FIELD DEMONSTRATION OF IN-SITU AIR STRIPPING USING HORIZONTAL WELLS*

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ABSTRACT

Under sponsorship from the U.S. Department of Energy, technical personnel from the Savannah River Laboratory and other DOE laboratories, universities and private industry have completed a full scale demonstration of environmental remediation using horizontal wells. The 139 day long test was designed to remove volatile chlorinated solvents from the subsurface using two horizontal wells. One well, approximately 90m long and 45m deep drilled below a contaminant plume in the groundwater, was used to inject air and strip the contaminants from the groundwater. A second horizontal well, approximately 50m long and 20m deep in the vadose zone, was used to extract residual contamination in the vadose zone along with the material purged from the groundwater. The test successfully removed approximately 7250 kg of contaminants. A large amount of characterization and monitoring data was collected to aid in interpretation of the test and to provide the information needed for future environmental restorations that employ directionally drilled wells as extraction or delivery systems.

INTRODUCTION AND SUMMARY

Remediation of soils and groundwater contaminated with organic and inorganic contaminants is an important objective of the Savannah River Site (SRS - Fig. 1) environmental restoration efforts. A wide range of technologies are available and emerging technologies are being developed and demonstrated to remediate contaminated subsurface materials. The goal is to provide a wide range of "tools" for this work. Development of a diverse and robust "toolkit" of technologies is the best path toward efficient environmental restoration that provides maximum protection of health and ecology at a minimum cost. Various extraction and in-situ remediations are currently being developed. Recently, applications of directional drilling technologies developed in the oil industry have been identified as a potentially important "tool" to allow improved access to the subsurface for all types of remediations.

Normally, extraction of contaminants or addition of reactants for remediation must be performed through vertical wells or boreholes. Directional drilling, including horizontal wells, offers a new and promising means to optimize these operations. Just as horizontal wells have improved the performance of oil recovery systems, they may similarly improve the performance of in-situ remediation, contaminant extraction, or monitoring technologies for environmental restoration. The geometry of horizontal wells conforms to typical subsurface systems, relatively thin but laterally extensive zones. Horizontal wells can be installed to remediate beneath buildings and waste sites, to remediate linear sources of contamination such as pipelines or streams, to prevent the spread of the edge of a plume, or to introduce reactants (e.g., for bioremediation). A variety of competing directional drilling methods have been developed. Each of these represents a possible new approach to installing delivery/removal systems to improve environmental restoration.

The first application of horizontal wells for environmental restoration is the In-Situ Air Stripping test at SRS. For this test, two wells were installed (Fig. 2). One well, below an area of contaminated groundwater, was be used to purge volatile chlorinated solvents from the groundwater by injection of air. The second well, was installed in the vadose zone beneath the location of an abandoned process sewer line that was known to have leaked chlorinated solvents; this well was used to remove solvent that has not reached the groundwater and to collect solvent stripped by the purge well. In-Situ Air Stripping has the potential to significantly reduce clean up time when compared to standard groundwater pumping followed by air stripping in an above ground tower. The demonstration site has been carefully characterized and monitored using surface and borehole geophysics, cross hole geophysical tomography, chemical analysis of soil, soil gas and groundwater, microbial characterization of soil and water, and pressure monitoring in all affected areas. Additionally, each of the horizontal wells has been fitted with a bundle of tubes that allow pressure/concentration measurements at various points along the well bore. The data that result from all of these tests will improve the technical basis for design of future directional drilling applications.

The 139 days of field operation at the demonstration site were successful; the operational and data collection goals identified at the beginning of the demonstration were met. We operated at approximately 90% utility and ex-

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Fig. 1. Location of the Savannah River Site in South Carolina.

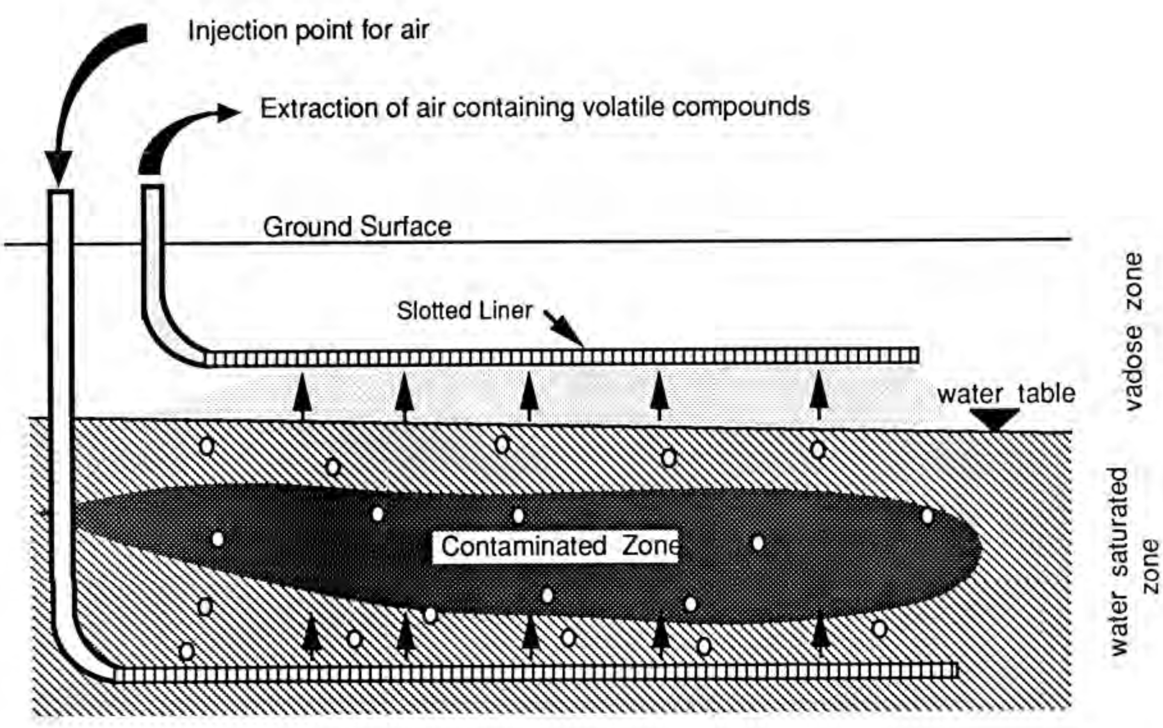

Fig. 2. Schematic Diagram of In-Situ Air Stripping Process.

The 139 days of field operation at the demonstration site were successful; the operational and data collection goals identified at the beginning of the demonstration were met. We operated at approximately 90% utility and extracted 45 to 60 kg of VOC from the subsurface each day. A total of almost 7250 kg of chlorinated solvents were removed from the subsurface during the test. Pressure and concentration data from the bundle tubes and vadose zone piezometers provide valuable data for future projects of this nature. These data, combined with the helium tracer test data, provide information on the types and importance of various heterogeneities in this typical natural system. Both low permeability and high permeability zones influenced the performance of the system. The importance of these zones to mass transfer in subsurface remediations (both in situ and extractive methods) will be evaluated using the collected data. Initial data from Sandia National Laboratory (SNL) and Lawrence Livermore National Laboratory (LLNL) suggest that the seismic and electrical tomography methods and the single point flow sensors will be able to distinguish changes in moisture and fluid flow in the subsurface caused by the extraction/injection.

Synopsis of Test

The following list is a synopsis of the activities at the site (unless otherwise noted, vadose zone pressure readings, extraction/injection well pressure and temperature readings, and extraction well concentrations were determined at least three times per day; groundwater, vadose zone piezometer and bundle tube concentrations were measured approximately weekly). Times are provided both in terms of date and elapsed time from startup to facilitate interpretation of the data provided later in the report. Collection of water samples continued following completion of the active demonstration phase in December.

Synopsis/Highlights of In Situ Air Stripping Test:

July 27 - Day 1 - Begin Test - Vacuum Extraction through horizontal extraction well (AMH2) at 16.4 standard cubic meters per minute (scmm).

August 11 - Day 16 -Air Injection through horizontal purge well (AMH1) initiated at low rate (1.8 scmm)

August 23 - Day 28 - Air injection rate increased to medium rate (4.8 scmm)

September 13 - Day 49 - Heating of injected air to approximately 64 degrees Centigrade initiated.

October 3 - Day 69 - Air injection rate increased to high rate (7.5 scmm).

November 16 - Day 113 - Air Injection portion of the test completed - Injection stopped and compressor demobilized

December 13 - Day 140 - Vacuum Extraction portion of the test completed - extraction stopped and vacuum blower demobilized

SYSTEM PERFORMANCE

Horizontal Vacuum Extraction Well Concentration and Pressure Data

The flow and vacuum conditions at the vacuum extraction well remained relatively constant throughout the test. The flow (measured by a calibrated pitot tube) generally ranged from 15.6 to 17.0 scmm. The vacuum at the wellhead stabilized at approximately 25 to 27 cm Hg. The temperature of the extracted gas was relatively constant at approximately 15 degrees Centigrade. The heating of the injection air had no measurable effect on the temperature of the gas extracted from AMH2.

The concentration and temperature of the contaminated vapors extracted from the horizontal vacuum extraction well (AMH-2) were measured approximately three times per day (more frequently at each change in operating parameters). As shown in Fig. 3, the total concentration of chlorinated solvents decreased rapidly during the first 2 days of operation and stabilized after approximately 3 days. Initial concentrations were as high as 5000 ppm (volume/volume) in the gas and the total concentration stabilized at approximately 300 to 400 ppm. This concentration represents an extraction rate of approximately 100 to 140 pounds of solvent per day. The average extraction rate for each of the injection/extraction conditions (e.g., vacuum only, vacuum plus low injection rate, etc.) was calculated and resulting data are plotted vs injection rate in Fig. 4. The vacuum extraction process removed contaminants at a rate of about 50 kg/day; injection of air at the medium and high injection rates appear to result in the stripping/removal of an additional 9 kg of solvents per day from the groundwater and the vadose zone below the extraction well. The cumulative VOC removal is summarized in Fig. 5. Almost 7250 kg of contaminant were removed from the vadose zone and groundwater at the demonstration site during the short testing period.

The concentration and vacuum data from the bundle tubes in the horizontal vacuum extraction well (AMH-2) indicate that, while operating, AMH-2 appears to draw water from the vadose zone in a manner similar to a suction lysimeter. Since the well dips to its lowest elevation at the terminal end, the final sampling position (at 67 m from top of casing) appears to be covered by water and the sampling position at 56 m may be covered by water periodically. These two sample tubes were more variable than the first four and the vacuum level becomes lower over time at these positions. Nonetheless, the vacuum data suggest that the entry of air into the screen occurs over much of the horizontal section and that heterogeneity in the system results in

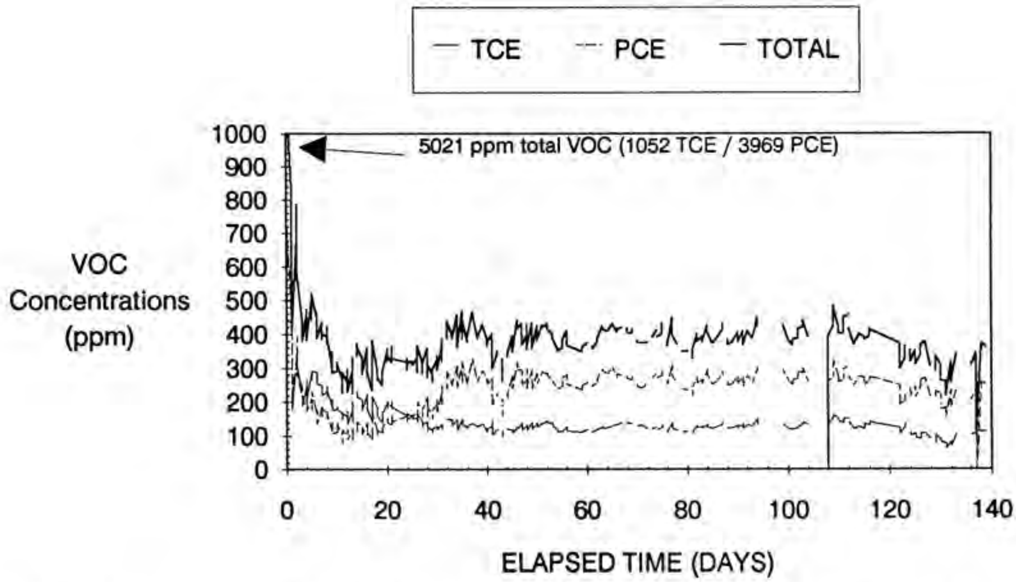

Fig. 3. Concentration of Chlorinated Solvents in the Air Extracted from Horizontal Well AMH-2.

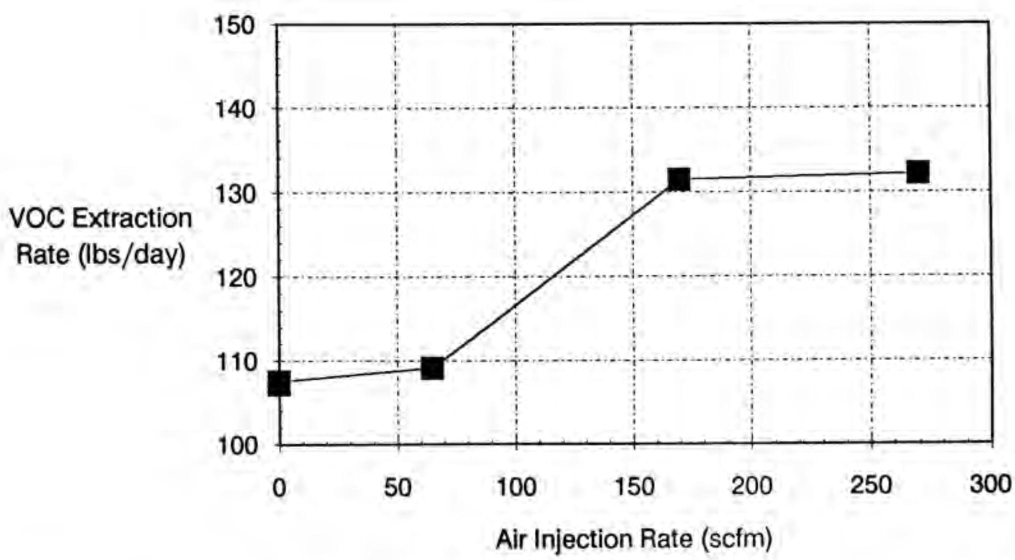

Fig. 4. Average VOC Extraction Rate as a Function of Air Injection Rate (metric conversions: 1 kg = 2.2 pounds, 1 cubic meter = 35.3 cubic feet).

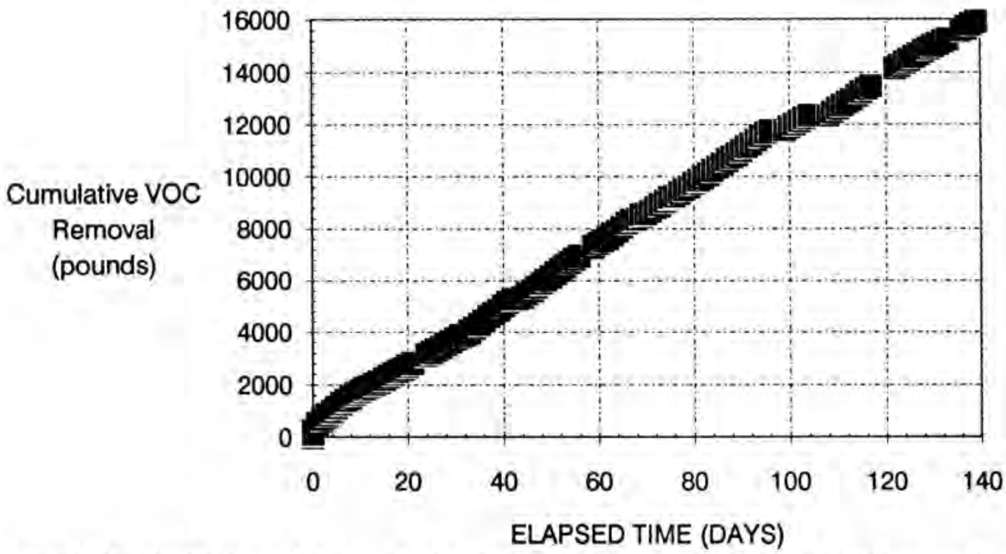

Fig. 5. Cumulative VOC removal during the in situ air stripping demonstration (metric conversion: 1 kg = 2.2 pounds.

more air entering in some segments of the well (e.g., 19 to 31 m) than in others (e.g., 31 to 44 m). Note that the vadose zone piezometers near the end of AMH-2 have significant drawdowns - suggesting that the water covering the bundle tubes does not completely fill the wellbore (i.e., air is entering all the way to the end of the well). The bundle tube concentration data support the conclusions from the pressure data. Water covering the final two sampling tubes precludes contaminated air from entering these tubes for sampling. Variations in concentration along the well are a measure of the concentrations of VOCs entering the well and of the amount of air entering the well. The concentrations are relatively stable in the bundle tubes closest to the wellhead; these sampling points represent a composite of the entire well screen. Transient behavior of the vacuum levels in the AMH2 bundle tubes (e.g., after the system was down or after a large rain event) also supported the above interpretation. The vacuum levels in the last two tubes were highest when the system was restarted after being off (i.e., no water in the wellbore) and the vacuum levels declined with time as water was drawn into the well following startup.

Vadose Zone Piezometer Data

The pressure in the piezometers respond rapidly to the vacuum system and were relatively stable throughout the test. Vacuum levels of several cm of water or greater are measured in all of the vadose zone piezometer clusters indicating that the zone of capture in the vadose zone extends across the entire demonstration site and that contaminants are not being spread in this zone. These data will be interpreted in detail in future publications, however, a few observations are listed below. Concentration vs time plots in the vadose zone gases varied greatly over the demonstration site as contaminated vapors were swept from the system and purge gases entered from below. For example, MHV1A (the lowest tube in one of the vadose zone clusters) exhibited an increase in concentration following the initiation of the medium injection rate. The concentrations in the zone monitored by this tube stabilized after a short time and appeared to decrease following completion of the injection activities. The zone monitored by this tube is between the water table and a clayey zone and is separated from the extraction well by clays. This zone appears to respond to the injection process as the gas migrates up to the extraction well through discontinuities in the clays of the vadose zone. The piezometer tubes that monitor the sandy zone in which the vacuum extraction well is completed yielded concentrations that were more constant. These data are consistent with the observed heterogeneity and dispersion of injected gases observed in the helium tracer test discussed later.

Groundwater Data

Groundwater samples for VOCs have been collected approximately weekly during the demonstration. Samples for microorganisms and biochemical markers have been collected every two weeks. A base map of the wells used in the plots is shown in Fig. 6. Sampling the wells takes approximately 2 to three days; each of the maps is labeled using the elapsed time from the start of the test to the first day of sampling. The time periods and operational conditions at each time are summarized in the figure captions. One map was selected to represent each operational condition for this report.

Figures 7 through 10 show the groundwater concentrations for trichloroethylene at each of the selected times.

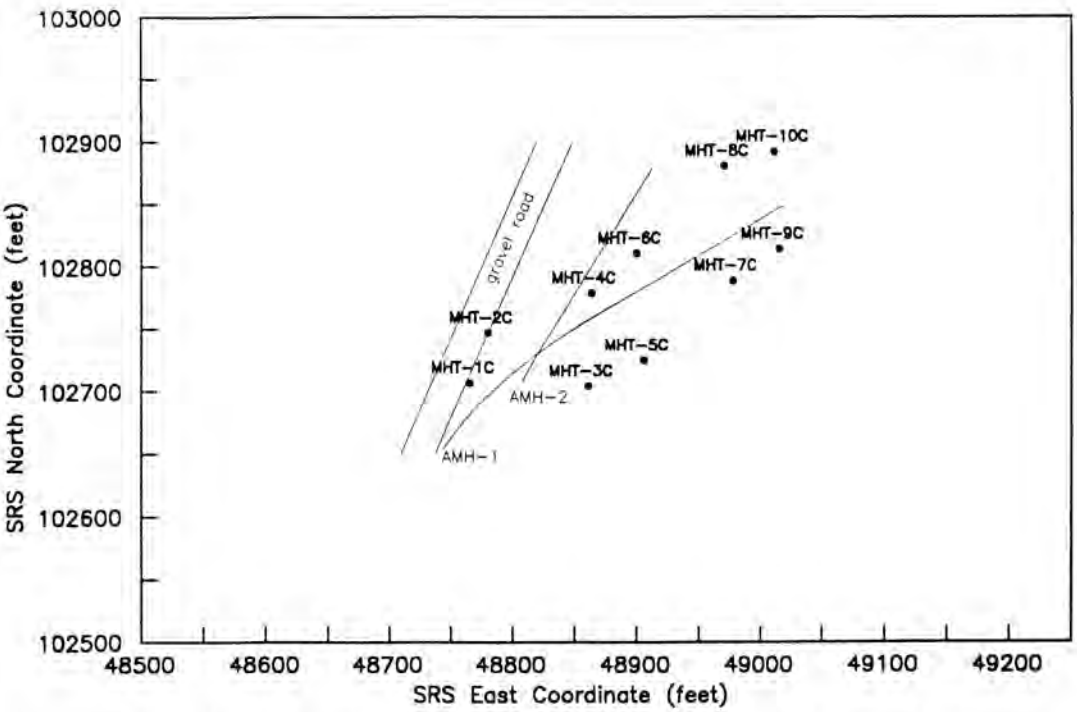

Fig. 6. Base map of groundwater wells contoured during in situ air stripping test.

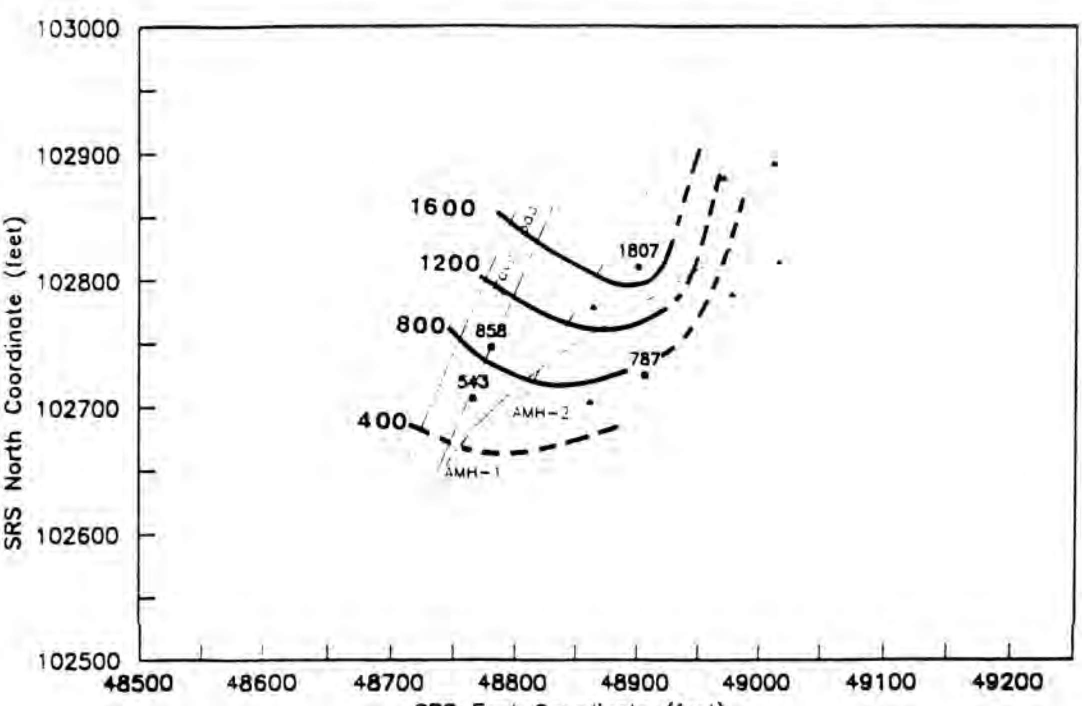

Fig.7. Trichloroethylene concentrations (ug/L) at the in situ air stripping demonstration site (Day 11-initial conditions/vacuum only).

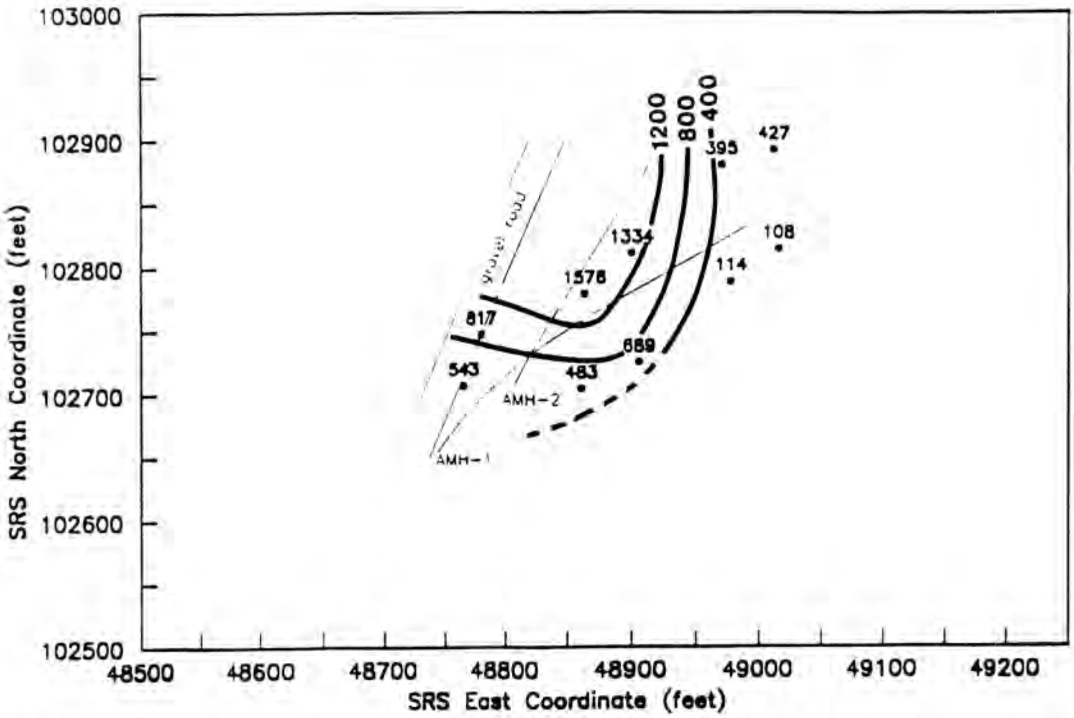

Fig. 8. Trichloroethylene concentrations (ug/L) at the in situ air stripping demonstration site (day 28-end of low air injection rate).

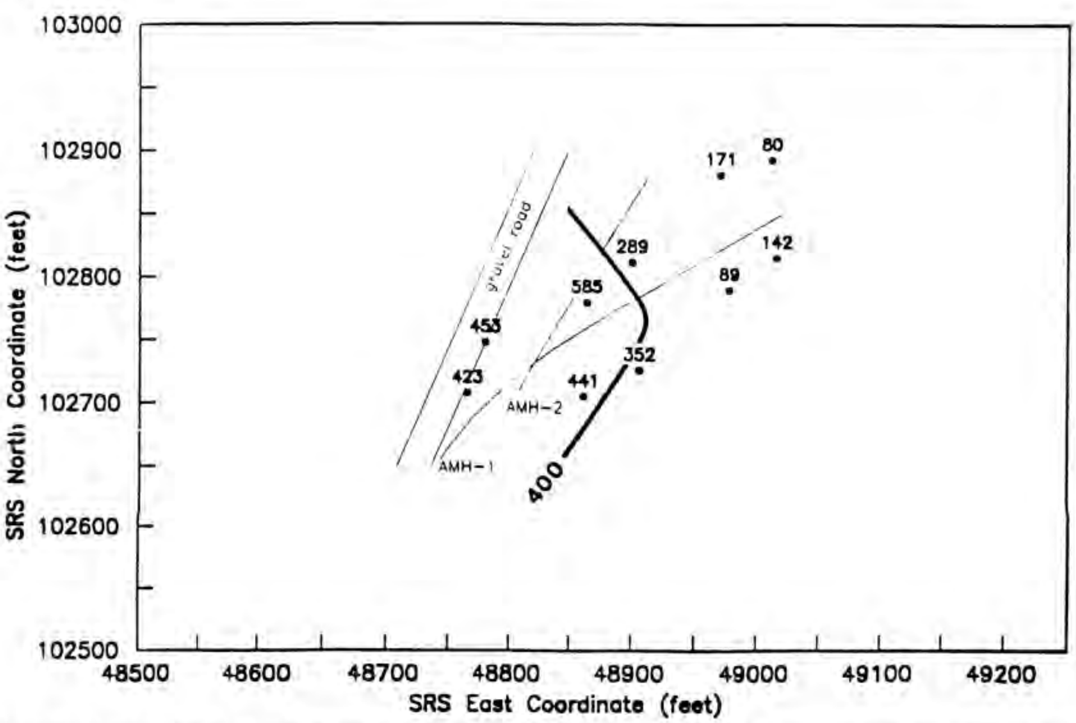

Fig. 9. Trichloroethylene concentrations (ug/L) at the in situ air stripping demonstration site (day 39-medium injection rate for 11 days).

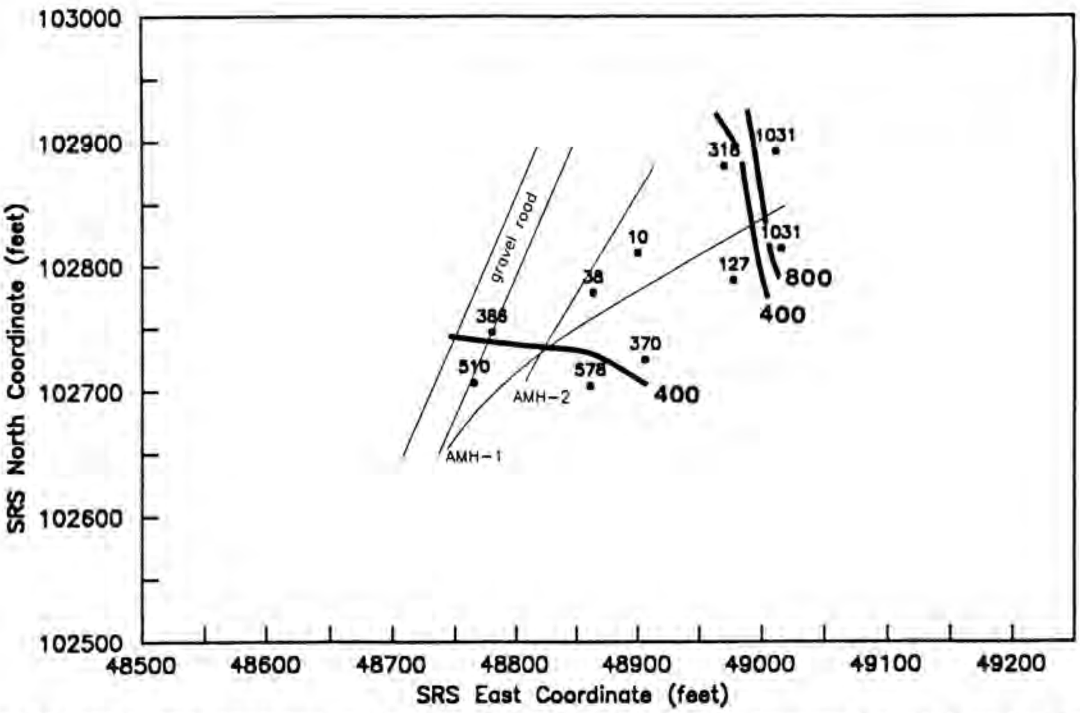

Fig. 10. Trichloroethylene concentrations (ug/L) at the in situ air stripping demonstration site (day 144-final conditions).

These time series data, combined with other data, provide valuable information about the performance of the demonstration. The plume maps clearly indicate that the air injection is impacting the groundwater. In particular, comparison of the initial conditions to the "final" conditions shows a significant overall improvement in water quality for both trichloroethylene and tetrachloroethylene. Trichloroethylene concentrations ranged from 500 μg/L to 1800 μg/L at the beginning of the test and from 10 to 1031 μg/L at the end of the test. Similarly, tetrachloroethylene ranged from 85 μg/L to 184 μg/L at the beginning of the test and from 3 to 124 μg/L at the end of the test. Concentrations in almost all wells declined between day 28 and 39 (following initiation of injection at the medium rate). This reduction is assumed to represent the purging of the in-situ air stripping process.

Examination of the later time periods reveals the appearance of a high concentration area in the southern and distal portions of the site (near the end of the injection well). While the area of increased concentration is near the edge of the demonstration site, it does not appear to result from lateral spreading of the contaminants (lateral spreading of the plume would have yielded a transitional map for day 39 rather than the relatively low concentrations at all monitoring points). Two hypotheses are currently being examined to determine the cause of the concentration increases: 1) upward migration of contaminants caused by the injection of air below the monitoring well screen, or 2) slight pressurization of the vadose zone between the water table and a zone of clays resulting in downward migration from the water table to the depth of the screen being measured. The microbiological measurements indicated that microrganism counts increased by two to three orders of magnitude in the groundwater sampled during the injection test.

Tracer Tests

A test using an inert tracer (helium) to determine the behavior of the injected gas was performed. The test consisted of adding 3 standard cylinders of helium to the injected air over a 24 hour period using a regulator and flow meter. All of the identifiable potential exit points for gas to leave the system were sampled to determine if: 1) the injected air is reaching the extraction well and 2) significant quantities of helium are being forced out of the system through monitoring wells. Since flow of injected air had been qualitatively noted by field sampling personnel, all 20 monitoring wells and the geophysical access holes that extended below the water table were monitored. Samples were collected using a 50 mL disposable syringe and the samples were placed in 30 mL preevacuated serum vials. These vials were analyzed using a helium mass spectrometer that has been modified to sample the serum vials at a constant rate. The mass spectrometer was calibrated in two steps. First, the mass spectrometer is tuned and the sensitivity adjusted to an internal calibrated leak (diffusion) standard in units of standard mL of He per second; after this step, gas standards prepared in the serum vials are used to convert the instrument reading to ppm (volume) and check the stability of the tuning. The results of the test are listed below:

- Elevated helium concentrations were measured in the horizontal vacuum extraction well (AMH2), confirming "communication" between the wells. The maximum concentration in AMH2 was approximately 30 ppm, significantly lower than the maximum injected concentration of approximately 1800 ppm. Additionally, the helium peak in the gas from AMH2 was much broader than the 24 hour injection (helium was still exiting AMH2 at the end of the test period). These observations suggest that the gas traveling between the two wells is dispersed as it flows through the several clayey/fine grained zones between the wells. At the end of the reporting test, approximately 45 percent of the injected helium had been extracted from AMH2.
- Elevated helium concentrations have been measured in all 10 water table wells indicating that the dry screen above the water table represents a pathway for the injected gas to flow. In two cases, MHT1D and MHT6D, the arrival times were very rapid (hours) and the concentrations were almost the same as the injected air indicating that the gas exiting these two wells was traveling through relatively high permeability flow paths. The volumetric flow rate was measured for the gas exiting these well heads to allow helium mass balance calculations. Despite the high concentrations and measurable flow, these wells account for loss of under 0.5 percent of the injected gas. No flow was measurable at any of the other water table wells.
- Elevated helium concentrations were measured in 6 of the 10 wells completed in the air injection zone (~150-155 feet deep). This suggests that some injected gas is entering the screens and exiting at the wellheads. No volumetric flows could be measured at any of the injection zone wells. Thus, these wells do not represent a significant component in the helium/injected gas mass balance.

In summary, the data confirm the fact that the subsurface at the test site contains high permeability and low permeability heterogeneities (typical of natural systems). Nonetheless, there is communication between the injection well (AMH1) and the extraction well (AMH2). AMH2 represents the largest component of the mass balance.

Related Tests/Reports

No geophysical reports have been written to date, however, contact with LLNL indicates that the electrical cross hole tomography has successfully mapped the moisture changes in the subsurface as the test conditions have been modified. Also, the Sandia National Laboratory single location 3D flow sensor responded rapidly to changes in injection conditions. Reports on these tests will be prepared in 1991.