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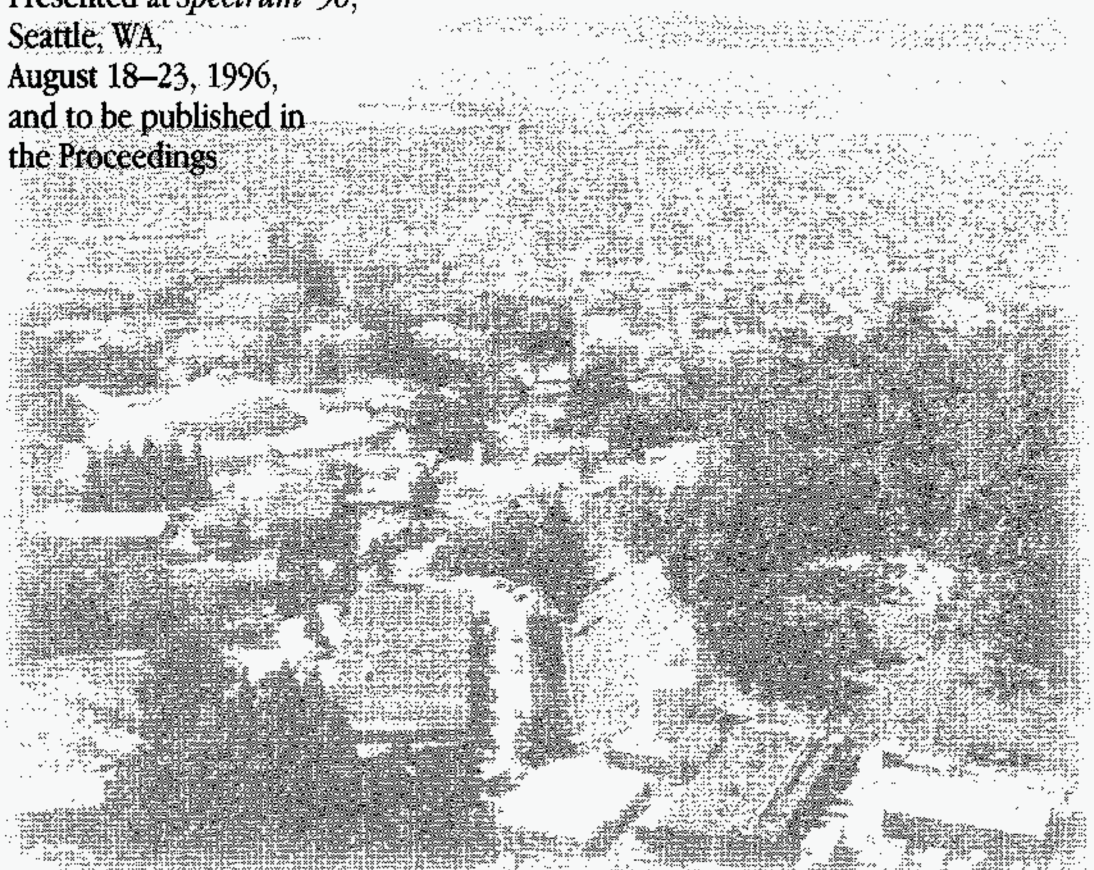

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A FIELD TEST OF A WASTE CONTAINMENT TECHNOLOGY USING A NEW GENERATION OF INJECTABLE BARRIER LIQUIDS

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ABSTRACT

A first stage field injection of a new generation of barrier liquids was successfully completed. Two types of barrier liquids, colloidal silica (CS) and polysiloxane (PSX), were injected into heterogeneous unsaturated deposits of sand, silt, and gravel typical of many of the arid DOE cleanup sites and particularly analogous to the conditions of the Hanford site. Successful injection by commercially available chemical grouting equipment and the tube-à-manchette technique was demonstrated. Excavation of the grout bulbs permitted visual evaluation of the soil permeation by the grout, as well as sample collection. Both grouts effectively permeated all of the formation. The PSX visually appeared to perform better, producing a more uniform and symmetric permeation regardless of heterogeneity, filling large as well as small pores and providing more structural strength than the colloidal silica. Numerical simulation of the injection tests incorporated a stochastic field to represent site heterogeneity and was able to replicate the general test behavior. Tiltmeters were used successfully to monitor surface displacements during grout injection.

I. INTRODUCTION

A. Technology Need

The development of effective *in-situ* contaminant containment technology is necessitated by the need to prevent further release of contaminants from buried sources and the need to contain existing contaminant plumes. Contaminants from buried wastes or from contaminated soil in the vadose zone can migrate toward previously uncontaminated regions of the subsurface. Excavation and disposal of contaminated soils may pose environmental health and safety problems, is expensive and often impractical. Contaminant removal is also expensive, very slow, and usually ineffective.

Subsurface barriers, formed by injection of barrier fluids that gel or solidify *in-situ*, can contain contaminants on-site and control the groundwater flow pattern, thus reducing the risk of off-site migration. Moreover, containment is necessary to prevent the spread of mobilized contaminants resulting from application of treatment technologies (e.g., soil flushing, surfactant mobilization) that increase the mobility of the contaminants.

B. Technology Description

Lawrence Berkeley National Laboratory (LBNL) staff have developed a subsurface containment technology using a new generation of viscosity-sensitive liquids which, when set in porous media, cause the media to exhibit near-zero permeabilities and contain the contamination in the subsurface by entrapping and isolating both the waste source and the plume by a chemically inert physical barrier[1,2,3,4].

The low-viscosity liquids are injected through multiple injection points in the subsurface. The intersecting plumes merge and completely surround the contaminant source and/or plume. Once in place, they gel or cure to form a nearly impermeable barrier. The technology can also be applied to encapsulate wastes in the subsurface. In applying this technology, however, it is important to match the fluid to the waste and to the soil conditions, and to control the gel time and the emplacement of the fluid to form the barrier[3,5].

C. Applications and Benefits

The LBNL viscous barrier technology can be applied at a wide range of sites where hazardous wastes (radionuclides, heavy metals, organics, mixed) have contaminated the subsurface environment, and include isolation of ponds and buried tanks, cap and liner repairs at landfills, etc. There are three ways to apply this technology: (1) permanent immobilization of the contaminants, (2) creation of an impermeable container to surround and isolate the contaminated areas, or (3) sealing of permeable aquifer zones, thus helping to confine traditional cleanup techniques (pump and treat) in the difficult-to-treat zones.

The LBNL containment technology offers a number of significant advantages. On-site containment and control of the groundwater flow pattern which limits the off-site threat and could supply a long-term solution. Site disturbance, if any, is minimal, as no excavation is required. Risk of human exposure is minimized. It is applicable to the whole spectrum of wastes and a wide variety of sites. It enables the complete isolation of the affected area from the regional groundwater flow by providing barriers to both horizontal and vertical flow. It is the only technology currently capable of providing horizontal barriers (bottoms) in containment systems. It is usually cheaper and more effective than conventional methods. The effectiveness of traditional clean-up techniques can be enhanced by allowing natural degradation and bioremediation to occur without risk of contaminant migration. Additionally, more intensive remediation technologies (such as soil washing, alcohol flooding, etc.) are possible without the risk of the mobilized contaminants spreading beyond the contained region.

D. The Barrier Liquids

Two general types of barrier liquids have been used[1,2]. The first is Colloidal Silica (CS), an aqueous suspension of silica microspheres in a stabilizing electrolyte. It has excellent durability characteristics, poses no health hazard, is practically unaffected by filtration, and is chemically and biologically benign. The increase in viscosity of the CS following injection is due to a controlled gelation process induced by the presence of a neutralizing agent or a concentrated salt solution, either one of which is added immediately prior to injection at ambient temperatures. The CS has a tendency to interact with the geologic matrix, and therefore, special formulations or techniques are required to minimize or eliminate the impact of such interactions.

The second type belongs to the PolySiloXane (PSX) family, and involves vinyl-terminated silanes with dimethyl side groups. The increase in viscosity in PSX is caused by the cross-linkage of the injected substances and the formation of a matrix of essentially infinite viscosity after the addition of a catalyst through a process akin to vulcanization. The cross-linking process is controlled by the quantities of the catalyst, crosslinker, and (occasionally) retardant added to the PSX prior to injection.

These materials pose no health hazard (have been approved by FDA for food contact), are unaffected by filtration, have low initial viscosity (under 10 cP), are chemically and biologically inert, and have been shown to be effective barrier liquids[1,2].

E. Previous Supporting Work

Substantial preparatory work was conducted to ensure the success of permeation grouting technology in the field. The work included identification and characterization of promising materials, evaluation of their containment potential by means of laboratory and pilot-scale experiments, and the development of appropriate numerical simulators. Many institutional issues involving interactions with regulatory agencies and industry partners also required resolution.

A wide search for fluids with desired properties identified CS and PSX as promising candidates. The rheological and wettability properties of these barrier fluids were measured. Laboratory studies of barrier fluid flow and emplacement in porous media were conducted, and it was determined that both CS and PSX are effective barrier liquids. Alternative processes were developed to alleviate possible effects of the soil chemistry on the CS gel times, and ways to control the gel time and the texture of the gels were identified. Protocols for the sequential injection of CS were established, and it was demonstrated that in laboratory tests hydraulic conductivities could be reduced to less than 10^{-8} cm/s after two injections. Processes to control the viscosity and gel time of PSX were also identified. PSX cross linkage times are far less sensitive to the soil chemistry than CS gelation, and hydraulic conductivities could be reduced to 10^{-10} cm/s after a single injection.

In collaboration with the manufacturers, new CS and PSX formulations were developed to meet barrier fluid requirements. The CS variant used in the field demonstration is stabilized by a permanent particle charge produced by isomorphic replacement of Si by Al on the particle surface. In the resulting Colloidal Alumina Silica (CAS) the charge is not pH dependent and it is even more environmentally benign because it is stable at a near-neutral pH of 6.5, in addition to being unaffected by the soil chemistry. The new PSX formulation has an initial viscosity low enough (8-10 cP) to allow injection using existing equipment.

A series of laboratory tests were conducted to investigate the barrier performance of the selected CS and PSX formulations at all length scales of interest: from sub-millimeter (pore micromodels) to one-dimensional experiments (column studies) to two-dimensional studies. Preliminary waste compatibility tests were conducted, and it was concluded that both CS and PSX are not significantly affected by a wide range of wastes contained in the buried tanks at Hanford.

The general-purpose TOUGH2™ model[6] was appropriately modified to predict the flow and behavior of gelling/cross-linking fluids when injected into porous media[7]. The expanded TOUGH2™ was used to design the laboratory experiments (one- and two-dimensional) of barrier fluid injection, and to conduct a sensitivity analysis of the relevant parameters[7,8].

In interactions with industry and regulatory agencies, LBNL developed an agreement with Bechtel to collaborate in the area of barrier fluid emplacement. LBNL also signed a confidentiality agreement with Dow Corning, the manufacturer of PSX, as a result of which Dow Corning made available to the project the new low-viscosity PSX used in the experiments and the field test. A Categorical Exclusion under NEPA regulations for the first-level field test was obtained, due to the environmentally benign nature of the barrier fluids.

In preparation for the field test, LBNL staff developed a design package for the application of the barrier fluid technology using TOUGH2™, completed a preliminary evaluation of geophysical techniques for monitoring barrier emplacement and performance, identified a local site in California with a subsurface geology similar to that at Hanford, and obtained permission from the owner and the regulators to conduct the first-level test at that site. Following the signing of the Host Site Agreement, the field test was conducted in January, 1995.

II. THE FIRST FIELD-LEVEL DEMONSTRATION

In the following sections, various aspects of the field demonstration are described. These include the objectives of the demonstration, a site description, specification of the barrier liquids, and the four stages in executing the demonstration: (a) well drilling and permeability measurements, (b) barrier fluid injection, (c) grouted bulb (plume) excavation and sample recovery, and (d) laboratory investigations of grouted samples[9].

A. Objectives

The objectives of the test were to demonstrate the ability to (a) inject CS and PSX using standard permeation grouting equipment, (b) track the grout fluid movement using tiltmeter measurements of ground surface deformation, (c) control of the grout fluid gel time under *in-situ* chemical conditions, (d) create a uniform grout plume in very heterogeneous matrices including cobbles, gravels, sands, silts and clays, (e) create intersecting/merging plumes of grout, and (f) decrease the permeability of the grouted soils.

The demonstration was not intended to prove the creation of continuous and/or impermeable barriers. Such an effort would be significantly larger in scope and involve merging and overlapping the injected barrier liquid plumes, as well as multiple injections.

B. The Site

The test site is located in central California in a quarry owned by the Los Banos Gravel Company (Figure 1). The quarry is situated along the western flank of the San Joaquin Valley,

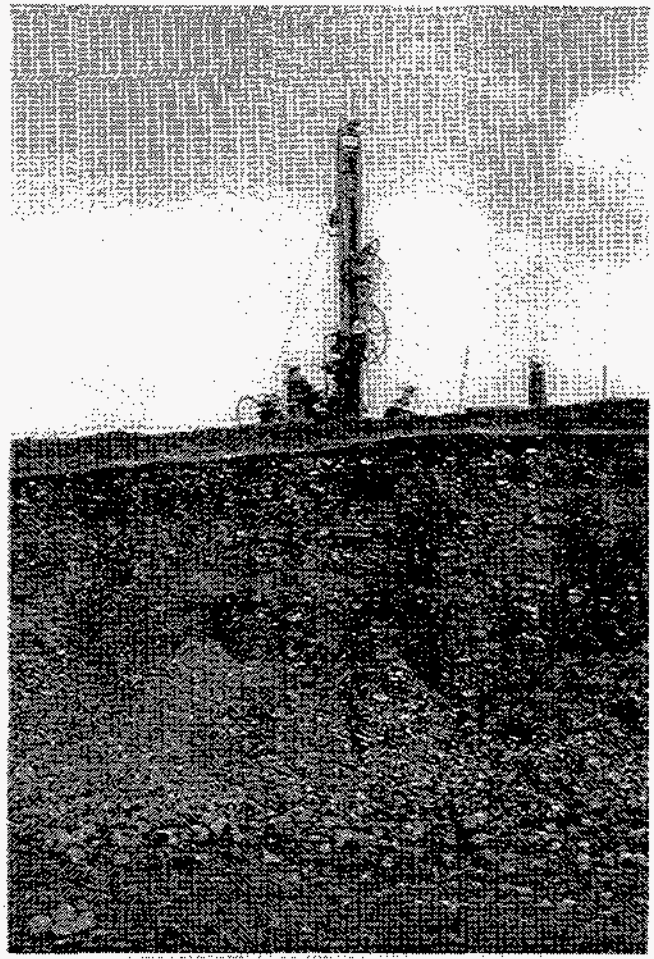

Figure 1. Test pad site set back from pit wall.

adjacent to the eastern margin of the central California Coast Ranges. The quarry exploits river gravels in a 100 km^2 alluvial fan generated by Los Banos Creek at the foot of the California Coast Range.

The deposits exposed at the quarry are primarily coarse sands and gravels, deposited on a distributary lobe of Los Banos Creek adjacent to its present channel. They are internally heterogeneous, with discontinuous and lenticular coarser and finer strata, and occasional lenses of well-sorted cross-bedded sands. Large gravel and cobble clasts are commonly set in the sandy matrix, and range between 1 and 10 cm, and sometimes larger. The matrix is predominantly coarse sand (0.5-1 mm), and comprises varicolored lithic fragments, along with grains of feldspar, quartz, and quartzite. Induration, where present, is caused by illuviation of clay into pores between sand grains; a fine film of yellow-brown clay can be seen binding the sandy matrix in most samples.

C. Barrier Liquids

The barrier fluids selected for injection included one type of PSX (2-7154-PSX-10, hereafter referred to as PSX-10; Dow Corning, Midland, MI) and one type of CS (Nyacol DP5110; EKA Nobel, Valley Forge, PA). In preliminary experiments, other variants of PSX and CS products were also tested. All the barrier fluids tested are environmentally benign and carry no warning label requirements.

Nyacol DP5110 is a CS in which silica on the particle surfaces has been partly replaced by alumina; its solid content is 30 wt.% and its pH is 6.5. A technical grade aqueous solution of $CaCl_2$, 35 wt.% (4 mol/L) was used to induce gelation for the field demonstration. Figure 2 shows the gelling behavior of the CS-$CaCl_2$ system used in the demonstration, as described by change in viscosity.

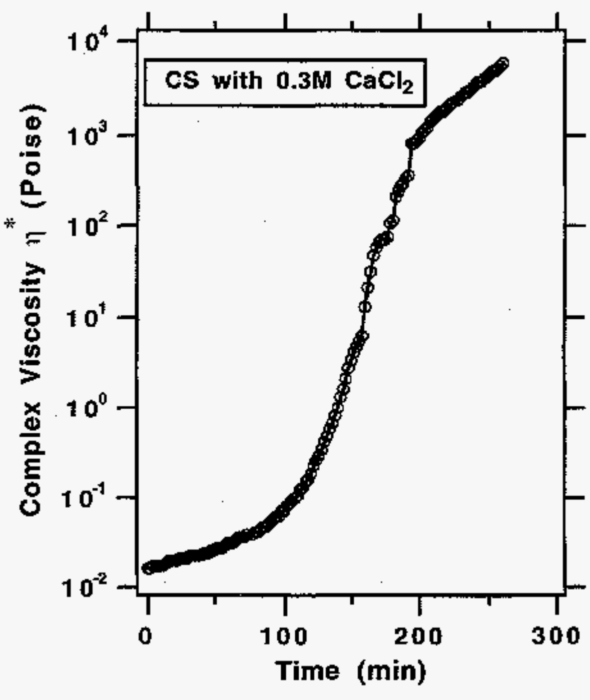

Figure 2. Time dependence of viscosity of the CS system used in the field test.

PSX-10 is a polydimethylsiloxane, divinyl-terminated to provide active sites for cross linking. It is formulated by the manufacturer with a cross linker (a small cyclic siloxane molecule) that can react with the terminations of the long chains in the presence of small concentrations of an organically-coordinated platinum catalyst. The polydimethylsiloxane and crosslinker are delivered already mixed, but unreacted. A catalyst is added by the user at the level necessary to achieve the desired gel-time. Figure 3 shows the crosslinking process of the PSX system, described by the time dependence of its complex viscosity.

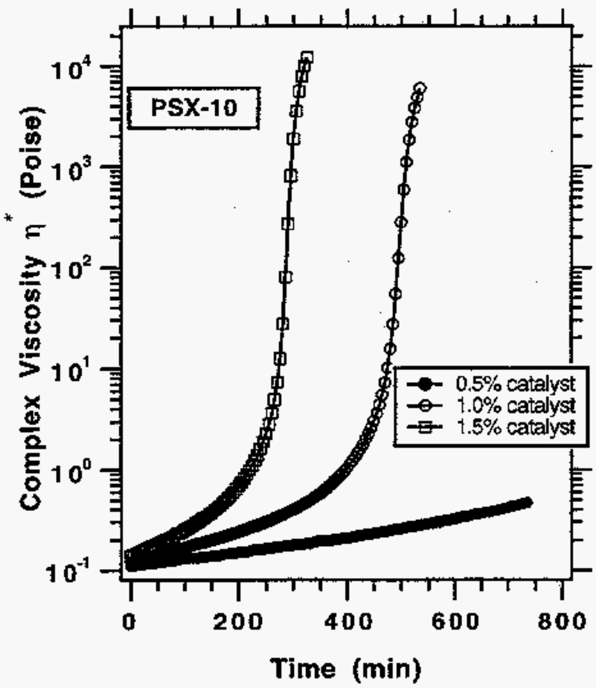

Figure 3. Time dependence of viscosity of the PSX system for different catalyst concentrations.

D. Well Drilling and Permeability Measurements

Four injection and four observation wells were drilled. Figure 4 shows the drilling rig in operation. The injection wells were drilled to a depth of 16 ft, while the observation wells were drilled to depths ranging between 12 and 20 ft. Following well completion, all the wells were fitted with appropriate tubing, and probes were punched through the bottom of the wells for air permeability measurements.

Air permeability measurements included single-probe static permeameter (SSP) tests and a new dual-probe dynamic pressure (DDP) technique developed at LBNL for measurement of air permeability between wells[10]. The SSP technique introduces air into a well at a constant rate, using Darcy's law and the assumption of a semi-infinite homogeneous medium to estimate permeability from the measured disturbance pressure and air flow rate.

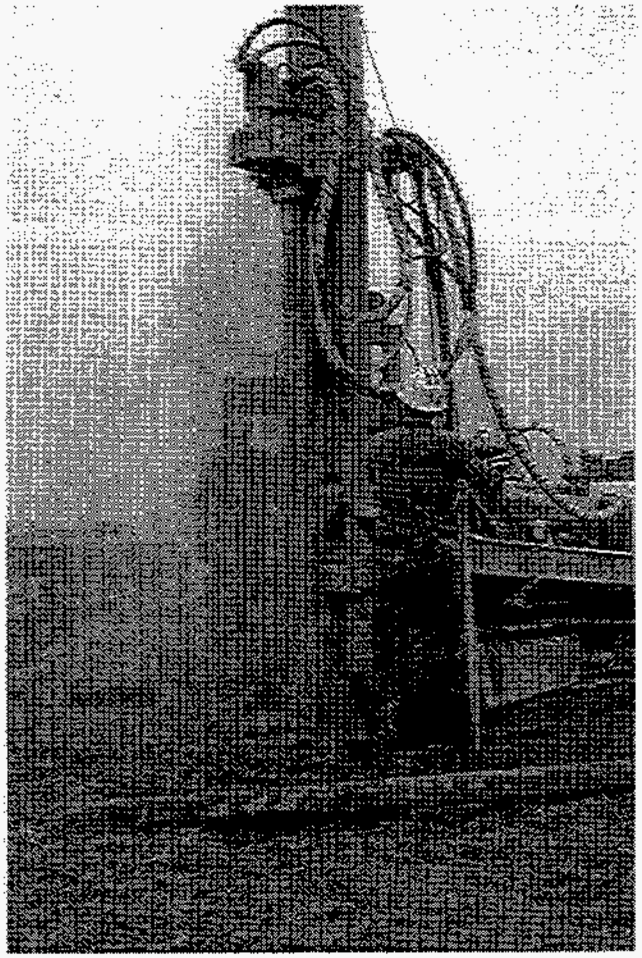

Figure 4. Drilling using the ODEX method.

The DDP technique uses the propagation time for a sinusoidally oscillating pressure signal (with a mean near-atmospheric pressure) to travel from a source well to a detector well as a measure of the air permeability. Pressure responses are continuously monitored at several observation wells. The SSP technique provides information on the permeability immediately surrounding each well, while the DDP technique provides information on the permeability between wells.

The static permeability measurements, conducted in all eight wells, indicated air permeabilities ranging from a high of 1.0×10^{-10} m^2 to a low of 3.6×10^{-13} m^2. For all but two wells the values ranged from 5.6×10^{-11} to 8.1×10^{-11} m^2.

The DDP mesurements yielded inter-hole air permeabilities between 3.5×10^{-9} m^2 and 1×10^{-11} m^2. These permeabilities are between 1 to 2 orders of magnitude higher than those obtained using the SSP technique. The apparent lack of agreement is due to conceptual differences between the two approaches: the static technique in essence measures the permeability at the point of injection, whereas the dynamic technique measures the mean permeability between a source and a receptor well along paths that are not necessarily the shortest. Though the magnitudes of the static and dynamic measurements differ, trends are consistent between the two techniques. These observations substantiate the validity of the two methods, and support the hypothesis that the differences between static and dynamic values are due to scale effects.

After completing the air permeability tests, all observation wells were plugged to prevent barrier liquids from flowing into the observation wells and bypassing the area to be grouted. The bottoms of the injection wells were also plugged.

E. Barrier Fluid Injection

The barrier liquids were injected through 3 ports in each well (at depths of 10, 12, and 14 ft) using the tube-à-manchette technique. Approximately 400 gallons of CS grout were injected into two wells, CS1 and CS2. About 120 gallons of PSX-10 were injected into a single well, PS1. The smaller scale of the PSX-10 injection test was dictated by budget considerations, as it is still a developmental product and economies of scale in its production have not yet been realized.

The barrier liquids (CS and $CaCl_2$ brine, PSX-10 and catalyst) were premixed at the surface using the agitators of the mixing tank and the recirculation equipment of the grouting system. For the CS injection, food-color dye was added to enhance its visibility during subsequent excavation of the site. Green dye was added to the batches injected into CS1, and purple dye into the CS2 batches. The same quantity of barrier fluid (66 gallons for CS, 40 gallons for PSX-10) was injected at each depth. Standard chemical grouting equipment was used for delivering the barrier fluids to the hole.

The procedure for injection followed those typically used in tube-à-manchette grouting (Figure 5). The injection sequence was carried out in order to maximize complete permeation of the soil in the vicinity of the wells. Thus injection began at the lowest port (14 ft), followed by injection through the uppermost port (10 ft) and, finally, injection through the intermediate depth port (12 ft).

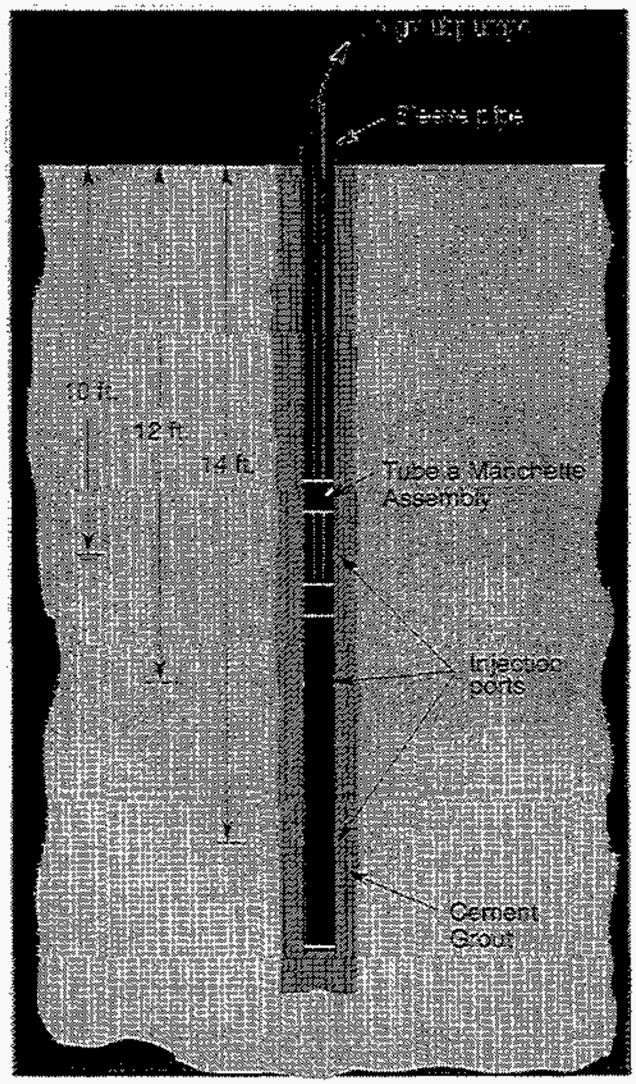

Figure 5. The tube-à-manchette grouting method.

The barrier fluids were injected without any significant rise in pressure, which would have indicated premature gelling. During injection the volume of injected grout and injection pressure were monitored. Average values of injectivity, a measure of the apparent permeability at each injection port, decreased with depth with values at the 14 ft depth an order of magnitude or more lower than those at shallower depths.

Eight tilt meters were installed at the injection site. The tiltmeter array recorded ground movement every 60 seconds throughout the test, and was able to detect movement of the injected fluids. Tiltmeters measure the angle of deviation of the land surface from the vertical axis. Because the deformation detected by tiltmeters is minuscule (nano- to micro-radians), LBNL staff decided to apply this technology to track the swelling and uplift at the earth's surface due to the intrusion of the barrier liquids.

Deducing the movement of fluids through the subsurface from surface tilt requires the solution of an inverse problem, which cannot presently be conducted in the field in real-time, although this is anticipated with the rapid advancement of computer technology.

F. Excavation and Visual Inspection

The excavation of the grouted plumes (Figure 6) was facilitated by the proximity of the wells to the exposed face of the quarry (20 ft) and the use of heavy earth moving equipment. The ground was excavated to a depth of up to 21 ft. Both CS and PSX-10 had satisfactorily gelled/crosslinked in the subsurface.

Despite the extreme soil heterogeneity, both the CS and the PSX-10 created fairly uniform plumes, indicating that the potential problem of flow along preferential pathways of high permeability (such as a gravel bed overlying a tight silty or clayey zone) can be overcome.

The CS grouted and sealed fractures and large pores in the clays. In open zones (such as gravels with cm-sized pores) it did not fully saturate the voids, but appeared to have sealed access to them. CS imparted sufficient structural strength to the matrix to permit 10 ft high vertical sections of the matrix (characterized by very loose, friable, and heterogeneous materials) to stand without collapsing (Figure 7).

PSX-10 was singularly successful in grouting the extremely heterogeneous subsurface at the site. PSX-10 created an almost symmetric plume, grouting and sealing gravels, cobbles, sands, silts, and clays (Figure 8). PSX-10 filled and sealed large pores and fractures, as well as accessible small pores in the vicinity of these pores/fractures. In extremely large voids in open zones, it coated the individual rocks in the gravel and appeared to seal access to and egress from these zones.

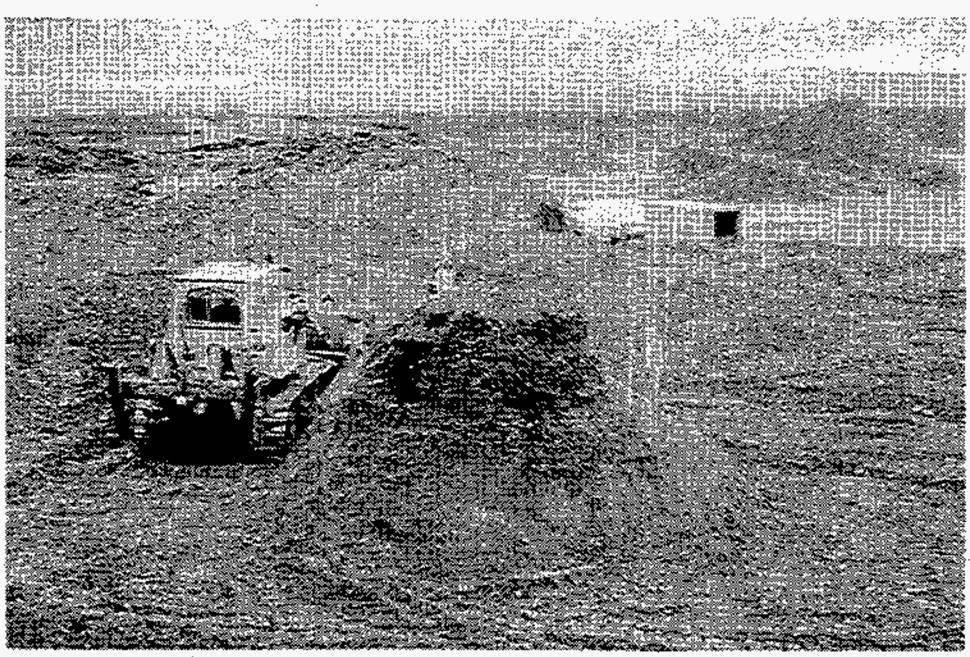

Figure 6. Excavation of the grouted plumes.

Figure 7. CS-grouted unconsolidated materials.

PSX-10 also invaded clays and silts, which is unusual. The mechanism through which this penetration is achieved has not been determined, but is under investigation. PSX-10 is relatively easy to identify in the subsurface. PSX-10 imparted structural strength and elasticity to the grouted soil volume, and gave sufficient strength to incoherent gravels to permit 20 ft high vertical walls to stand (Figure 9). It fully penetrated clean sands which resisted disaggregation due to its considerable elasticity.

III. POST-EXCAVATION ANALYSES

The grouted plumes were excavated primarily to determine the volumetric extent of the grouted zone. LBNL staff also took advantage of the excavation to recover boulder-size chunks of grouted sand from which smaller samples could be taken for permeability measurement in the laboratory. Grab samples of ungrouted matrix were taken at various depths from locations adjacent to the grouted bulbs. Moisture content and material gradational analyses, as well as permeability measurements were performed on these samples.

The moisture content of the ungrouted soil was very low, but increased with depth from about 2.5 wt.% to 5 wt.%, with most of the increase occurring at depths of 10 ft and greater. The gradational analysis showed an increase in fines with depth from 1-2 wt.% to 8-9 wt.%. An abrupt increase in fines is seen at depths greater than 10 ft. A correlation in moisture content with fines would be expected. The gradational analysis also correlated with the injectivity profile and visual observations that the amount of fines increased with depth.

The permeability of grouted sand depends primarily upon two factors: the permeability of the grout itself, and the degree of grout saturation in the pore space. The lower limit of permeability is achieved when the pore space is completely filled with grout. To estimate this lower limit, special samples were prepared by a method in which sand is poured into liquid grout in molds. This method ensured a complete filling of pore space by the grout, and resulted in an absolute lower limit of permeability that is unattainable with a single injection under field conditions. Other samples were prepared in the laboratory by injecting grout upward into sandpacks in order to minimize the ammount of trapped air. Samples prepared in this manner represent the lower limit of permeability that could be achieved by injection in the field.

The permeabilities of the grouted sand samples were measured using a Wykeham-Farrance flexible wall permeameter (Humboldt Equipment, Durham, NC). Samples from the field were cored or carved from the boulder-sized chunks for insertion into the permeameter. Coring using a soil-sampling tube was possible only with a material containing no pebbles. The extreme heterogeneity of the formation at the Los Banos site made it difficult to sample and make permeability measurements. Hence, the number of field samples subjected to permeability testing was limited.

In Table 1, the three types of samples are represented; i.e., (i) samples prepared by pouring the sand into the grout; (ii) samples prepared by laboratory injection into sandpacks; and (iii) field samples. These three types of samples have increasing ungrouted voids.

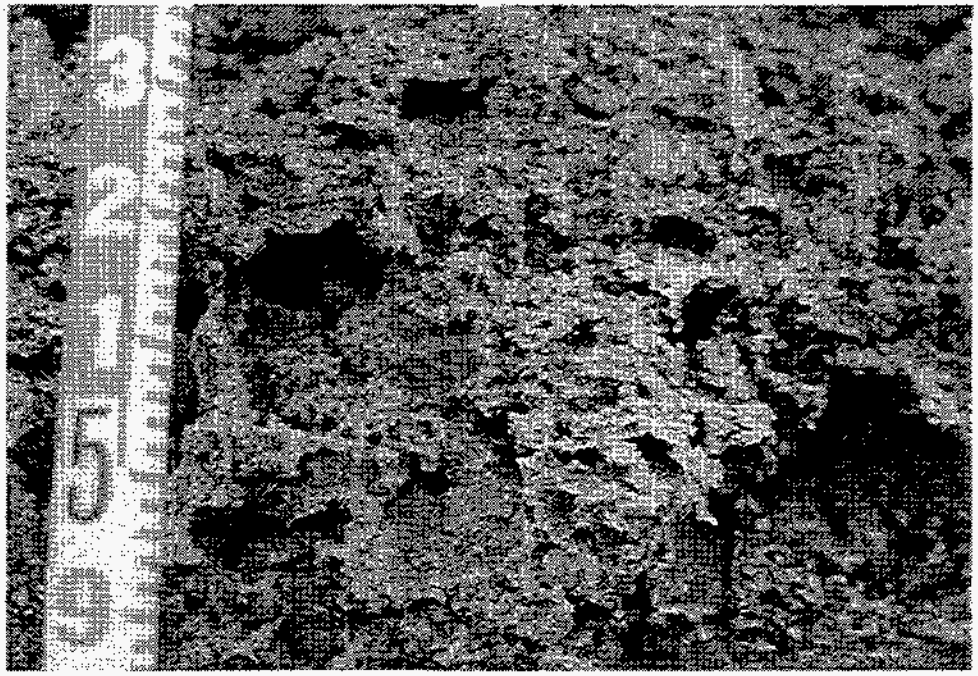

Figure 8. PSX-grouted unconsolidated materials.

Because the field samples are expected to have the greatest amount of ungrouted voids, multiple injections will be required to achieve permeability reductions of type (ii) in field applications[2]. This goal was not pursued in the first-level field injection, as the reduction of permeability to a near-zero level was not among the objectives of this field demonstration for the reasons discussed earlier.

A review of the hydraulic conductivity data confirms that it increases with the increase of ungrouted voids. In comparing the laboratory prepared samples with nearly complete grout saturation, (i), those grouted with PSX-10 had lower hydraulic conductivity than those grouted with CS. Sands with an initial hydraulic conductivity on the order of 10^{-4} m/s can attain a final hydraulic conductivity of 10^{-10} m/s level after grouting with CS, while PSX-10 reduces hydraulic conductivity even further to 10^{-12} m/s. These differences reflect the different permeabilities of the grout materials.

The Hanford-PSX-10 #2 sample shows unusually high hydraulic conductivities for laboratory-grouted cylindrical samples which can be due to an imperfect outer cylindrical surface that allowed flow between the rubber membrane and the grouted core. With increasing confining pressure, the hydraulic conductivity decreases, confirming the visual observation of surface imperfections. Such side-flow effects are expected to be far more pronounced in the cored or carved field samples.

In the case of field grouted sand and pebbles, the observed hydraulic conductivities reflect incomplete saturation of the pore space. Damage to samples during recovery, transport, storage and trimming to fit the apparatus could also have contributed to increases in hydraulic conductivity. Similar values were observed whether CS or PSX-10 grout was used, but this may not mean anything since they were different samples from different locations and with different soil textures. Partial saturation of pore space is also suggested by the observation of the larger than expected plumes. This supports the view that grout desaturation occurred due to plume spreading. LBNL's plume emplacement model predicts that this phenomenon will always occur in the vadose zone.

The problem arising from plume spreading and incomplete sealing can be solved by multiple, sequential injections of grout. Moridis et al.[2] demonstrated this technique in sandpacks.

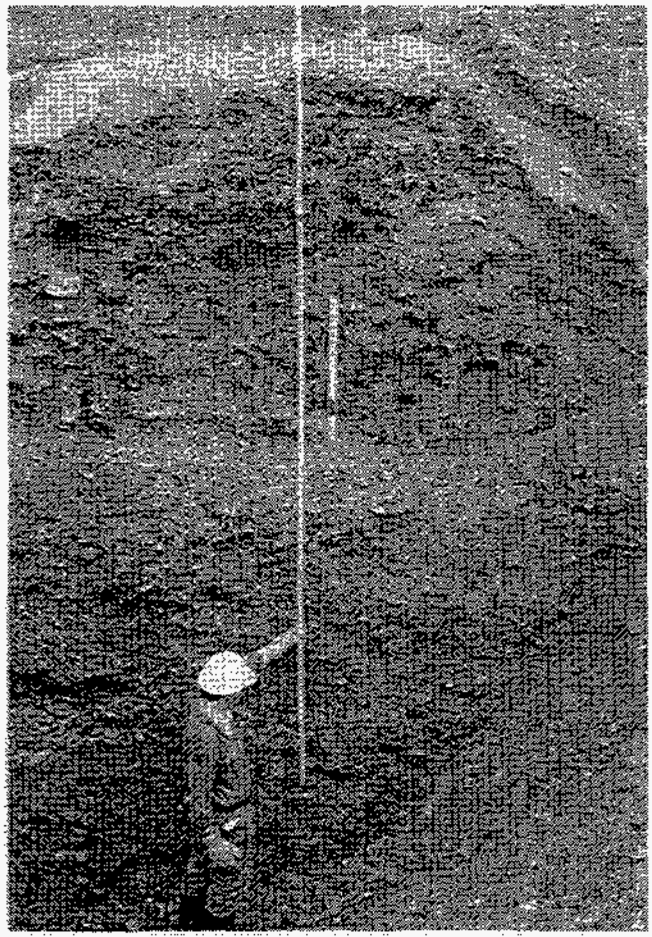

Figure 9. The 20-ft high CS-grouted plume.

Because plume spreading does not occur in sandpacks, the desaturating effect was achieved by saturating the sandpack with grout and then blowing air through the sandpack to displace the grout. Hydraulic conductivities ranging from 3×10^{-7} to 1×10^{-5} m/s were observed after the first injection, which are similar to the values of order 10^{-6} m/s observed in Los Banos field samples. After two or three such injections, hydraulic conductivity was reduced to 10^{-10} m/s, i.e. close to the type (i) laboratory result.

The grouted Los Banos material is 2 orders of magnitude less permeable than the ungrouted sand fraction of these materials. The sand fraction is less permeable than the actual soil due to its finer texture. Compared to the field measurement of air permeability, these samples indicate a permeability reduction by 3 to 4 orders of magnitude. In that respect, the results are very encouraging.

Data from the tiltmeter measurements were inverted in order to relate the tiltmeter measurements to the shape and extent of the injected grout plume. Based on the inversion results, the ground motion due to injection could be predicted. The peak vertical displacement of the land surface due to injection of CS was found to be 0.18 micrometers. The preliminary work suggests that tilt measurements can be used to monitor subsurface injections. However, further refinement of the technique is required for future application.

IV. SUMMARY AND CONCLUSIONS

A first stage field injection of colloidal silica and polysiloxane grout was successfully completed. The fluids were injected at depths of 10 ft to 14 ft in a heterogeneous unsaturated deposit of sand, silt and gravel, typical of many arid DOE cleanup sites and particularly analogous to the conditions of the Hanford Reservation.

Both grouts effectively permeated gravel and sand beds. Despite the extreme heterogeneity, both the CS and the PSX-10 created fairly uniform plumes. Within the grouted plumes, both large and small pores were grouted. The CS grouted plume did not have substantial cohesiveness or strength, but allowed vertical sections of the soil to be exposed. Unlike CS, PSX-10 imparts structural strength and elasticity to the grouted soil. PSX-10 is relatively easy to identify in the subsurface and gave sufficient strength to very loose gravels without any cohesiveness to form vertical walls.

Characterization of *in-situ* permeability at the site was carried out using both the SSP and DDP methods. The dual probe technique, sampling a larger volume of material, gave permeabilities at least an order of magnitude higher than the single hole measurements. Tiltmeters were used successfully to monitor surface displacements during grout injection. The resulting data were then inverted to model the shape of the subsurface plume, which had produced the observed surface displacement.

In conclusion, the first field test was a success and the test objectives were all achieved.

Table 1. Hydraulic Conductivity Measurements on Laboratory and Field Samples of Grouted Sand

Sample	Sample Type	Sample Length (in.)	Hydraulic Gradient (-) x10^3	Cell Bias Pressure (psi)	Hydraulic Conductivity (m/s)
Hanford sand, PSX-10,#1	laboratory injection	4	69.767	14	4.08×10^{-12}
Hanford sand, DP5110, #1	laboratory injection	2	13.953	20	1.03×10^{-09}
		2	13.953	40	6.33×10^{-10}
		2	13.953	60	4.60×10^{-10}
		2	41.86	60	4.20×10^{-10}
Los Banos sand, PSX-10, #1	cored field sample	3	9.302	5	2.28×10^{-6}
		3	9.302	10	1.52×10^{-6}
		3	9.302	20	1.14×10^{-6}
		3	27.907	20	1.24×10^{-6}
Los Banos sand, PSX-10, #2	cored field sample	3	4.651	10	4.52×10^{-6}
		3	4.651	20	2.75×10^{-6}
		3	4.651	40	2.15×10^{-6}
Hanford sand, DP5110, #2	sand added to DP5110	3	9.302	5	6.48×10^{-10}
		3	9.302	10	3.39×10^{-10}
		3	9.302	20	2.02×10^{-10}
Los Banos sand, DP5110, #1	carved field sample	2	6.977	5	3.96×10^{-6}
		2	6.977	10	3.07×10^{-6}
		2	6.977	20	2.59×10^{-6}
Los Banos, DP5110, #2	carved field sample	2	6.977	5	6.02×10^{-6}
		2	6.977	10	3.63×10^{-6}
		2	6.977	20	2.85×10^{-6}
Hanford, PSX-10, #2	laboratory injection	3	46.512	10	2.90×10^{-6}
		3	27.907	20	3.37×10^{-7}
		3	27.907	40	1.70×10^{-8}
		3	55.814	40	1.18×10^{-8}
		3	55.814	60	6.03×10^{-9}

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REFERENCES

1. G.J. Moridis, P. Persoff, H.-Y. Holman, S.J. Muller, K. Pruess, P.A. Witherspoon, and C.J. Radke, "Containment of Contaminants through Physical Barriers Formed from Viscous Liquids Emplaced Under Controlled Viscosity Conditions', *FY 1993 Annual Report,* Lawrence Berkeley Laboratory Report LBL-29400, Berkeley, CA (1994).

2. G.J. Moridis, P. Persoff, H.-Y. Holman, S.J. Muller, K. Pruess and C.J. Radke, "New Barrier Fluids for Containment of Contaminants", *Proceedings of ER '93 Environmental Remediation Conference*, Augusta, GA, Lawrence Berkeley Laboratory Report LBL-34673, Berkeley, CA (1993).

3. P. Persoff, G.J. Moridis, J.A. Apps, K. Pruess and S.J. Muller, "Designing Injectable Colloidal Silica Barriers for Waste Isolation at the Hanford Site", *33rd Hanford Symposium on Health and the Environment --In-Situ Remediation: Scientific Basis for Current and Future Technologies,* G.W. Gee and N.R. Wing, Eds., pp.87-100, Battelle Press, Richland, WA. (Nov. 7-11, 1994). (Lawrence Berkeley Laboratory Report LBL-35447, Berkeley, CA)

4. P. Persoff, S. Finsterle, G.J. Moridis, J. Apps, K. Pruess, and S. Muller, "Injectable Barriers for Waste Isolation", *Proceedings of ASME/AIChE National Heat Transfer Conference*, Portland, Oregon (Aug. 5-9, 1995), AICHE Symposium Series *91* (306) pp. 58-67. (Lawrence Berkeley Laboratory Report LBL-36884, Berkeley, CA).

5. G.J. Moridis, P. Persoff, J.A. Apps, L. Myer, K. Pruess, and P. Yen, "A Field Test of Permeation Grouting in Heterogeneous Soils Using a New Generation of Barrier Liquids", Lawrence Berkeley Laboratory Report LBL-37554, Berkeley, CA (1995).

6. K. Pruess, "TOUGH2 - A General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow", *Lawrence Berkeley Laboratory Report LBL-29400*, Berkeley, CA (1991).

7. S. Finsterle, G.J. Moridis, and K. Pruess, "A TOUGH2 Equation-Of-State Module for the Simulation of Two-Phase Flow of Air, Water, and a Miscible Gelling Liquid", Lawrence Berkeley Laboratory Report LBL-36086, Berkeley, CA (1994).

8. S. Finsterle, G.J. Moridis, K. Pruess, and P. Persoff, "Physical Barriers Formed from Gelling Liquids: 1. Numerical Design of Laboratory and Field Experiments", Lawrence Berkeley Laboratory Report LBL-35113, Berkeley, CA (1994).

9. G.J. Moridis,. L. Myer, P. Persoff, S. Finsterle, J.A. Apps, D. Vasco, S. Muller, P. Yen, P. Williams, B. Freifeld, and K. Pruess, "First-Level Field Demonstration of Subsurface Barrier Technology Using Viscous Liquids", Lawrence Berkeley Laboratory Report LBL- 37520, Berkeley, CA (1995).

10. K. Garbesi, "Toward Resolving Model-Measurement Discrepancies of Radon Entry into Houses", Lawrence Berkeley Laboratory Report LBL-34244, Berkeley, CA (1994).