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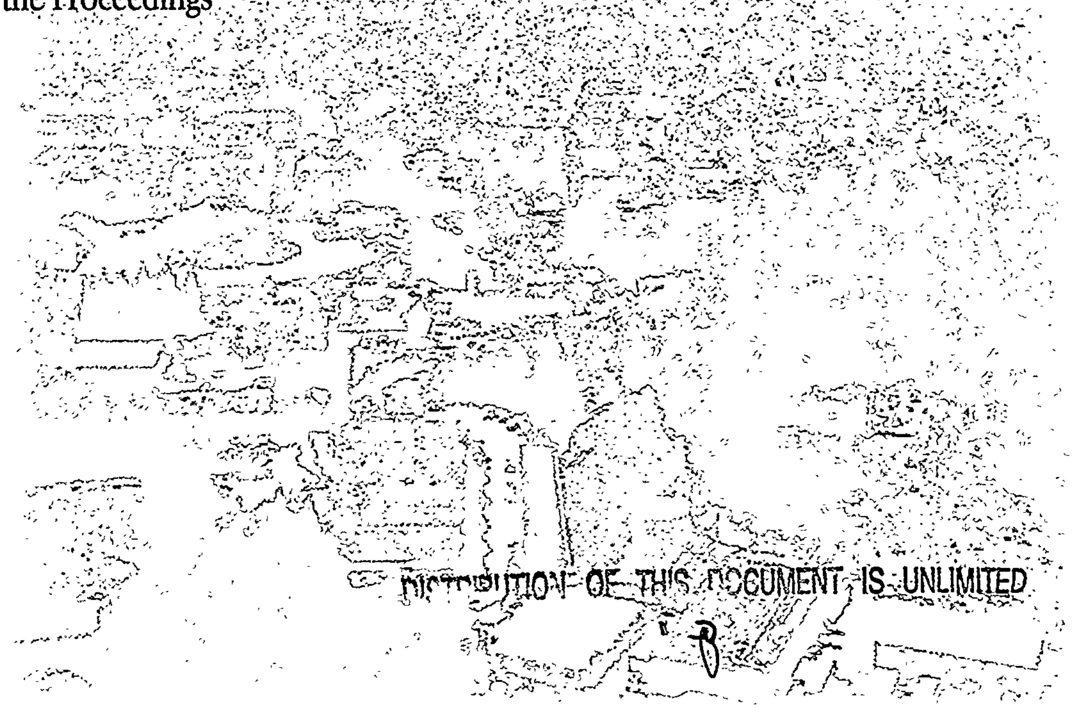

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DISCLAIMER

DEVELOPMENT OF A DESIGN PACKAGE FOR A VISCOUS BARRIER AT THE SAVANNAH RIVER SITE

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1. INTRODUCTION

This paper describes elements of a design for a pilot-scale field demonstration of a new subsurface containment technology for waste isolation developed at the Lawrence Berkeley National Laboratory (LBNL), which uses a new generation of barrier liquids for permeation grouting. The demonstration site was Retention Basin 281-3H, a shallow catchment basin at the Savannah River Site (SRS), originally built to control contaminated runoff for the H Reactor, and which has been contaminated mainly by radionuclides.

The LBNL viscous barrier technology employs barrier liquids which, when injected into the subsurface, produce chemically benign nearly impermeable barriers through a very large increase in viscosity. The initially low-viscosity liquids are emplaced through multiple injection points in the subsurface and 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 it is important to match the barrier liquid to the waste and to the soil conditions, and to control the gel time and the barrier emplacement (Moridis et al., 1994; Persoff et al., 1994, Moridis et al., 1995).

The barrier liquid to be used in this application 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 a strong electrolyte added immediately prior to injection at ambient temperatures. The CS has a tendency to interact with the geologic matrix, and therefore, a surface-modified formulation is used. This CS variant is significantly less susceptible to soil (Moridis et al., 1995), and is stabilized at a near-neutral pH by a permanent particle charge produced by partial isomorphic replacement of surficial Si by Al. Detailed information on the CS properties and behavior, as well as on the interaction with the SRS soils and on the selection procedure can be found in Moridis et al. (1996).

2. PROBLEM DESCRIPTION AND ISOLATION APPROACH

Basin 281-3H is a shallow retention/seepage basin at the Savannah River complex, which contains standing water and is contaminated mainly by radionuclides. Of particular concern are ^{137}Cs, ^{90}Sr, and ^{238}Pu. The groundwater table is thought to be shallow (possibly a perched water table) and to vary seasonally between 1.2 and 3.6 m from the surface. Most of the contamination is believed to be in the top 0.3-0.6 m from the surface and from the basin bottom. In addition to the contamination in and around the basin, a pile of contaminated excavated soil is located on the west side of the basin. Radionuclide-laden water migrates towards the water table through infiltration of rainfall or when a rising watertable intercepts the contaminated zone, and creates a plume carried by the regional groundwater flow. Waste containment and isolation are a prerequisite for placement of the soil pile in the basin.

Current plans for Retention Basin 281-3H call for removal of the contaminated water from the basin, moving the contaminated soils into the basin, and isolating the basin from the surrounding environment. Waste isolation includes (a) establishing a hydraulic barrier beneath the contaminated material in the basin to prevent infiltration of contaminated water, and (b) placement of a low permeability cap on top of the contaminated material. The humid conditions at the site dictate the use of CS: CS is water based, and as such it can easily seal the water-filled pores. Compared to the other baseline technologies (such as slurry walls and removal and disposal) the LBNL subsurface barrier technology offers several advantages. It entirely isolates the affected area from the regional groundwater flow by providing barriers to both horizontal and vertical flow. It makes possible the isolation of waste through the least intrusive approach. Because it relies on permeation, no soil is excavated during injection and the risk of human exposure is substantially reduced.

3. DESIGN OBJECTIVES AND CRITERIA

The design criteria include: (a) spatially averaged hydraulic conductivity between the isolated soil volume and the surroundings of 10^{-9} m/sec or less, (b) minimum cumulative thickness of the grouted soil horizons in the direction of potential flow of 0.9 m (3 ft) or more, and (c) demonstrated lack of hydraulic communication between the isolated volume and the surrounding soils. In this paper, however, we do not discuss verification-related design issues.

4. BARRIER SPECIFICATIONS AND CONCEPTUAL MODEL

Figure 1 is a plan view of the retention basin 281-3H. The basin dimensions are 61 m (200 ft) by 36.6 m (120 ft) by 1.83-2.44 m (6-8 ft). Figure 2 is a cross-section of the basin prior to barrier emplacement. The soil pile (i.e. the most contaminated soils) is first placed at the bottom of the basin and is distributed as uniformly as possible. The top 0.6 m (2 ft) of the soil of the area within the basin fence are then stripped and placed in the basin. The contaminated soils are then be covered with 0.6 m (2 ft) of clean soil to provide the necessary physical and radiation protection for the barrier emplacement operations.

The barrier conceptual model and geometry are shown in Figure 3, and involve the creation of a compound barrier system which seals all the permeable zones to a depth of 6.1 m (20 ft) and incorporates(a) a minimum of 0.9 m (3 ft) and a maximum of 1.2 m (4 ft) cumulative thickness of grouted horizons, coupled with and complementing (b) the naturally low permeability of soils at the basin site. This design provides a needed additional level of safety, and protection and isolation of all potential primary and secondary sources of contamination to a depth of 6.1 m (20 ft) from current grade. The primary sources are the contaminated soils inside the sealed basin, and the secondary sources are created by contaminants outside the basin. Preliminary permeability data (Moridis et al., 1996) indicate that acceptable permeable zones to a depth of 6.1 m are rather few and quite thin. Emplacement of this barrier in essence involves injections at multiple target zones, but the total thickness of CS-grouted horizons is not expected to exceed 0.9-1.2 m. The total volume of CS is estimated between a minimum of 910,000 kg and a maximum of 2,135,000 kg.

The main reason for adopting this conceptual design is the fact that the bulk of radioactivity is estimated to be at least 200 Ci, and is expected to be concentrated mainly in the soil pile. These soils will be placed at the bottom of the basin. A significant amount of water, the primary migratory vehicle of the contamination, will remain in the basin after drainage and will be in contact with highly contaminated materials. The additional level of safety required by the radioactivity necessitates the sealing of any conductive pathways between the bottom of the basin and the groundwater. Such conductive pathways are suggested by the fact that the water level fluctuations in the basin cannot be fully accounted for by rainfall and evapotranspiration. The barrier conceptual model in Figure 3 is based on the assumption that low permeability sediments are present underneath the basin, with discontinuous zones of locally high permeability. Such a soil profile is suggested by preliminary permeability analyses (Moridis et al., 1996). Should the natural sediments underneath the basin involve zones with hydraulic conductivities of 10^{-6} m/sec or higher in a matrix with a predominant hydraulic conductivities of 10^{-8} m/sec, the creation of the barrier in essence complements the naturally low permeability. In this sense the barrier emplacement in the lower horizons (beneath the basin) involves identification and sealing of the permeable layers, while the CS at the bottom of the basin will prevent contaminant migration from the basin toward the groundwater.

5. THE BARRIER EMPLACEMENT METHOD

After evaluating several barrier emplacement alternatives, lance injection was selected as the barrier emplacement method. Lance injection offers several attractive features. The injections are closely spaced, and accurate emplacement is easy to achieve. It requires no drilling fluids, and no cuttings or slurry are expelled during penetration. Three lances can be simultaneously forced into the soil using a hydraulic mechanism, thus increasing the rate of barrier emplacement while eliminating the risk of contaminant dispersion in the air, which could pose a problem when using pneumatic techniques such as ODEX for well drilling. It has a significant cost advantage compared to traditional well drilling techniques because it doesn't require well completion. Injection begins from the top of the intended injection zone, and proceeds downward (downstage method). It eliminates the downward spread of contaminants, a common problem of drilling methods. Lance injection results in a barrier consisting of overlapping grout bulbs (see Figure 3), and allows repeated injections and/or re-treatment of the grouted zones. It allows visual monitoring of work at all times, and is compatible with many methods of emplacement and post-injection barrier verification.

6. BARRIER EMPLACEMENT DESIGN CALCULATIONS

6.1. Injection Grids and Strategy

The injection pattern involves two grids (Figure 1) : the primary grid (i.e. the first pass) and the secondary grid (second pass), which is offset from the primary and injects into the centers of the primary grid. The grid spacing is expected to range between 0.6 and 1.5 m, and will be more accurately estimated after additional permeability tests. The injection strategy is dictated by the saturation conditions of the subsurface, and differs for saturated and unsaturated conditions. Unsaturated conditions allow somewhat higher pressures, simultaneous injection from all three lances (in 3-pronged systems), and shorter gel times. Saturated conditions could preclude simultaneous use of more than two lances (to avoid less than satisfactory coverage), and require lower injection pressures and longer gel times (several hours long).

Simulations of constant pressure gel injection into a fully saturated two-dimensional Cartesian mesh have been performed in order to continue the exploration of gel content between multiple side by side injection ports. For all simulations, a gel of 4.5 cP viscosity is injected into a horizontal, 2-D water saturated domain with a uniform permeability of 5×10^{-13} m^2 (0.5 darcy).

The simulations involve port spacings and pressures expected in field application, and model two different injection scenarios in order to maximize gel content between ports. Figure 4 is a plan view illustrating gel placement after 1800s (0.5 hrs.) of simultaneous 2 port injection and 1.5 hrs. natural evolution. Observations are made at t = 2 hrs. Port locations are labeled and the 2-D grid is halved along the line of symmetry at port 2. Grid blocks between injection ports 1 and 2 are 1 mm in length (x axis). Initial pressure conditions throughout the domain were set at roughly 2.22091×10^5 Pa (2 atm or 32 psi) based on a subsurface depth of 4.57 m (15 ft). The constant pressure injection was set at 6.89×10^5 Pa (100 psi). Contour lines of gel mass fraction in Figure 4 indicate that there is a zone between the two injection ports with less than 10 % gel due to this injection scheme. If injection were continued, this area would eventually be filled with gel and a low gel zone would not exist. The relevancy of this series of simulations is to show that given an injection period beyond which we cannot extend, there may exist a zone between injection ports of low gel content. If this is the case, a manner in which to maximize gel coverage in the area between the injection ports is the selection of optimal injection schemes.

Figure 5 shows grout placement at t = 2 hrs. for the second injection scheme, a staggered gel injection. Gel injection occurs via port 1 for 0.5 hrs. at 6.89×10^5 Pa (100 psi), followed by injection from port 2 at the same constant pressure for the next 0.5 hrs. The system is then allowed to evolve naturally. Comparison of these two simulations shows that the staggered scheme increases gel content in the zone between ports for the same time allowed for injection from all ports and essentially the same amount of injected gel. The obvious conclusion is that a staggered injection scheme favors a more effective and uniform filling of the pore space with CS.

6.2. Injection Under Variably Saturated Conditions

The TOUGH2 simulator (Pruess, 1991) using the EOS11 (Finsterle at al., 1994) gelation module was used to perform preliminary simulations of water injection under saturated and unsaturated conditions. For these preliminary calculations, we inject water only with no CS present. From a series of simulations, we constructed injection curves. The injection curves are plots of water injection rate *vs.* lance tip pressure for injection at constant pressure conditions for various values of permeability. The approximately linear relations between pressure (P), permeability (k), injection rate (q), and viscosity (m) in the system allow relatively easy interpolation between curves, and straightforward approximation of injection rates and pressures.

The conceptual model of the system considers a single lance injection in a two-dimensional radial (*r-z*) system with homogeneous isotropic permeability. Parameters for the problem are presented in Table 1. In Figures Figure 6 and 7 we show the injection curves for unsaturated and saturated injection scenarios, respectively. The injection rate plotted is the time averaged mass injection rate over the first 10 minutes of injection.

The injection curves for unsaturated conditions (Figure 6) show that injection rates are relatively small for the low k formations expected at the site. We see further that there is a k below which we effectively cannot inject water over any reasonable time period due to the low injection rate. Note that injection curves for all lower k's will plot between the x-axis and the $k = 5\times10^{-14}$ m^2 curve. Thus the surface defined by the constant k curves has a very sharp drop-off at about $k = 5\times10^{-13}$ m^2. As k increases above 10^{-13} m^2, injection rates increase significantly. The corresponding hydraulic conductivity K values (in m/sec) are obtained by multiplying k by the factor 9.81×10^{6}. In Figure 7 we show the injection curves for saturated conditions. Under saturated conditions, injection rates are slightly smaller than in unsaturated conditions due to the need to displace existing water in the formation under saturated conditions. We observe the same steep edge to the surface defined by the permeability curves as observed in the unsaturated case. However, as k increases, we do not see as rapid an increase in injection rates as we see for the unsaturated conditions.

These simulations show that it may be difficult to inject significant quantities of water or gel over any practical time frame into the low-permeability formations expected at the H-Area site. The simulations do not account for permeability heterogeneity or anisotropic permeability which may allow higher injection rates. To account for the effects of the CS viscosity (expected to be in the 5-6 cP range), the pressures or injection rates illustrated in Figures 6 and 7 have to be scaled accordingly by dividing rates or multiplying pressures by the CS viscosity.

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Table 1. Parameters for the Injection Curve Simulations

Parameter	Symbol	Value
porosity	ϕ	0.3
compressibility	COM	4.4×10^{-8}
permeability	k	$10^{-11} - 5\times10^{-14}$ m^2
temperature	T	15 ^{o}C
viscosity of injected water	μ	1.136×10^{-3} Pa s
lance injection interval	L_i	0.16 m
lance injection depth	d_i	6.49 m
max. capillary pressure	$P_{cap\ max}$	10^5 Pa
residual liquid saturation	S_{lr}	0.20

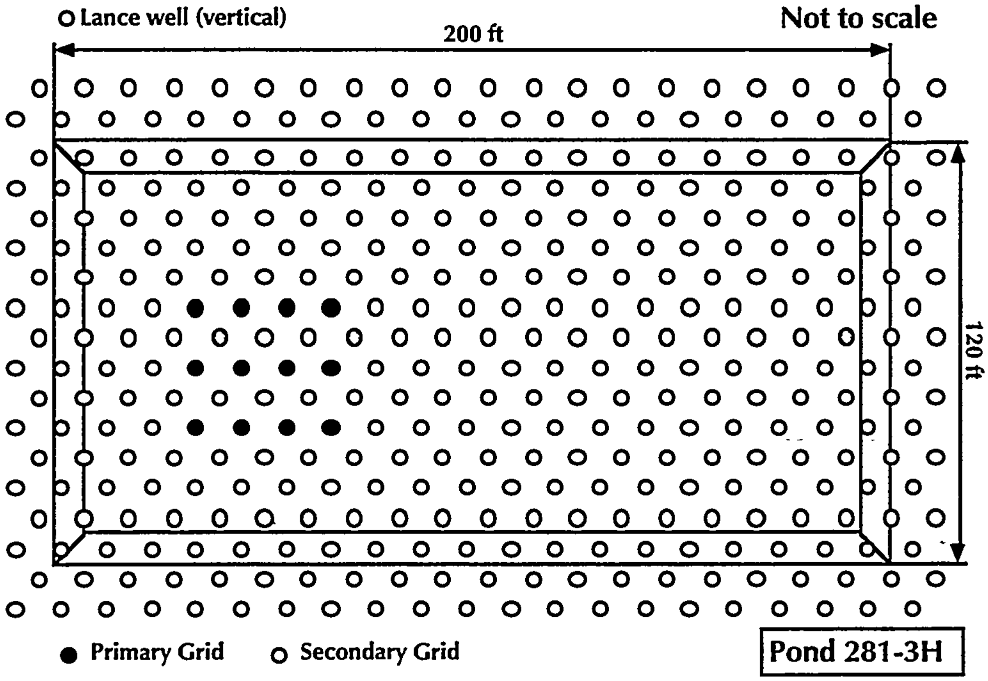

Figure 1. Plan view of the basin and of the subsurface barrier emplaced using lance injection.

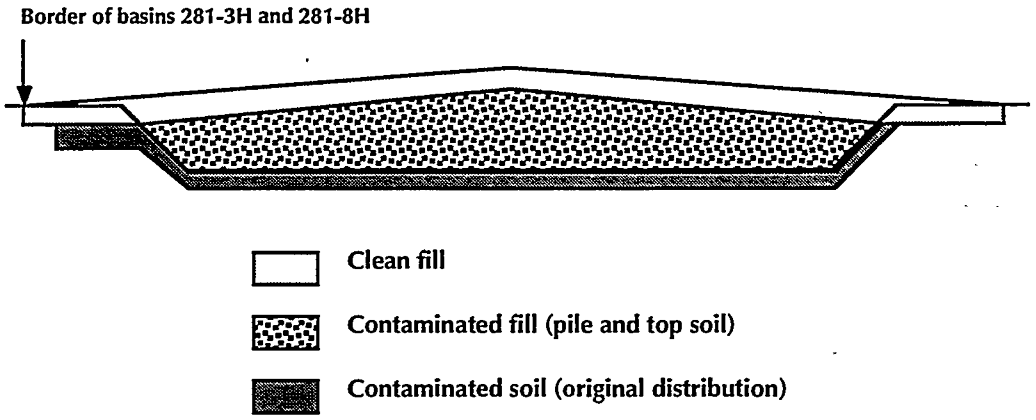

Figure 2. A schematic of the barrier immediately before the barrier emplacement.

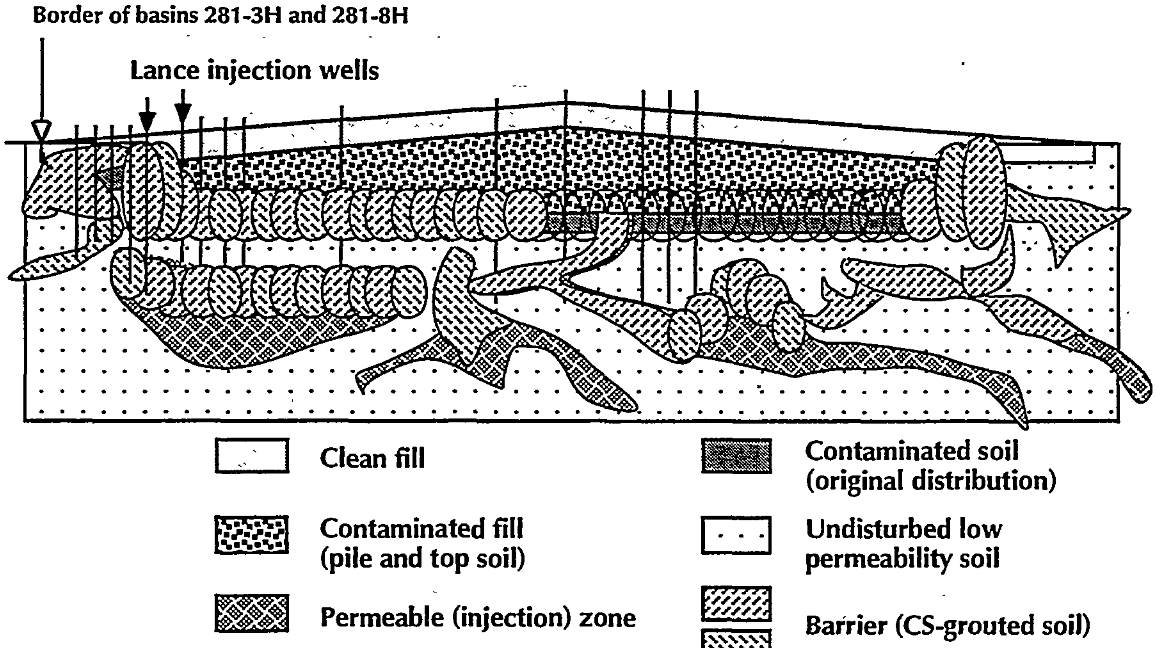

Figure 3. Conceptual model of the barrier.

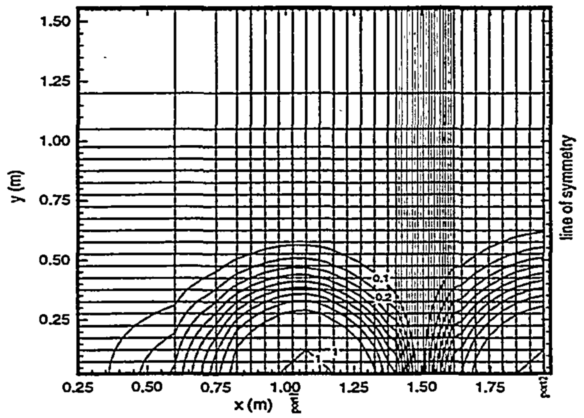

Figure 4. Simultaneous 2 port grout injection.

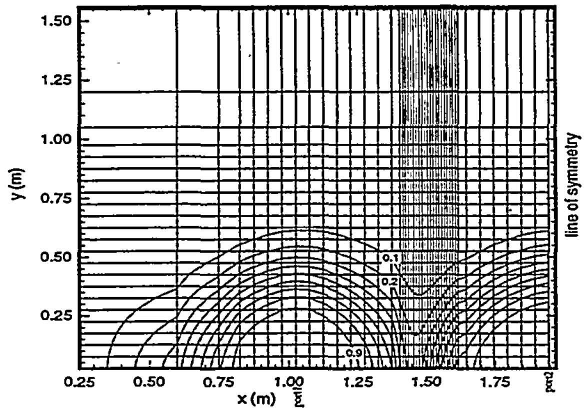

Figure 5. Staggered middle port injection.

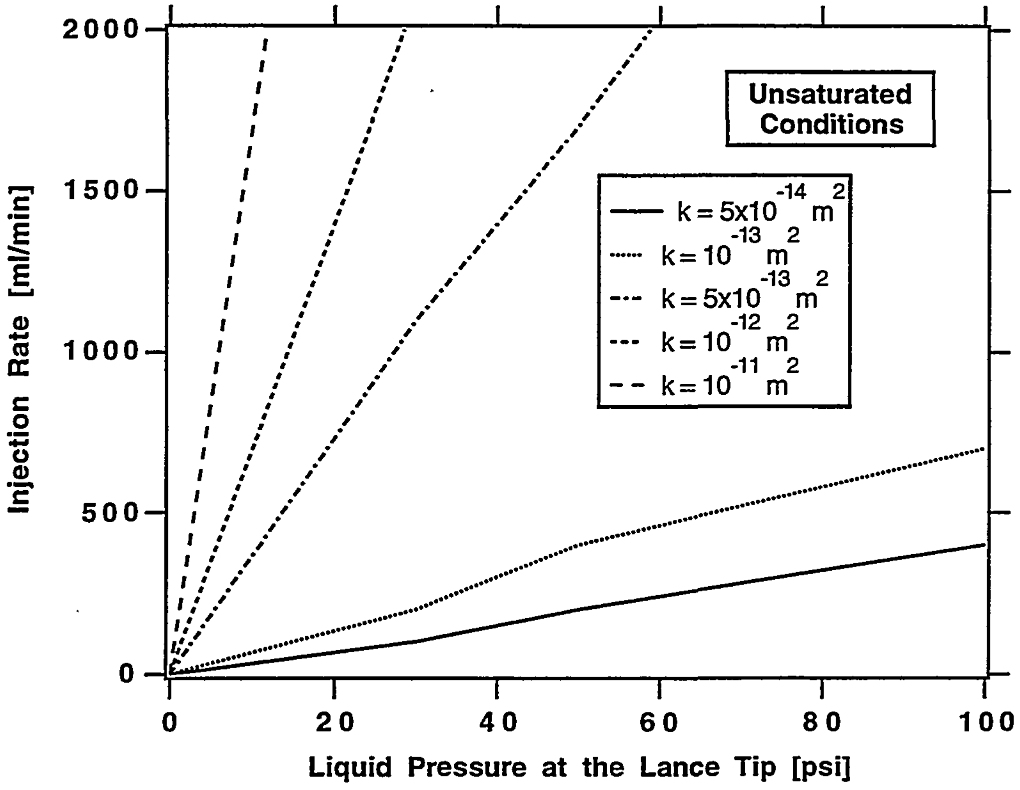

Figure 6. Injection curves for saturated conditions (water injection).

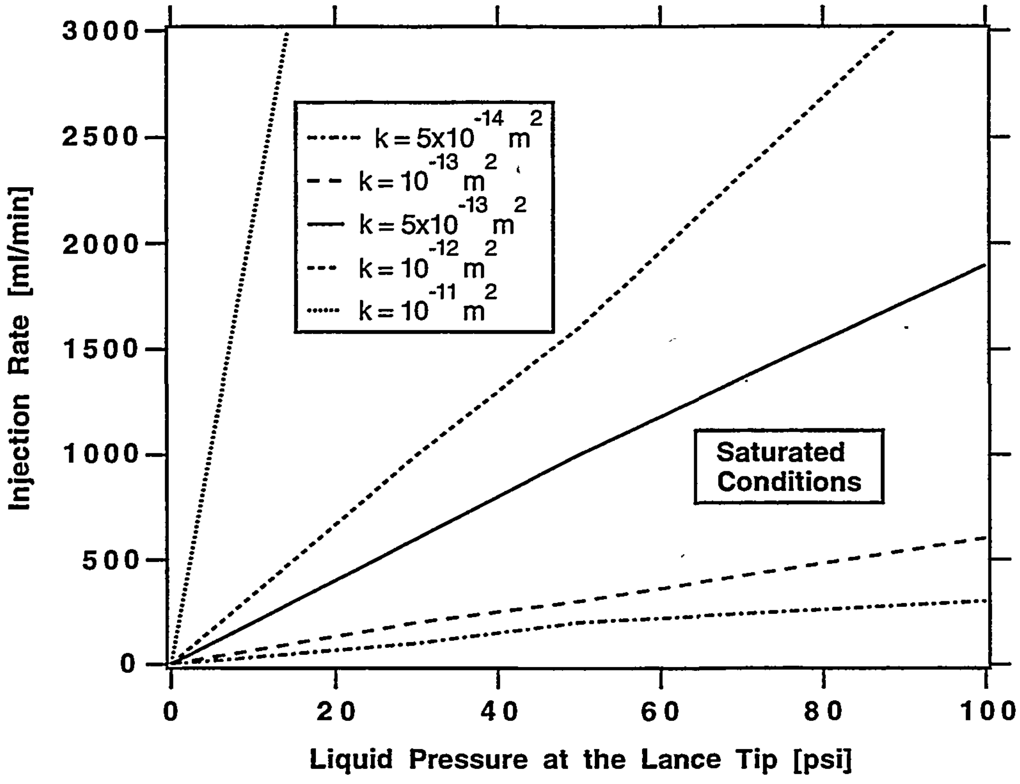

Figure 7. Injection curves for saturated conditions (water injection).