DYNAMIC UNDERGROUND STRIPPING PROJECT

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ABSTRACT

LLNL is collaborating with the UC Berkeley College of Engineering to develop and demonstrate a system of thermal remediation and underground imaging techniques for use in rapid cleanup of localized underground spills. Called "Dynamic Stripping" to reflect the rapid and controllable nature of the process, it will combine steam injection, direct electrical heating, and tomographic geophysical imaging in a cleanup of the LLNL gasoline spill. In the first 8 months of the project, a Clean Site engineering test was conducted to prove the field application of the techniques before moving to the contaminated site in FY 92.

INTRODUCTION

Concentrated underground organic contaminant plumes are one of the most prevalent ground water contamination sources. A typical source of a concentrated plume is a leaking underground storage tank. When the stored liquid escapes from the tank slowly, it can take years for the operator to become aware of the problem. By that time the solvent or fuel can percolate deep into the earth, often into water-bearing regions. Collecting as a separate, liquid organic phase called Non Aqueous Phase Liquids (NAPLs), these contaminants provide a source term that continuously compromises surrounding ground water. This type of spill one is of the most difficult environmental problems to remediate. Attempts to remove such material by pumping the ground water have been likened to cleaning a soapy sponge by repeated rinsing; a huge amount of water must be washed through the system to clean it, requiring tens of years. Pumping at some sites for many hears has resulted in clean effluent water, but when the pumps where shut off and restarted several years later, the ground water was again contaminated.

APPROACH

Dynamic Underground Stripping was conceived as a technique to use large amounts of added energy to speed the contaminant removal process. Because it is a highly energetic process, we identified real-time monitoring of the progress as a necessity both for process control and to ensure that contaminants were not inadvertently mobilized or moved to unanticipated areas. This need for real-time monitoring yields a further benefit; because it is possible to provide actual images of the underground processes, it is possible to identify which underground regions have been affected by the process and which have not.

Many methods have been proposed for underground heating. Our approach was to seek complementary methods that would systematically and efficiently heat large blocks of earth, on the order of 50 yards on a side, while providing controlled removal of the contaminant and associated ground water. The principal technology for accomplishing this is steam injection coupled with vacuum extraction Developed at the UC Berkeley College of Engineering, this technique provides an efficient way to heat the ground, as well as a controllable sweeping mechanism to move and extract contaminants. Laboratory experiments have shown the efficient removal of a number of solvents and fuels (Udell and Stewart, 1989, 1990). Small scale field testing by Berkeley showed, however, that steam did not penetrate clay layers well and that an additional mechanism was required to dry and clean the impermeable layers that are common in the soils of the Western United States.

After considering a number of options for heating clay layers, we determined that the most efficient and controllable method over the fairly large scales of interest to Dynamic Stripping was direct electrical resistance heating, using the clay layers themselves as the heating element when large currents are driven through them. This technique targets the clay-rich layers which are not well penetrated by steam injection and should be self limiting; as the clays heat up and dry out, current will stop flowing.

Our application of Dynamic Stripping is shown schematically in Fig. 1. In a typical application, the concentrated plume would be surrounded by injection wells, with one or more extraction wells located in the center. The injection wells would be screened in the more permeable areas, and in less permeable areas the well would be completed for electrical current (conductive packing material and a stainless steel electrode). Remediation would begin with pumping of the extraction wells to depress the water table in the center of the pattern, followed by steam injection at 50-60 psi. Injection pressure is controlled by depth, and would be lower in shallow applications.

As steam is forced into the formation, the earth is heated to the boiling point of water. The advancing pressure front displaces ground water toward the extraction well. Near the steam-condensate front, organics are distilled into the vapor phase, transported to the steam condensation front, and condensed there. The advancing steam zone displaces the condensed liquids toward the recovery well where they are pumped to the surface. The amount of heat required to bring the ground to 100°C is the principal control on how much steam must be injected; pressure and steam delivery rate

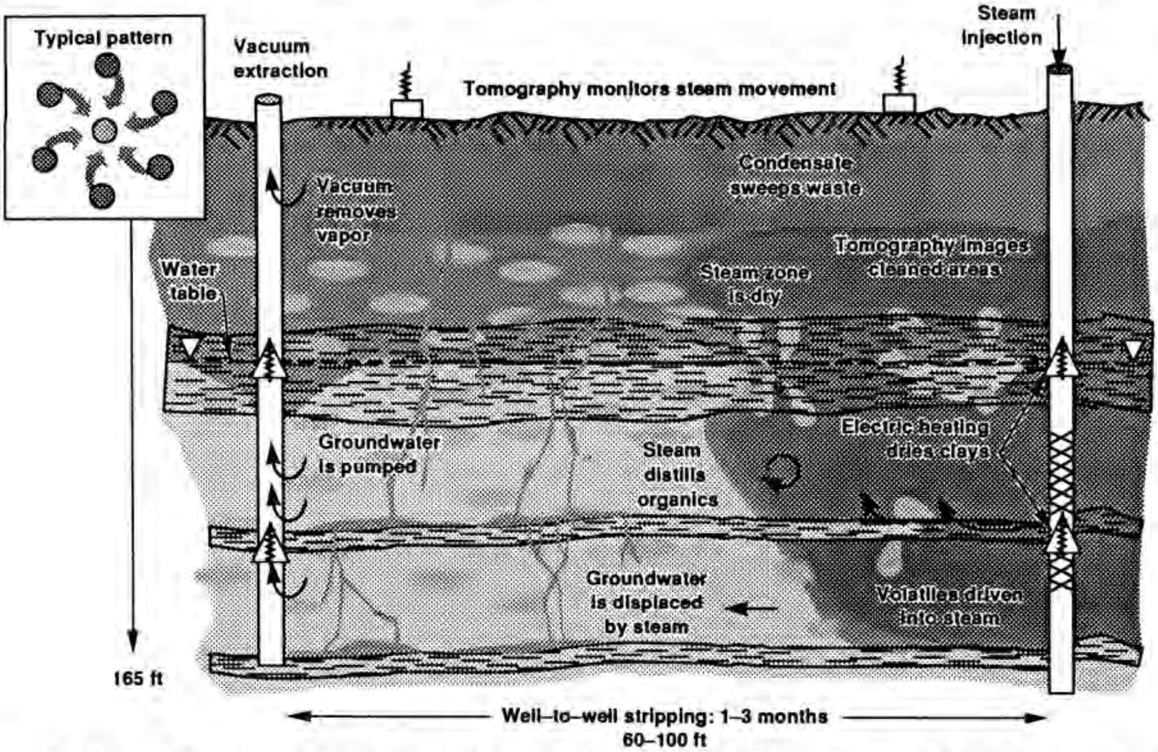

Fig. 1. Schematic view of the dynamic underground stripping process. The containment (ovals and streamers) is displaced toward the extraction well by steam injection and by electrical heating of the impermeable, clay-rich layers (shown by the horizontal line pattern).

affect the rate at which the whole field can be heated and the shape of the advancing steam front.

When the steam reaches the extraction well, vacuum extraction becomes the most important removal mechanism. As steam input stops, a drop in steam zone pressure slightly reduces the boiling point of any residual water or contaminants (such as that held by capillary forces), forcing them to boil and convert to removable vapor. Our work has shown that it is possible to raise the initial ground temperature to >115°C.

At this point in the process not all of the contaminated sediments may have been contacted by steam. Electrode assemblies placed in the impermeable layers are turned on, passing 480V current at several hundred amperes per electrode. This heats the clay and fine-grained sediments and causes water and contaminants trapped within to vaporize and be forced into the steam zones, where the vacuum extraction can remove them. This heating may be followed by one or more additional steam injection phases for contaminant removal, and to keep permeable zones hot as ground water returns. Details of the phasing of steam and electrical heating processes will be established at the LLNL Gasoline Spill Site test; it is not feasible to run them concurrently because of the electrical hazard and the necessity for manned operation of the boiler.

The goal of the combined processes is to achieve a hot, dry, contaminant-free cylinder of earth. This creates a large contrast for geophysical imaging techniques to use in observing the areas that have and have not been heated. Among the methods used are Electrical Resistance Tomography (ERT), seismic tomography, induction tomography, passive seismic monitoring, and temperature and conventional geophysical well logging in dedicated monitoring boreholes.

LLNL GASOLINE SPILL SITE CLEANUP

Site requirements for the first phase of demonstration of dynamic stripping included a relatively well characterized and accessible underground organic contamination. The Livermore site gasoline spill is such a site. This site presents multiple challenges since the non-aqueous phase liquid (gasoline) is both above the water table and dispersed in water-saturated soil (a three-phase system). Approximately 17,000 gallons were spilled, of which about 5,000 gallons is now trapped beneath the water table due to a 30 ft rise in the water table. The remainder is in the vadose zone; a significant amount of the vadose zone contamination has been removed by vacuum venting operations and ongoing natural bioremediation which appears to be enhanced by the oxygen-enrichment of the venting operation. Bioremediation does not appear to be significant in areas of high gasoline concentration or free-phase gasoline.

Evaluations of the LLNL Gasoline Spill Site are contained within the LLNL Remedial Investigation Report, Thorpe, et al. (1990) , and the LLNL Feasibility Study, Isherwood et al., (1990). Effluent treatment will be handled by the LLNL ER program. This task will draw heavily on LLNL's experience in the operation and permitting of similar systems. Vapor phase treatment will first remove steam with a condenser. A catalytic oxidizer will destroy the remaining gasoline vapors. A similar system is now functioning for the ongoing test of vadose zone vapor extraction at the site. Liquid phase treatment initially cools the water and then a separator removes free phase gasoline. This limits the gasoline content in water to 15 mg/L. We anticipate that most of the gasoline will be treated by the separator. An ultraviolet light and peroxide oxidation machine will destroy 99.8% of the gasoline that remains after separation. The final polishing of the liquid stream will be accomplished by air stripping. The cleaned ground water will be discharged along with other treated water from the site, by re-infiltration at an up-gradient site or on-site use at LLNL.

Figures 2 and 3 show lithological and biological characterization results for the LLNL Gasoline Spill Site. The lithology is heterogeneous, with alluvial deposits consisting of interbedded sands, silts, and gravels deposited in a similar environment to that present today. There are several permeable water-producing zones, and contours are shown for benzene in soil corings. Bacterial characterization is being conducted both to evaluate the ongoing natural remediation processes, and as a baseline to determine the effects of dynamic stripping on the existing populations. Bacterial remediation is one method that may interface well with dynamic stripping for the cleanup of distal, low-concentration regions not cleaned by steam or not cleaned to regulatory limits. The bacterial population was evaluated using analysis of individual bacteria by fluorescent microscopy, and enumeration and analysis of cultured strains. At a nearby uncontaminated site viable bacteria ranged from 106 colony-forming-units per gram soil at the surface to 102 at 120 ft, with most of the decrease occurring in the first 20 feet. At the LLNL Gasoline Spill Site the interior of the plume contained much higher microorganism counts at depth (Fig. 2). The population diversity was large at shallow depth, while in several of the deeper zones of high gasoline concentration (up to 2000 ppm) had single species. These bacteria are rapidly degrading gasoline based on laboratory metabolic studies. Low concentration zones had lower total bacteria but greater species diversity.

Current plans call for six injection wells around the periphery of the spill zone. Steam will be injected into permeable zones at and below the water table, while the intervening layers will be electrically heated. Up to three extraction wells will be used to maintain the high ground water removal rates required. The upper vadose zone will be avoided for the present in order to study and make use of the existing gasoline-degrading bacterial cultures in that region. The demonstration at the LLNL Gasoline Spill Site is expected to be completed in FY 92.

CLEAN SITE ENGINEERING TEST

The novel and high-energy nature of the techniques used in this process required that a test of the overall system engineering be conducted at an uncontaminated site that had similar geology to the LLNL Gasoline Spill Site. Sandia National Laboratory, Livermore agreed to allow the use of an open field approximately 400 yds southeast of the LLNL Gasoline Spill Site. The overall lithologic units are similar there, although the water table is slightly deeper (~116' vs ~105'). Because of the alluvial nature of the sediments in this area, only gross correlations of units can be made, but the sites both contain permeable gravel layers interspersed with low-permeability silt and clay layers.

A generalized cross section of the Clean Site Engineering Test ("Clean Site") geology is given in Fig. 3. The fine-grained layer at 100-125' is highly impermeable, while the gravels below, especially from 135-145', are very permeable. This unit has a measured permeability (by pump test) of about 20 darcies. A thin fine-grained layer then separates this gravel layer from another at 160'.

Beginning in February, a total of 23 165'-deep wells were installed at the Clean Site, composed of: 11 temperature and ERT imaging wells with 2" fiberglass casing for temperature logging and electrodes on the outside of the casing for ERT, 3 large diameter monitoring wells with 6" fiberglass casing, for geophysical logging and cross-hole measurements, 2 extraction wells, 3 injection wells, and 4 combined electric heating/piezometer wells for water level measurements (Fig. 4). Ten additional 20' deep wells were drilled at the southern edge of the site for a small scale electrical heating test area.

Every well at the Clean Site functioned as both a characterization well and an operational or monitoring well. This was successfully coordinated by designing the monitoring instrumentation (ERT electrodes, thermocouples, piezometer casing, etc.) for ready installation as soon as characterization was completed. A number of the wells performed multiple monitoring functions. This facilitated the collection of a very high density of information in the monitoring phase with a minor expenditure for construction.

Steam Injection

The first major test at the Clean Site was of steam injection, which began on July 23, 1991. A 10 Million BTU portable, propane-gas-fired boiler was used to inject an average of 8.5 gpm (as water) of 50 psi saturated steam. The final steam injection well (two others were tested) was steel cased with a 20' stainless steel screen from 135-155'. While steam was

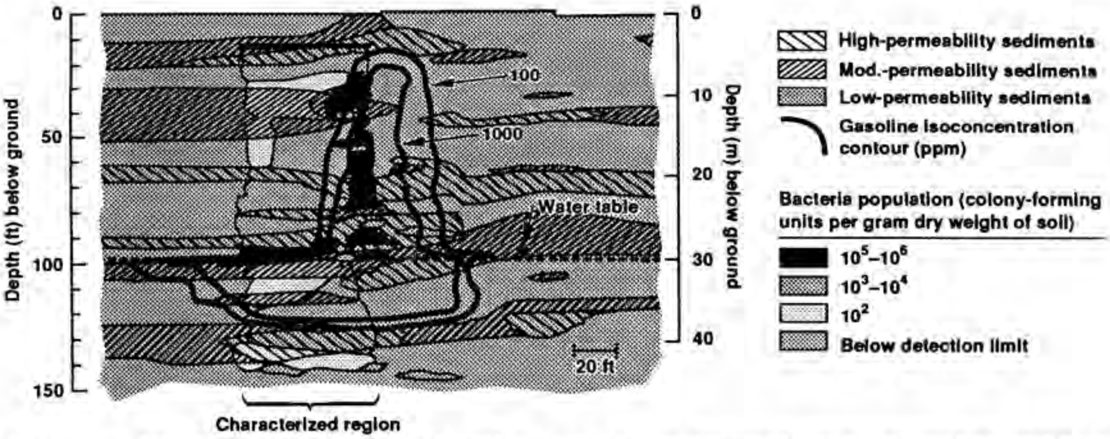

Fig. 2. Characterization of the LLNL Gasoline Spill Site showing lithology, present location of gasoline, and bacterial activity.

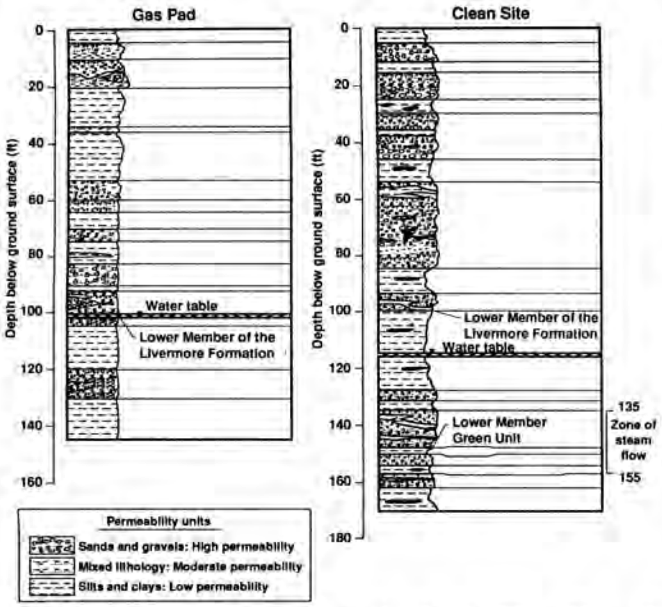

Fig. 3. Generalized stratigraphic section for the Clean Site and Gasoline Spill Site.

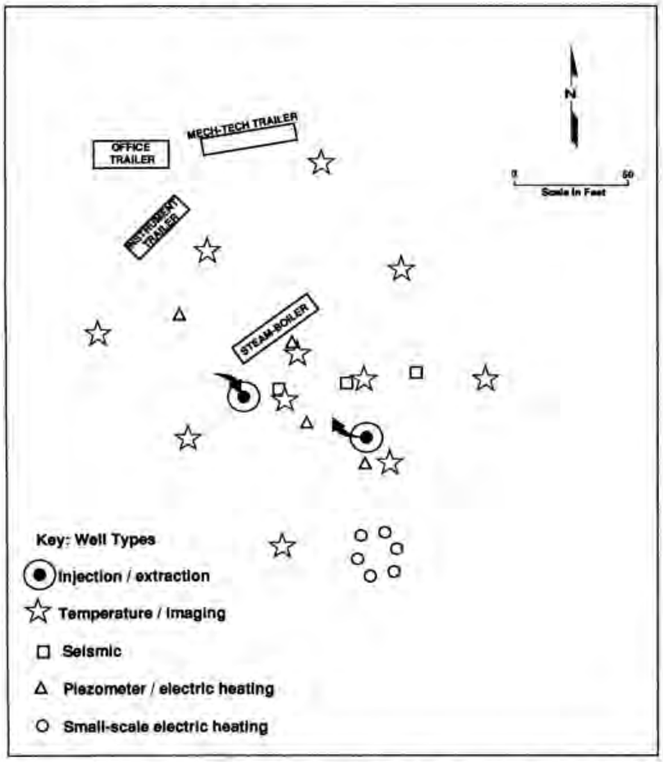

Fig. 4. Well locations and types at the Clean Site Engineering Test.

injected, ground water was extracted at about the same rate from an extraction well 65 feet away. Ground water extraction was terminated 10 days later, while injection was continued for another 14 days to examine the effect of pumping on the directionality of steam movement. A total of 295,000 gallons of water were injected as steam, while 147,000 gallons were extracted.

Steam movement was monitored both by geophysical tomography and by temperature measurements in the monitoring wells. The *latter are considered* to be the "ground truth" in the system, and measurements were made at 1 foot intervals in areas with warm water or steam. These measurements showed that the steam stayed below the 125' fine-grained layer uniformly as it expanded to the southeast from the injection well. At the distal wells steam was seen in the lower gravel section (160') as well as in the 135-145' gravel zone. The *steam* stayed below the water table (~116'), which occurs in a relatively dense, fine-grained clay and silt layer (Fig. 3). The steam front was preceded by a slight rise in the water table surface, such that water levels rose as much as 5 ft in the center of the pattern 1-2 days before steam was noted in the well. Water levels rose a lesser degree in more distal wells (e.g. 0.5 ft at 200 yds distant) when extraction was occurring at the same rate as injection; this rise was controllable by adjusting the pumping rate. Steam never contacted the two temperature monitoring wells northwest of injection well. Initial steam movement was highly oriented toward the extraction well, with the steamed sector slowly opening with time to about a 270° arc. This may have been due to extraction shaping the steam plume, but it appears more likely that it is a function of the shape of the high permeability zone.

Steam reached the extraction well approximately 150 hr after injection began. Noticeable temperature rises had begun about 24 hr before. Since the well was being held under a vacuum of about 15 psi, ground water boiled at about 85°C. This was the observed temperature of the extracted water for the duration of the vacuum extraction phase except during two pulses of higher pumping rate (30 gpm) when the temperature dropped, apparently due to influx of cooler ground water. The ground water pump was an air-displacement type (necessary to avoid emulsifying gasoline at the LLNL Gasoline Spill Site) and after 250 hours of operation, several failures occurred in the reinforced rubber air lines. The failures were attributable to the lines rubbing against sharp objects in the well string as the pulsed air lines filled and deflated. The pump was removed, which allowed another phenomena to occur; because the steam zone was below the water table, the open extraction well geysered every 2 minutes. This effect could be stopped for several hours by putting several hundred gallons of cold water into the well.

Injection was stopped on schedule when steam reached all the distal monitoring wells; however, on the day of planned stoppage the injection rated fell dramatically to several gallons per hour. This may have been due to saturation of the aquifer or some other process. No operational problems were encountered with the injection system or boiler. The boiler was operated using all portable utilities: propane from a tanker was air-mixed to natural gas density, and electric power was from a portable generator. Propane was used to minimize air emissions.

All parts of the injection system were sampled for water chemistry. Samples from condensing pots on the injection well showed a significant sodium signature of the softened boiler feed water, instead of being pure distilled water. This must have been due to entrained water droplets. Pumped effluent did not show this signature, however.

The area raised to steam temperature (>100°C) was approximately 10,000 yd^3. A total of 42,100 gal of propane gas were required at a cost of $.45/gal, for a total energy cost of $2/yd^3. The area raised to steam temperature is uncertain because steam expanded beyond several sides of the monitoring network; our estimate excludes heated ground that did not reach the boiling point.

Conclusions from the steam test include:

- An impermeable "cap" layer can keep steam flowing horizontally over long distances (in excess of 50 yds).
- Water levels "behind" the injection well rose when extracting at the same rate as injection, but could be lowered by increased pumping.
- Steam can be handled safely for this operation.
- Steam injection is a very efficient way to heat the ground.
- A steam zone can be established below the water table without excessive energy loss.

Steam Monitoring

The primary objectives of the monitoring effort are: 1) to image and provide real-time feedback, control and monitoring of the steam front; and 2) to determine the nature and extent of the active processes associated with the heating and how they affect the formation. At the Clean Site the abilities of a number of techniques to meet these objectives were tested. Underground steam presents a significant target for geophysical imaging through its thermal signature, changes in fluid-filled porosity and its effect on soil chemistry. Geophysical techniques fielded include electrical resistance tomography, seismic tomography (cross-borehole), induction tomography, passive seismic monitoring, temperature measurement techniques and conventional geophysical well logging.

The geophysical monitoring activities proved to be very successful in providing detailed information on steam movement. As expected, the steam produced strong changes in some of the physical properties of the sediments Temperature measurements from the dedicated temperature monitoring wells (Fig. 4) provided the "ground truth" for describing the steam progress through the field (Fig. 5). Temperature measurements and induction logs obtained in the temperature monitoring wells were essential for correlating changes seen in the tomographic images. Commercial geophysical logs were obtained before well completion (caliper and resistivity), and before and during steam injection (induction, neutron porosity, and gamma-gamma density).

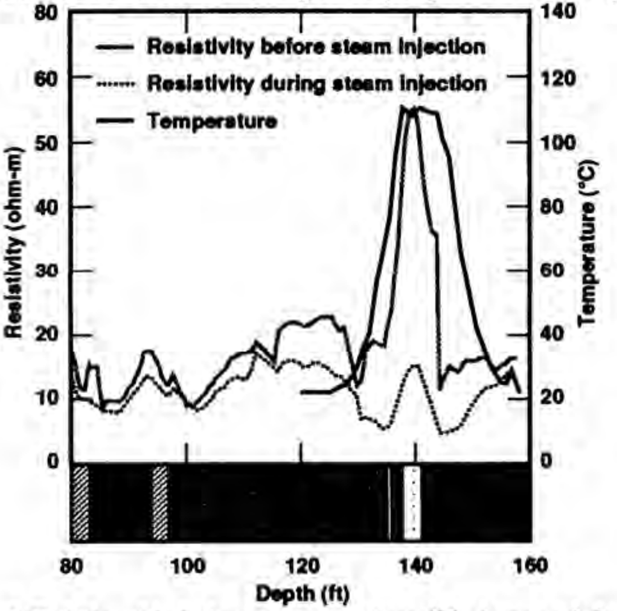

Fig. 5. Relationship between temperature, lithology, and electrical resistivity during steaming at the clean site engineering test.

Electrical resistivity profiles (from resistivity and induction logs) proved to be a sensitive predictor of effective permeability and provided the best estimate of where steam would flow (Fig. 5). During steam injection, electrical resistivity decreases in the steam zone, which is largely attributable to thermal effects (Fig. 5). In some wells electrical resistivity increased in unheated zones ranging up to a few feet from the heated zone; this appears to be associated with fluid movement. Other effects such as fluid movement or changes in water chemistry may be occurring; one possibility is that the sodium content of the injected fluid changes the conductivity of clays by substituting for less-mobile calcium.

The presence of a standing water table is not apparent in resistivity profiles and neutron logs, apparently due to its occurrence in relatively tight, fine-grained sediments. Although there is a decrease of up to 4% in observed neutron porosity in the steam zone, there are other significant changes higher in the formation where temperature changes did not occur. Results from the other logging methods appear to have been affected by downhole temperatures: additional processing to correct for the thermal disturbance of the tools will be needed before these data can be adequately interpreted.

Electrical Resistance Tomography (ERT) proved the most successful technique for providing near real-time imaging of the active processes between wells (Fig. 6). Figure 6 shows a set of three images with accompanying temperature and lithologic information. ERT clearly show the progress of the steam front as a zone of lowered resistivity. The shallow electrical resistance anomalies probably are water infiltration plumes from the surface use of fresh water during final well completion activities; we are investigating these anomalies which appear in several imaging methods.

Cross-hole seismic tomography data were collected three times during steam injection, following baseline tests of two receiver types. Hydrophones were found to be better than accelerometers for detecting the airgun signal. An observed velocity change of about 3% in the steam zone is of the predicted magnitude and is seen more clearly at seven days when the steam had crossed the entire image plane. Although the seismic results are less detailed than the ERT, seismic cross-hole may be useful when dedicated ERT electrodes cannot be emplaced, and existing wells must be used for imaging.

Passive seismic monitoring did not detect any unambiguous steam-related events, although other cultural noise was located. There may not have been any acoustic emissions during steam injection due to the high permeability of the steam zone.

Cross-hole electromagnetic induction tomography also uses a source/receiver combination in adjacent holes and would be applicable in existing holes. Application at the Clean Site yielded good agreement with the induction logs and ERT images, and a layered-model inversion shows the steam zone thickening (downward) with time, as was observed.

An important objective of the monitoring activities is to evaluate the potential of each of these technologies for monitoring the active processes on different scales. One of the reasons for fielding several similar techniques is to evaluate the relative strengths and weakness of each and determine the trade-offs between their application in terms of cost and

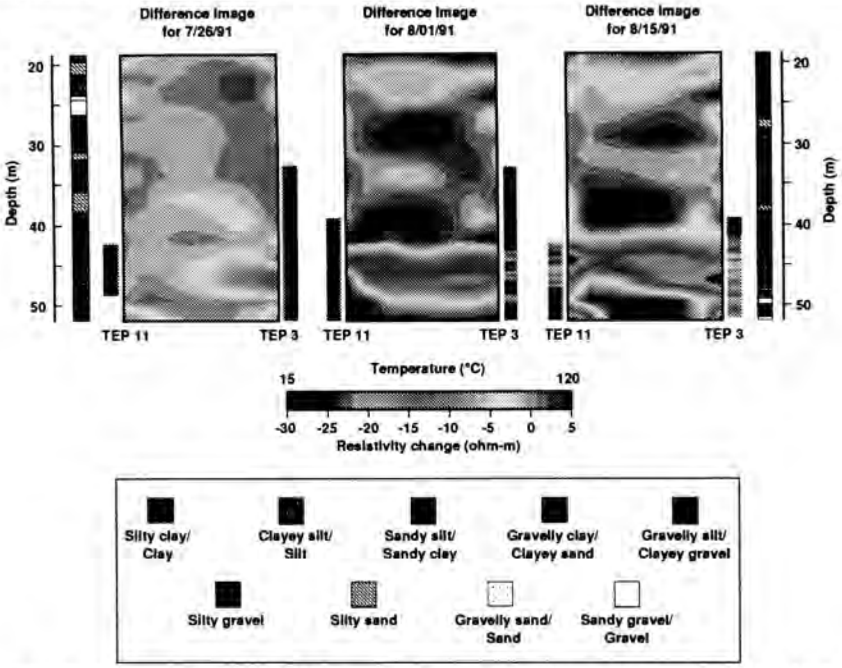

Fig. 6. Electrical Resistance Tomography views of the steam zone at the clean site engineering test. These are constructed by comparing initial baseline data with data taken during steaming. In the 7/26 image the injection plume has just entered the region between these wells, moving within the silty gravel layer, but no significant temperature rise is noted in the wells. By 8/01, the steam has reached both wells, and a significant temperature rise is seen in TEP 3. Development of two steam layers at the end of the test is seen in the 8/15 image.

utility. Although we have not yet completed this comparison, we have identified various factors affecting each techniques' overall performance. Examples of these limiting factors include cultural interference and the presence of conductive materials in the field, (such as steel well casings) for the electrical methods and trade-offs between frequency and power in seismic sources. Unfortunately the Clean Site only provided a single large layer as a target for imaging of steam, but the results for that layer at the distal wells where smaller multiple steam zones existed were of sufficient accuracy to make us confident that multiple steamed areas could be imaged, such as we expect at the LLNL Gasoline Spill Site.

Key results from the monitoring work include:

- ERT provides detailed images of steam movement; its use is indicated where dedicated monitoring wells can be installed.
- Seismic cross-hole logging is sensitive to steam movement but provides lower resolution than ERT. For this type of lithology, its use is indicated where existing wells must be used.
- Induction logging can provide good predictions of steam movement, and reveals changes in electrical properties over a broader zone than the thermal disturbance.
- Several different techniques are available which can accurately identify steamed and unsteamed layers under a variety of conditions.

Electrical Heating

During 1991 electrical heating experiments focused on a small scale test, with full scale testing continuing into 1992 at the Clean Site. Full scale testing utilizes four stainless steel electrodes made of 1'x4' stainless steel tubing, spaced evenly from 85' depth to 145' depth. Set in a triangular pattern, the wells are designed to heat the center of the steamed area. Small scale testing was done in wells 20' deep with one electrode per hole. The small-scale area was just south of the main area (Fig. 4).

Electrical heating has been used in commercial petroleum production to enhance the flow of viscous oil (e.g. Hiebert et al., 1986). Although the aim is to reach higher temperatures in Dynamic Stripping, the methods used are similar. At the small scale test, a hexagonal well pattern allowed each pair of adjacent wells to be wired to one phase of standard 3-phase, 480V power from a portable generator. This makes the electrodes' effective area larger than the exposed metal surface, and reduces localized heating at the electrodes while enhancing current flow in the center of the pattern. This favors direct heat generation in the center, rather than heat diffusion from the edges which is inefficient over large distances.

Predicted and actual results from this test are shown in Fig. 7. Only 1/2 of the 6-spot pattern is shown. White dots are heating and monitoring wells; the contours are drawn from the predicted results. The prediction assumed a homogeneous material and is strictly 2-dimensional. The wells connected by 'dumbbells' are connected to different power phases; hence there is a large current flow, and heating, between them. The white area is between two wells at the same phase. In a remediation operation these wells would be cycled to even the heating pattern. Although there is significant heating near the electrodes in this design, the large, uniform central area heats at 2°C or greater per day. This would be sufficient on reasonable time scales to remove contaminating solvents from a clay layer not penetrated by steam. Improvements in the electrode design can further smooth the heating pattern and increase the heating rate. After 240 hr of operation 24 hours/day, the

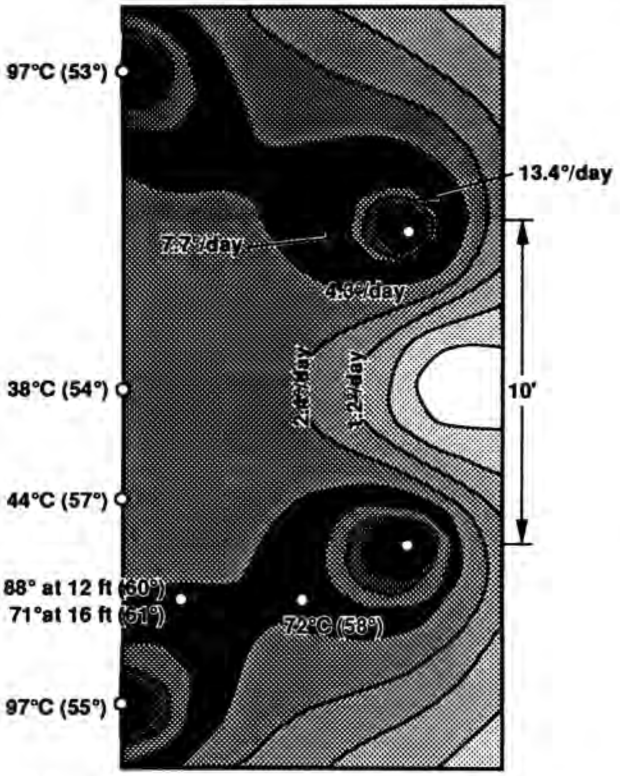

Fig. 7. Predicted and observed heating rates in the small- scale electrical test at 16' depth, after 10 days of heating. Predicted values given by contours; observed values are indicated at specific points (monitor wells).

pattern was operated during daylight hours for 5 more days to test whether continuous operation was cost effective. Temperatures continued to rise at more than 1° per day, indicating that nighttime cooling was insignificant. and there was no loss of overall efficiency in day-only operation. After shutting off the pattern at a 44°C center temperature and essentially 100°C well bore temperature, the temperatures equilibrated over the next week to a center temperature of 55°C with well bores no more than 10° hotter.

The total heated area in the small scale test was about 400 cubic yards (there is some uncertainty in the heated volume outside the electrodes as we did not instrument that area). This required 15,000 KW-hours to heat to 55°C, for an average of 1 KW-hr/°Cyd^3. At a commercial *cost of $.055/KW-hr this* extrapolates to an energy cost of $5/yd^3 to electrically heat soil of this type to the boiling point of water.

Conclusions from the electrical heating work include:

- Six electrode, three phase heating is sufficiently uniform for field applications.
- Electrode design must be robust for field use.
- Fine-grained clay and silt layers in gravel matrix draw the expected large proportion of the current.

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