these experiments. The TCA was dyed red with Sudan IV to allow visual observation of its behavior.

A smaller test cell (48” x 18” x 2”) was also used to evaluate NAPL dissolution under both saturated and unsaturated conditions. P-xylene was used to represent NAPL dissolution behavior under baseline and excited conditions. This NAPL was also dyed red with Sudan IV to expedite visual observation.

The contaminated tank cells were instrumented with thermocouples, accelerometers, pressure transducers, hydrophones, and fitted with sampling ports. These instruments were connected to a computerized data collection and storage system. One novel feature of the data acquisition system used for Phase II was that acoustic signal frequency, phase, and amplitude for tests conducted in Boulder, Colorado could be monitored and controlled from Huntington Beach, California.

Results

Clean Tank Cell

A water filled “clean” tank was used to evaluate the multiple source phase-tuned array design, signal propagation and control. Figure 6 presents the clean tank with a vertically mounted array of five acoustic sources and five pressure transducers. The transducers were mounted a mobile array to allow mapping of the spatial distribution of the induced acoustical intensity field.

Figure 6. Water-Filled, Clean Tank Cell Showing the Test Set-up with a Five Acoustic Source Array and Five Pressure Transducers

Figure 7 shows the resulting acoustic intensity map for a 24” by 24” region within the clean tank cell using five acoustical sources and no phase tuning. The central portion of this region has a maximum acoustical intensity of 17 W/m^2. Figure 8 shows the acoustic intensity with phase tuning to optimize the constructive interference at a position 30” in from the left hand side of the tank and 20” above the bottom. The resulting acoustic intensity at the focal point increased from approximately 17 W/m^2 in the unphased condition to over 70 W/m^2 with phase tuning. This latter acoustic intensity value is within the region of Phase I results as shown in Figure 1.

The acoustic focusing result provides laboratory validation in water that phase tuning increases acoustic intensity at the focus regions and validates the numerical phase tuning model developed in Phase I (see Introduction). The ability to focus acoustic energy in the far field will allow for the cost-effective deployment of AER technology. These results support the field observations reported by Aleshin, et. al., 1990; Beresnev and Johnson, 1994; Nikolaevskiy, 1989; and Nikolaevskiy,

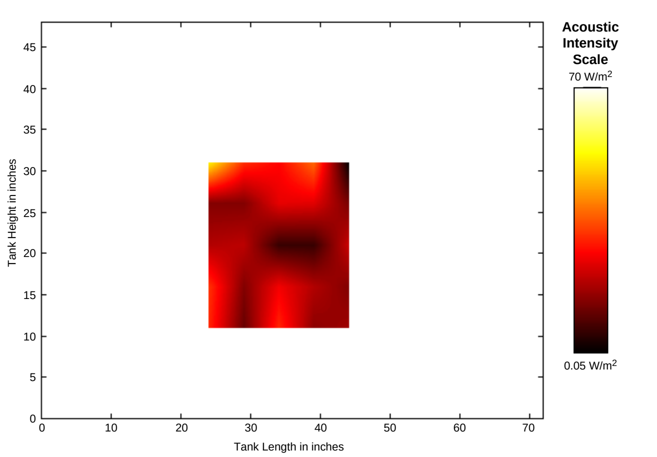


Figure 7. Water-Filled, Clean Tank Non-Phase Tuned Acoustic Source Array Intensity Map

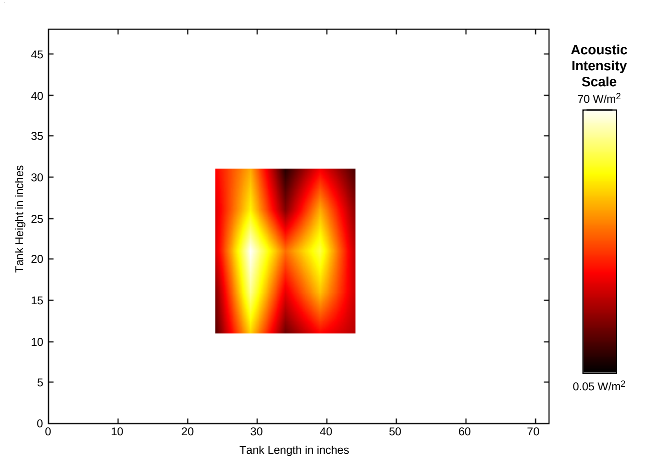


Figure 8. Water-Filled, Clean Tank Phase Tuned Acoustic Source Array Intensity Map; Array Focused for Maximum Constructive Interference at the (x, y) Location (30", 20")

et. al., 1996. These authors have reported the beneficial impacts of using acoustic energy for enhanced oil production.

Contaminated Tank Cell Testing

The “contaminated” tank was used to (1) evaluate the propagation, coupling, and control of the multiple acoustical source array in soil-water-TCA, and (2) obtain TCA flow and transport data.

Figure 9 presents a schematic of the contaminated tank cell used at CU-PML. The shaded border and three vertical bars are 1/8” walled, 2” x 3” structural steel tubing. The walls, bottom, and ends of the tank consist of 1” thick Plexiglas and part of the tank walls were partially lined with ⅛” tempered glass to protect the Plexiglas from the TCA. Open wells, at each end of the test cell, were used to establish the regional hydraulic gradient. One sidewall of the tank is fitted with 26 ports in four vertical columns identified as A through D. The ports were primarily designed used for fluid sampling. There was one injection port in approximately the center of the B-ports. The bottom row of ports to the right of the C-ports were also completed to simulate horizontal wells. Two piezoelectric acoustic source arrays, consisting of 5 sources per array, centered 6" apart along a spacing rod, were positioned centered about the contaminant target area.

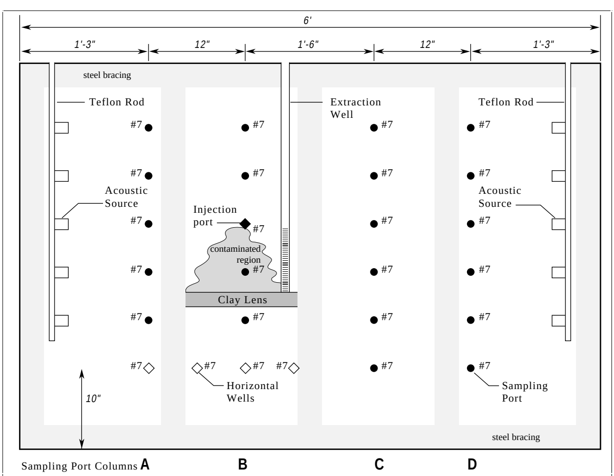


Figure 9. Contaminated Tank Cell at CU-PML Illustrating the Set-Up for Experiment 1, See Text

Experiments 1 and 2 at CU-PML consisted of a TCA introduced in a saturated fine sand above a clay aquitard (Figure 9). The two acoustical source arrays in this experimental set-up were phase-tuned to maximize acoustical intensity at four different locations. Figures 10 and 11 are relative acoustic intensity maps for two of these focus points. These figures show that acoustical energy can be focused and steered within a heterogeneous soil-water system.

The ability to focus acoustic energy in the far field in a soil-water system is a critical step in the successful deployment of AER technology.

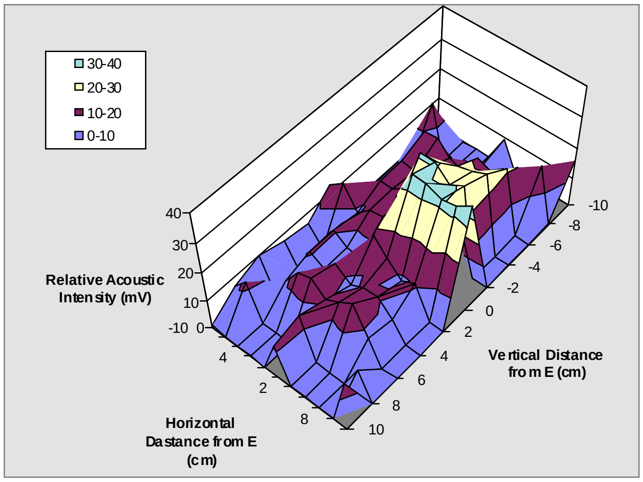


Figure 10. Experiment-1 Relative Acoustic Intensity for Focal Point (0,0); Point E is Approximately 2.4" Below the Injection Point in Figure 9

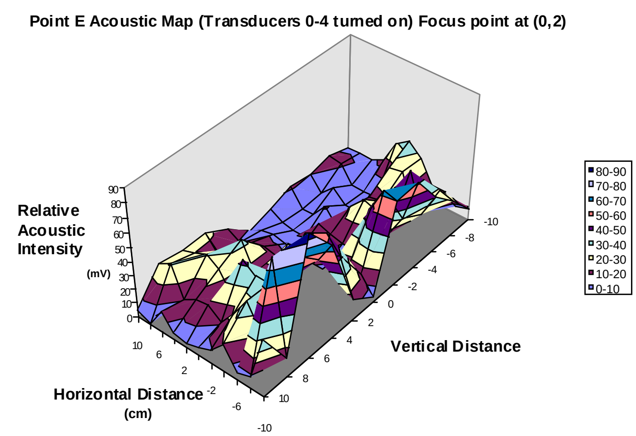


Figure 11. Experiment-1 Relative Acoustic Intensity for Focal Point (0,2); Point E is Approximately 2.4" Below the Injection Point in Figure 9

The acoustical intensities generated in the soil-water-TCA test cell were considerably lower than those measured in the water-filled clean tank, and in the Phase I. Note that the acoustical intensity in Figures 7 and 8 are W/m^2, while relative acoustical intensity in millivolts (mV) is reported in Figures 10 and 11. Similar outcomes regarding low acoustical intensities were observed in the subsequent four CU-PML experiments. Experiments 3 -5 were designed to address the migration of TCA through a low permeability clay heterogeneity.

It was determined that significant and insurmountable acoustical signal attenuation was occurring in the contaminated tank cells. Potential acoustical signal attenuation mechanisms identified were:

1. the presence of small quantities of air within the saturated sand pack;
2. the tank test cells were under a drained condition;
3. acoustical impedance mismatch between the acoustical sources constructed and the water-saturated sand;
4. the high acoustical source operating frequencies (7.5 kHz);
5. compressional to shear acoustic wave mode conversion;
6. grain to grain motion absorbing the energy; and
7. some combinations of the above factors.

The first three of these potential signal attenuation explanations appear to be the most significant. Dr. Ernie Majer of LBNL was consulted on this issue, and he reported a similar occurrence in testing acoustical sources in a large “swimming pool” type experiment conducted at the Oregon Graduate Center. Even after 2 - 3 months, during which time many of the microscopic air bubbles trapped on soil particles could slowly dissolve in to the water, the acoustic signals had still not reached levels comparable to what he was routinely measuring in the subsurface. According to Dr. Majer, the acoustical signal intensity loss experienced in the Phase II tank cell was an experimental flaw of the tank cell set-up.

These signal attenuation mechanisms could be overcome with more energetic acoustic sources. Consequently, an “off-the-shelf” externally mounted, air-driven vibrator was purchased and tested at CU-PML. Although more energetic than the piezoelectric sources, the air-driven vibrator was not sufficiently energetic enough to overcome the Phase II laboratory test conditions. It appears that to obtain excited DNAPL flow and transport behavior either specially designed and built acoustical sources and test cells are required or Phase I type testing is necessary. It is our recommendation that Phase I type testing be utilized because the data acquisition process would be much more cost-effective.

In addition to the signal attenuation issue, experimental problems were encountered with (1) injection port failure, (2) structural flaws in the low permeability clay heterogeneity, (3) bowing and vibration of the tank walls under excited conditions. These experimental difficulties caused incomplete experiments and the acquisition of no meaningful excited flow and transport data.

Dissolution and Hydraulic Conductivity Testing

An externally mounted air-driven ball vibrator operating in the nominal 300 Hz range was used to evaluate NAPL dissolution under baseline and excited conditions. P-xylene, as a representative NAPL, was introduced into a coarse-grained sand inhomogeneity within a water-saturated fine-grained sand pack in the small test cell (see Approach).

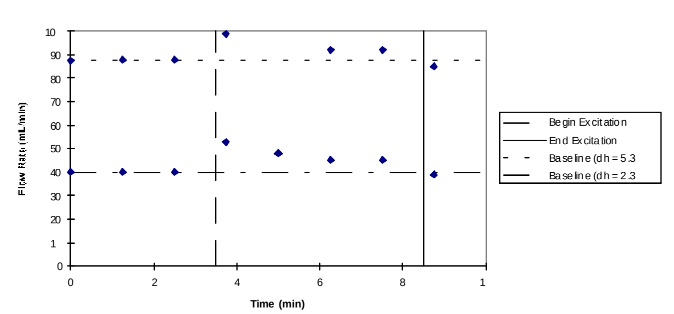


Figure 12. Dissolution Test Cell Hydraulic Conductivity Results

The cell transmissivity was estimated under both baseline and excited conditions for hydraulic head differentials of 5.3 and 2.3 cm (Figure 12). Baseline flow rates for the two hydraulic heads of 89 and 40 ml/min correspond to gross Test Cell hydraulic conductivities of 0.1226 and 0.1214 cm/sec, respectively. The excited condition flow rates peaked for the above two hydraulic heads at 99.5 and 53 ml/min shortly after acoustic excitation was initiated, corresponding to gross hydraulic conductivities of 0.1625 and 0.1366 cm/sec, respectively. While the flow rates at both hydraulic heads declined, with time, the final excited condition flow rates of 90.5 and 43.5

ml/min are still significantly above the baseline values. The decline in flow rate is an artifact of the test apparatus and attributed to initial stages of plugging of the cell pump filters.

These hydraulic conductivity increases with excitation in the fine sand are in marked contrast with the Phase I hydraulic conductivity results. In Phase I, no changes in the hydraulic conductivity of sand were observed. Fines migration reducing the permeability of the tank is an operation issue to be addressed in Phase III. We plan to use oil field technology to minimize this tendency in the field.

P-xylene was injected into a course grain inhomogeneity and allowed to stabilize over night. Aqueous samples were collected from the test cell effluent well and analyzed using a gas chromatograph. After stabilized baseline steady state NAPL concentrations were obtained, AER was initiated. Figure 13 shows the resulting increases in relative NAPL concentration and flow rate from one of the tests. The p-xylene concentrations during AER increased to twice the baseline concentrations. The subsequent relative concentration and flow rate decrease are caused by plugging of the extraction well and are an artifact of the test apparatus. A subsequent dissolution experiment also showed an approximately 100% increase in relative p-xylene concentrations after acoustic excitation was initiated (Figure 14).

Acoustic intensities during these dissolution experiments were extremely weak, less than $1 W/m^2$.

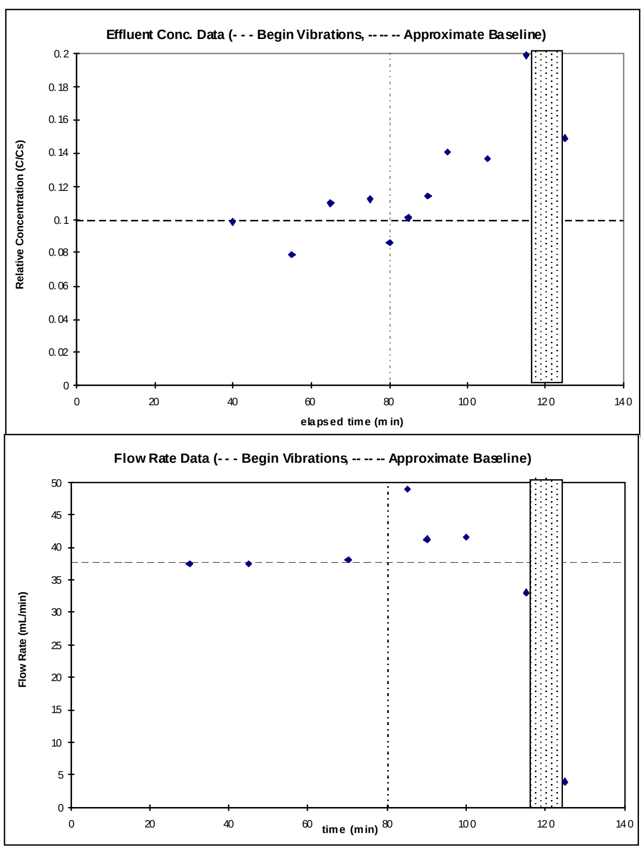


Figure 13. Dissolution Test P-Xylene Concentrations and Test Cell Flow Rates; Shaded Region Indicates Fines Plugging the Flow System Filters

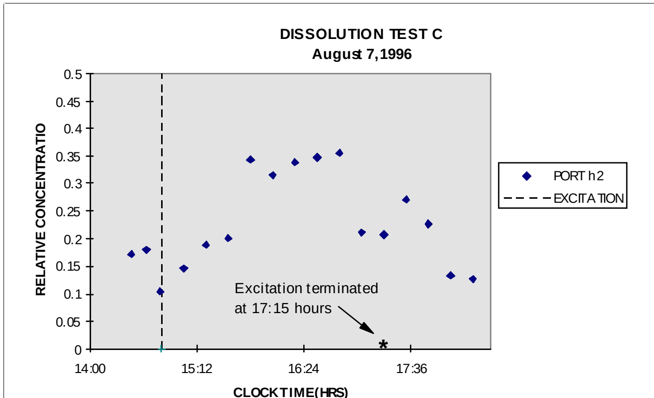


Figure 14. Dissolution Test Results Showing a Two-Fold Increase in P-Xylene Concentration With Acoustic Excitation

It is expected that significantly higher excited aqueous concentrations can be obtained under stronger acoustical intensity conditions.

Vadose Zone Dissolution Test

A simulated vadose zone soil vapor extraction dissolution experiment was conducted. Preliminary interpretation of the baseline and excited vapor concentration data indicate that the data were extremely noisy and no definitive conclusion can be drawn from this test.

Acoustic Modeling and Engineering Analysis

Three-dimensional modeling of phase-tuned focused source arrays was conducted to evaluate performance for typical contaminated sites. The model consisted of a half space with average acoustic velocity of 1,800 m/s and average density of 1.8 gm/cm^3. The acoustic intensity (as opposed to amplitude) reflection coefficient at the surface was taken as 1.0. These model parameters would be typical for near surface soils. A second, imperfect reflector boundary (with an acoustic intensity reflection coefficient of 0.2) was taken at a depth of 12 m. The acoustic intensity map for an array consisting of 6 x 10 kW sources located at a depth of 10 m on the perimeter of a 15 m radius circle with an acoustical focus at the center, was estimated for an observation plane at a depth of 5 m. The models were run for attenuation coefficients of 0, 0.2, 1.0 and 10 db/m.

These attenuation factors are in the range observed for ground water and vadose zone conditions, however, signal attenuation is frequency dependent. Limited data is available in the literature on signal attenuation in the low frequency range. At DOE's Savannah River Site (SRS), the ground water and vadose zone attenuation factors, experienced with signal frequencies in the range of 3 to 5 kHz, are ~ 0.1 db/m and 10 db/m, respectively (E. Majer, person. commun., 1996). At the Lawrence Livermore National Laboratory (LLNL) Dynamic Underground Stripping Program, Dr. Majer obtained signal attenuation data in the LLNL vadose zone, while using source frequencies on the order of 500 Hz, which suggested much lower than attenuation factors than those observed at SRS. At the time of this writing, Dr. Majer was reviewing the data to quantify the LLNL vadose zone attenuation factors. Similar observations have been reported in Johnston (1981). At the time of this writing, the attenuation factor for vadose zone conditions at frequencies less than 100 Hz is not known. For the purposes of this current work, an attenuation factor of 1 db/m for vadose zone conditions will be used.

Figure 15 shows the resulting acoustic intensity for 0.2 db/m attenuation, comparable to the SRS observed saturated zone attenuation. The maximum acoustic intensity of ~ 160+ W/m^2 induced at the focus point (or hot spot) is close to that above the six sources. Based on our Phase I results, this should be sufficient intensity to affect the soil hydraulic conductivity and contaminant mobility. Note that in Phase II dissolution tests, the aqueous concentration of the NAPL was doubled during excitation under an acoustical excitation of ~ 1 W/m^2. The beam steering results in Phase II indicate that the hot spot can be swept throughout the target area to be remediated.

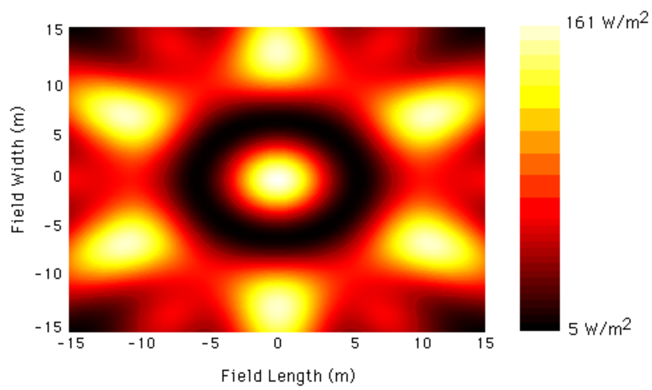


Figure 15. Acoustic Intensity Verus Location Produced 6x10 kW sources that CoherentlySum for a Maximima at the Center of the Array in domain of 30m x 30m; Attenuation Factor for this AER Simulaton is 0.2 db/m Comparable to a Ground Water Hydrogeologic Condition

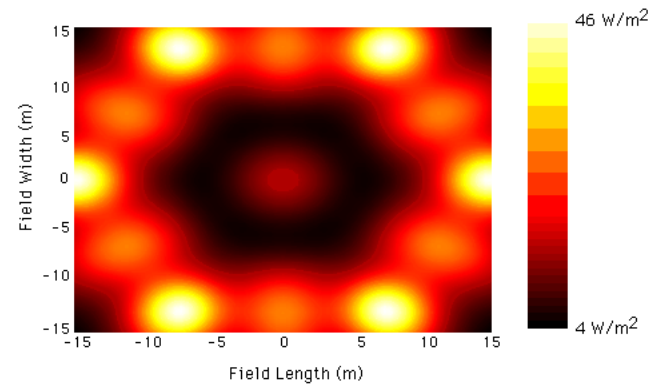


Figure 16. Acoustic Intensity Verus Location Produced 6x10 kW sources that CoherentlySum for a Maximima at the Center of the Array in domain of 30m x 30m; Attenuation Factor for this AER Simulaton is 1.0 db/m Comparable to a Ground Water Hydrogeologic Condition

Figure 16 shows the results for the 1 db/m attenuation factor case considered representative of vadose zone conditions under AER at the time of this writing. In this case, the maximum intensity of ~ 25 W/m^2 at the focus point is observed with six sources. This intensity is on the low-side of the Phase I conditions but much greater than conditions measured during Phase II. At the time of this writing, optimization modeling is being conducted to determine the optimal conditions for AER in the vadose zone. Factors being considered are acoustic source power level, distances of the sources from the center of the contaminant spill and deployment strategies.

An engineering system analysis for phase-tuned acoustic source arrays suggests that there is some total number of sources, above which instabilities in source phase and frequency locks will reduce the maximum acoustic intensity, faster than the effects of adding additional sources. This array source number will be source type specific and depend upon the ability to control the specific source type phase and frequency.

As part of the Phase II effort, we have investigated potential acoustic source types which may be applicable for AER. These include commercially available surface vibrators, such as Vibroseis™ sources; down hole acoustic sources currently under development and/or in limited supply; such as high power piezoelectric, magnetostrictive, hydraulic and mechanical vibrator sources; and concept sources, such as combustion, steam, and/or fluid resonator sources. Final source selection will be completed in Phase III.

Field Applicability of AER

The acoustic signal intensity losses observed during Phase II testing between tests in water filled and water saturated soil filled two-dimensional Test Cells is comparable to those described by Anderson and Hampton (1980), Dunn (1986) and Knight and Nolen-Hoeksema (1990). They are also comparable to the observations of Dr. Majer at the Oregon Graduate Center, cited above.

All of the above referenced discussions described laboratory conditions which are not representative of in-situ conditions. The conclusion to be drawn from this is that acoustic measurements in soils containing water just do not scale up from small-scale laboratory measurements or down from field measurements to the large-scale two-dimensional Test Cell tanks, used for Phase II, or to large three-dimensional test cells, like those at the Oregon Graduate Center.

LBNL has also provided the current study with field data from SRS and LLNL which have bearing on the AER attenuation issue. At SRS, there was minor acoustic source attenuation below the water table; but vadose zone acoustic signal attenuation was significant at the high frequencies (3 - 5 kHz). There is some evidence from vadose zone testing conducted at LLNL that signal frequencies in the 500 Hz range would not suffer the significant signal attenuation, ~ 10 db/m, observed during vadose zone testing at SRS at the kHz frequency range. Vadose zone AER deployment strategies are being evaluated at the time of this writing.

Applications

The Phase II investigation has shown that AER technology can be deployed in the field using a phase-tuned source array strategy. The two-dimensional laboratory experiments conducted did not provide the expected data on the flow and transport of DNAPL under baseline and excited conditions. The only useful flow and transport data acquired during the contaminated test cell experiments indicate that excited aqueous concentrations increased by two-fold under a very weak acoustical intensity field. It appears that Phase I one-dimensional bench-scale laboratory tests are better suited to obtaining flow and transport behavior, than the Phase II two-dimensional large scale tank tests.

Data generated in Phase II support the Phase I conclusion that AER is an enabling technology with the potential of greatly increasing the effectiveness of existing NAPL remediation methodologies such as ground water pump and treat, and emerging technologies such as surfactant flooding. These results indicate that AER has the potential of providing a faster, better, and cheaper remediation.

AER is important contribution to environmental remediation because the extraction of (1) NAPL from both permeable and low permeability soils, and (2) dissolved contaminants from low permeability soils is very difficult and costly at best with current and emerging technologies. Very few technologies exist that can cost-effectively and efficiently increase the contaminant recovery rates from the subsurface. Bioremediation may greatly assist a certain class of contaminants but there is no current bioremediation technology for NAPL contamination and/or low permeability soils. Examples of NAPL emerging technologies that are either being used or being demonstrated are air sparging, steam injection, and soil heating. Figure 17 compares AER with these three technologies. Additionally, Table 1 presents a summary of the features, advantages, and benefits of AER based upon the cumulative Phase I and Phase II data.

FUTURE ACTIVITIES

Phase III - Large Scale Field Tests is planned to begin in January 1997 and continue for about 16 months. During this phase, acoustical sources along with the required computer adaptive control

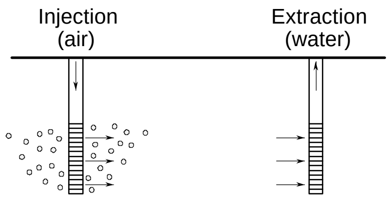
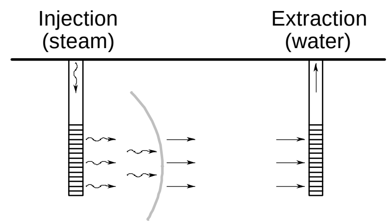
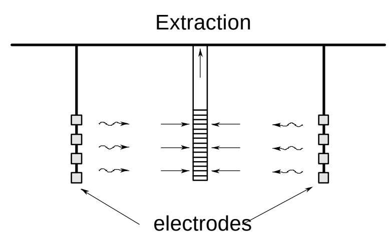
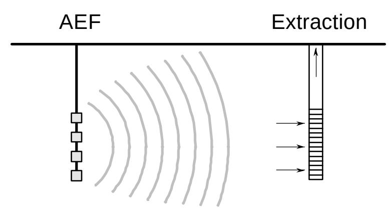
TECHNOLOGY	GRAPHIC DESCRIPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES	RELATIVE COST
Air Sparging		Air is injected into the subsurface and allowed to bubble through the aquifer, carrying volatilized contaminant with it. Air can be heated prior to injection.	Proven technology. Relatively low energy.	Applicable only to volatile or semivolatile compounds. Inappropriate for an inhomogeneous subsurface and for low permeability soils.	Low
Steam Injection		Steam is injected into contaminated soil, forcing volatilization of contaminants. Steam / vapor is then pumped to the surface.	Rapid and highly effective.	Applicable only to volatile or semivolatile compounds. Requires extensive site preparation. Maybe inappropriate for an inhomogeneous subsurface and for low permeability soils.	High
Electric Heating		An electric current is passed through the soil, heating and volatilizing contaminants.	May work well in clayey and dense soils.	Applicable only to volatile or semivolatile compounds. Limited experience to date. Requires complete segregation of the site. Requires high energy input.	High
Acoustically Enhanced Remediation		An Acoustic Excitation Field (AEF) is applied to the soil while water or vapor is pumped to the surface for treatment. Technology is contaminant insensitive, see text.	Applicable to any material which can be transported or dissolved in a fluid phase. It is expected to work well in clayey and dense soils. AER can augment existing remediation methodologies.	Untested technology.	Low to medium

Figure 17. Comparative Analysis of Acoustically Enhanced Remediation With Three Emerging Technologies

Table 1. Acoustically Enhanced Remediation (AER) Technology Features, Advantages, and Benefits

AER TECHNOLOGY FEATURES	TECHNOLOGY ADVANTAGES[1]	BENEFITS TO CUSTOMER
Removes subsurface free-phase liquid contaminants (or non-aqueous phase liquids, NAPLs) either lighter than water NAPL (LNAPL) or denser than water NAPL (DNAPL)	Overcomes the subsurface forces that hold a NAPL within the pore space of an aquifer, allowing the removal of more NAPL faster and to a greater degree than conventional remediation technology.	Allows reaching the clean-up goal faster than conventional technologies such as ground water pump and treat (P&T), reducing the life-cycle cleanup cost.
	Can be deployed over a large volume of the earth.	Can be deployed more cost-effectively than emerging technologies such as steam flooding.
	Can be deployed in combination with existing and emerging remediation technologies.	Existing remediation infrastructure can be augmented rather than totally replaced, providing a considerable savings in time and money.
	Is more cost effective than conventional P&T, our baseline comparative technology.	Site owners can significantly reduce environmental remediation liability cost.
Does not require specification of the DNAPL subsurface location.	Can remediate a large subsurface treatment volume, conservatively approximated by a circle with an estimated diameter of 75 meters, consequently, the specific DNAPL location only needs to be known within ± 30 meters which is much, much smaller than a NAPL source area.	Provides for lower cost on the characterization phase because the number of boreholes, soil samples, analysis, etc., can be significantly reduced.
		Provides a more effective cleanup since the region to be remediated can undergo multiple acoustical excitations.
Remediates low permeability soils	Can increase the permeability of low permeability soils[2].	The water and contaminant flux are significantly increased from low permeability soils making the remediation effort more effective and less costly.
Remediates large volumes of soil	Can effectively treat a region of the subsurface that is approximately estimated at 75 meters in diameter with a single wellfield unit deployment[3]	Remediates a large volume of subsurface material thus reducing life cycle remediation costs.
Achieves cleanup standards	Can allow sites to reach cleanup goals faster and at lower cost[4].	The technology provides both a cost-effective and technically effective remediation methodology to achieve clean-up goals that are currently not achievable with existing technologies.
Enhances remediation of dissolved contaminants	Flushes subsurface contaminated soils more effectively by increasing the water and contaminant flux through the subsurface.	Can reduce remediation cost through extraction of the subsurface contaminants faster and more efficiently.
Augments existing remediation technologies	Can be used in conjunction with most subsurface fluid extraction remediation technologies.	Customer does not have to decommission existing treatment systems to install AER. Instead, it provides faster throughput to the existing treatment system, thus reducing the long-term costs.
Is containment insensitive	Can be used to remediate volatile, semi-volatile, and non-volatile, radionuclides, and metals.	Customer can use one basic technology to remediate many types of contaminants increasing the return on investment.

1 Advantages based on current status of the R&D effort.

2 The problem of low permeability soils has been reported by the National Research Council to be the principle impediment of both conventional and emerging environmental remediation technologies (National Research Council, 1994, Alternatives for Ground Water Cleanup, National Academy press, 315 pp).

3 Standard wellfield deployment is a "spot-pattern" with either 3-, 5- or 7- acoustic excitation boreholes/wells with a central extraction well. The number of acoustic excitation boreholes/wells is a function of the contaminant distribution, volume to be treated, and the geologic setting.

4 This is achieved by coupling acoustic remediation and pump and treat technology with other existing or emerging technologies such as surfactant flooding

systems will be developed, and field pilot scale treatability tests are planned for third and fourth quarter 1997. A clean site "proof-of-concept" test will be conducted along with potential 4 contaminated site tests a DNAPL acoustically enhanced soil vapor extraction test in low permeability soils and in moderate permeability soils, and a DNAPL acoustically enhanced ground water extraction test in low permeability and in high permeability soils.

Stakeholders consisting of local communities groups, U.S. Environmental Protection Agency, state and local regulatory agencies will be incorporated in the planning and execution of these field tests.

Acknowledgments

We thank our COR, Karl-Heinz Frohne, for keeping our feet to the fire and focusing our attention on the critical issues. We also wish to thank DOE and METC for the ROA program which has allowed this research effort to move forward.

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