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*Performance of Horizontal Versus
Vertical Vapor Extraction Wells*

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PERFORMANCE OF HORIZONTAL VERSUS VERTICAL VAPOR EXTRACTION WELLS

by

Kay H. Birdsell, Nina D. Rosenberg, and Kimberly M. Edlund

ABSTRACT

Vapor extraction wells used for site remediation of volatile organic chemicals in the vadose zone are typically vertical wells. Over the past few years, there has been an increased interest in horizontal wells for environmental remediation. Despite the interest and potential benefits of horizontal wells, there has been little study of the relative performance of horizontal and vertical vapor extraction wells. This study uses numerical simulations to investigate the relative performance of horizontal versus vertical vapor extraction wells under a variety of conditions. The most significant conclusion that can be drawn from this study is that in a homogeneous medium, a single, horizontal vapor extraction well outperforms a single, vertical vapor extraction well (with surface capping) only for long, linear plumes. Guidelines are presented regarding the use of horizontal wells.

EXECUTIVE SUMMARY

Vapor extraction wells used for site remediation of volatile organic chemicals in the vadose zone are typically vertical wells. Over the past few years, however, there has been an increased interest in horizontal wells for environmental remediation. In some cases, such as remediating areas where vertical access is limited (under buildings or waste sites), horizontal wells are clearly advantageous. In other cases, the advantage of horizontal over vertical wells is less clear. Despite the interest and potential benefits of horizontal wells, there has been little study of the relative performance of horizontal and vertical vapor extraction wells. Conclusions about horizontal wells from experience in the petroleum industry and with groundwater pump-and-treat may not be directly applicable to vapor extraction systems.

This report focuses on the relative performance of horizontal versus vertical vapor extraction wells under a variety of conditions. The study is based on numerical simulations of highly simplified systems, assuming perfect knowledge of the plume. We study the role that plume geometry, surface capping, well placement, screen length and extraction rate have on remediation in a homogeneous material. We then examine more realistic cases with heterogeneous media.

The most significant conclusions that can be drawn from this study are the following:

- In an accessible, homogeneous medium, a single horizontal, vapor extraction well outperforms (i.e., achieves a lower level of residual contamination in a shorter amount of time) a single vertical, vapor extraction well at a capped site only for a long linear plume. Here, "long" means that the plume extends beyond the radius of influence of the vertical well. However, the radius of influence of a vertical well can often be increased so that it

"beats" the horizontal well by increasing its extraction rate. Also, two vertical wells with site capping may outperform a single horizontal well if the plume extends beyond the radius of influence of the single vertical well. A horizontal well often outperforms a vertical well in the absence of site capping.

- For heterogeneous systems, site-specific simulations are required to determine the most effective remediation strategy. However, we believe that the above conclusions are generally true for an accessible, heterogeneous medium (e.g., low permeability clay lenses in a relatively high permeability sand) as well. Clay lenses can produce significant contaminant shadows by diverting flow. These shadows can be predicted given information about the properties and location of the clay lenses and the location and orientation of the extraction well.
- Given that horizontal wells are generally more expensive to install than vertical wells, vertical vapor extraction wells used in conjunction with site capping are recommended over horizontal vapor extraction wells with a few exceptions. These exceptions are for long (see above) contaminant plumes, at sites where vertical access is a problem, or in cases where surface capping is difficult. For long linear plumes, a site-specific, cost-benefit analysis to balance relative performance with costs (e.g., installing the different wells, purchasing and operating blowers, and treating different quantities of contaminated air), contaminant levels and cleanup goals is suggested.
- For maximum removal efficiencies during vapor extraction the following guidelines are suggested. Surface capping should be used with vertical extraction wells. Both horizontal and vertical wells should be screened over the entire length of the plume. A horizontal well should be placed at the lower edge of the plume (perpendicular to flow direction) and aligned with the plume's major axis in the horizontal plane. A vertical well should be placed in the center of the plume.

This study did not consider the relative performance of horizontal versus vertical vapor extraction wells for fractured media. Horizontal wells may provide an advantage for remediating areas with contaminant located in vertical fractures by intercepting a greater number of fractures than possible with a vertical well. Also, this study considered only vapor extraction. It could be extended to include groundwater pumping and air sparging wells.

INTRODUCTION

Vapor extraction is a common environmental technology for remediating contamination of volatile organic chemicals (VOCs) in the vadose zone (Baehr et al. 1989; Johnson et al. 1990). The principle behind this technology is straightforward. Fresh air is drawn by vacuum through a contaminated soil toward an extraction well. The fresh air flushes contaminated air from the soil pores. By replacing contaminated air with fresh air, additional contaminants in the liquid phase volatilize in order to reestablish vapor-liquid equilibrium. These vapor phase contaminants are then removed by further vapor-phase extraction. The fresh air can be drawn from the ground surface or supplied by an injection well.

Vapor extraction wells used for site remediation are typically vertical wells. Over the past few years, however, there has been an increased interest in horizontal wells for environmental remediation. The use of horizontal wells for in situ air stripping (air injection combined with vapor extraction) was demonstrated in 1990 at the Department of Energy's (DOE's) Savannah River site (Looney et al. 1991b). In general, horizontal wells are more costly to install than vertical wells (Schroeder et al. 1992). In some cases, such as remediating areas where vertical access is limited (under buildings or waste sites), horizontal wells are clearly advantageous. In other cases, the advantage of horizontal over vertical wells is less clear.

Despite the interest and potential benefits of horizontal wells, there has been little study of the relative performance of horizontal and vertical wells. The one comparative modeling study related to environmental restoration of which we are aware (Langseth 1990) concerns pumping wells in the saturated zone. The author concludes that horizontal wells generally offer better performance than vertical wells where the plume is vertically thin. Horizontal wells have been used effectively in the petroleum industry (JPT 1993). The situation in both these cases, however, is very different from environmental remediation in the vadose zone. With respect to groundwater pumping wells, natural hydraulic gradients exist, contaminant plumes are more likely to be long and narrow in the horizontal plane, and the top boundary condition is the water table rather than the ground surface. In the petroleum industry, drilling costs are much higher and zones of interest are confined and often vertically fractured. We are aware of only one comparative field study in which "side-by-side" tests of horizontal and vertical vacuum extraction wells were conducted. This test, performed at the Savannah River site (Looney et al. 1991a), was rather limited, however, because the extraction phase using the vertical wells was only 21 days long. More extensive, comparative performance assessments can assist in environmental remediation design and are necessary to a cost-benefit analysis of horizontal versus vertical wells.

This report focuses on the relative performance of horizontal versus vertical vapor extraction wells under a variety of conditions. The study is based on numerical simulations of highly simplified systems. We study the role that plume geometry, surface capping, well placement, screen length and extraction rate have on remediation in a homogeneous material. We then examine more realistic cases in which the geologic medium is heterogeneous.

MODELING APPROACH

Model Assumptions

Our approach is based on numerical simulations of highly simplified systems. We assume perfect knowledge of the porous media (either completely homogeneous or homogeneous with one or two clay lenses) and of the plume. We also assume that vapor extraction can be treated as a single (air) phase flow problem. The water phase is considered to be immobile since it moves much slower than the air phase during vapor extraction. The contaminant is distributed between the liquid and vapor phases according to Henry's law, which assumes a linear, equilibrium relationship exists between the liquid and vapor phase contaminant concentrations in dilute solutions. Studies of such simple systems compliment more complex "history-matching" simulation studies (Robinson et al. 1994).

We use the code TRACR3D for all our calculations. TRACR3D is a three-dimensional, finite difference code that models the flow of air and water in saturated and unsaturated porous media and transport of multiple chemically reactive, radioactive and sorbing tracers (Travis and Birdsell 1991). Material properties, such as porosity and permeability, can vary in space. The model allows considerable flexibility in boundary conditions and the location of injection and extraction wells. In this study, the following transport processes are modeled: advection, diffusion/dispersion, and transport of contaminant between liquid and vapor phases.

Simulations

We simulate remediation with a single vertical well or a single horizontal well, and in one case, two vertical wells. Figure 1 shows a sample geometric configuration used for the different well scenarios. For the vertical well, a sink, which represents the blower, is located at the top of the screened region but below the ground surface. For the horizontal well, the sink is located at the center of the well. The well is treated as an extremely permeable medium with an enhanced permeability along the well axis. This treatment of the well allows extraction to occur effectively along the screened interval without assuming uniform extraction. Two vertical well scenarios are considered in this study, one at a capped site and one at an uncapped site, to examine whether surface capping enhances contaminant removal by eliminating short circuiting of air along the bore hole. The cap size covers the entire plume as suggested by Gamliel and Abdul (1993). Capping is not used with horizontal wells as short circuiting from the surface is much less severe.

The modeling study has two main parts. The first concerns remediation of contaminant plumes in a isotropic, homogeneous medium (sand). The second concerns remediation of contaminant plumes in a heterogeneous medium (sand with one or two clay lenses). We make assumptions about the nature of the contaminant plume (e.g., shape, concentration levels). We then simulate a remediation effort, calculating the pressure (flow) field and contaminant concentration field at various times. The residual contamination in the model domain over the course of the cleanup is also calculated.

The homogeneous cases include two series of simulations. First, two "realistically shaped" plumes are generated: a point-source plume and a linear plume. These are then remediated by a single vertical well (capped and uncapped surface) and a single horizontal well. For each of these plumes, the contaminant leaches as a water-born solute during plume generation in order to form the desired shape. The two plumes are then used as the initial conditions for subsequent vapor extraction simulations. A bulb-shaped plume results from a point source (e.g. a leaking barrel) located at the center of the grid. A linear plume results from a line source (e.g. a leaking pipe) placed at the surface above the horizontal well. The plumes are nonuniform with higher concentrations near the original source and lower concentrations near the extremities of the plume.

Identical extraction rates (100 standard cubic feet per minute or scfm) and screened intervals (30 m) are used during vapor extraction for each well configuration.

Next, a series of simulations was run with block-shaped plumes of uniform concentration (0.5 mg/l or ppm) to evaluate the role of plume volume and aspect ratio in more detail. In these "contests" between horizontal and vertical wells, we optimize the screened interval and well placement of each well as determined from preliminary simulations. An extraction rate of 100 scfm is used. Multiple wells are considered briefly.

The second main part of this study involves heterogeneous media—sand with one or two clay lenses. Block-shaped plumes with uniform contaminant concentration are used in these simulations. The clay lenses are completely within the contaminated region. As with the simulations of block-shaped plumes in a homogeneous medium, the screened interval and well placement are optimized.

Most of the calculations are three-dimensional, although some of the simulations of heterogeneous systems were run in two dimensions. For the three-dimensional runs, only 1/4 of the model domain is simulated due to symmetry. No-flow boundary conditions are used along the four sides and the bottom. The bottom boundary condition reflects the absence of air flow along the water table. The initial air pressure field is in equilibrium with an atmospheric upper boundary condition. For the simulations with a surface cap, that region of the top boundary uses a no-flow boundary condition.

Medium and Contaminant Properties

The homogeneous medium is assumed to be sand with an initial saturation of 30% and an isotropic, saturated permeability of 20 darcys. For the heterogeneous case, a single or double lens with the hydraulic properties of a clay is added to this system. For most cases, the clay has a saturated permeability of 0.1 darcy in the horizontal and 0.03 darcy in the vertical. Some simulations using two different isotropic, saturated permeability values were also run for the clays to test the effect of clay permeability on remediation, 10^{-3} darcy and 10^{-5} darcy. In this study, the ratio of the sand to clay permeability values is of more importance than the absolute permeability values.

The contaminant used for the simulations is trichloroethylene (TCE). A Henry's law constant of 0.4 g (liquid water)/cm³ (air) and an air-phase, molecular diffusion coefficient of 0.1 cm²/s are used. The contaminant is assumed to be nonsorbing, although the effects of linear sorption are discussed briefly later in the text.

REMEDIATING A PLUME IN A HOMOGENEOUS MEDIUM

General Comments

The effectiveness of the simulated remediation efforts that are presented below is extremely high. This sort of success would not be experienced in a real field situation. Cleanup is likely to be slower and less complete due to retarding processes and heterogeneities. Robinson et al. (1994) have shown that diffusion from low conductivity regions, kinetic vaporization rates (rather than Henry's law behavior), or adsorption onto solids are plausible mechanisms to explain inhibited remediation efforts. Nonetheless, the qualitative results presented below are valid for a fairly uniform medium since the remediation is controlled by the plume geometry and the air flow patterns created by the well configuration. For processes which can be described with a linear retardation model, only the time scale of the remediation effort changes. The effect of heterogeneities is investigated later in this paper.

Since the extraction rate was held constant for most of the simulations in this study, a few simulations were run where the extraction rate was varied for a particular plume geometry to test its effect on the relative performance of the two well configurations. Suppose that a horizontal well best remediates a particular plume shape. As the extraction rate is varied the same amount for each well configuration, the horizontal well remains the "winner." As the extraction rate is increased, the efficiency for both well configurations increases, but the absolute difference in efficiencies between the well configurations decreases. This implies that, for some cases, the vertical well operating at a higher extraction rate could clean up the plume as well as the horizontal well. This is, in fact, demonstrated later in the paper. For a clayey medium where diffusion limitations control cleanup, this may not be true.

Because we are considering linear processes in these calculations, changing the initial concentration (e.g., using 50 ppm rather than 5 ppm) or the sand permeability (e.g., using 200 darcys rather than 20 darcys) would cause the same sort of results as varying the extraction rate. The time-scale to reach a particular cleanup level would change, but the winning cleanup strategy would not change. Only isotropic media are considered in these calculations. For anisotropic media, which generally have higher horizontal than vertical permeabilities, the relative performance of the vertical well to the horizontal well would increase compared to the results presented here.

Flow Fields for Horizontal and Vertical Wells

We begin by examining the zones of influence for a single vertical well and a single horizontal well. Figure 2 shows the steady air pressure fields for the vertical well at a capped site, the vertical well at an uncapped site, and the horizontal well all in the homogeneous sand. In this example, the wells were screened over the same length (30 m) and use the same extraction rate (100 scfm). Air phase velocities reach a steady state within 11 to 17 hours after extraction is begun for the three scenarios.

The vertical well with surface capping maintains a higher vacuum at the well (as shown by the darkest region along the well axis), and the vacuum extends further radially than for both the vertical well without surface capping and the horizontal well. These pressure data mean that a vertical well at a capped site maintains a larger radius of influence than at an uncapped site. For our purposes, the radius of influence (ROI) refers to the zone that is remediated, although it is often estimated in terms of pressure data where the ROI is chosen to be the distance from the well where the pressure is nearly atmospheric (Johnson and Ettinger 1992). The no-flow condition imposed by the surface cap allows for a vacuum (pressure less than one atmosphere) to exist directly beneath the cap, which covers roughly the same area as the dark region of the upper surface shown in the figure. The atmospheric boundary condition at the upper surface quenches the vacuum for the uncapped vertical well. Flow is perpendicular to the surfaces of constant pressure

(equipotential surfaces). These figures show that flow is horizontal near the top of the vertical well at the capped site. Flow is subhorizontal from the surface to the vertical well at the uncapped site, implying short circuiting. Vector plots confirming these results are shown and discussed later in this paper.

For the horizontal well, the vacuum above the well is again quenched by the atmospheric boundary condition maintained at the surface. However, the pressure gradient occurs over the full depth to the well rather than over the very shallow depth to the top of the vertical well at the uncapped site. The full radius of influence of a horizontal well is not achieved, unless the well is very deep, due to the influence of the atmospheric boundary condition at the upper surface. (Note that the well should not be placed at a depth beyond its radius of influence, or no air from the surface will flow toward the well.) The equipotential surfaces above the well are nearly horizontal causing vertical flow downward from the surface. A steep pressure gradient exists directly below the well due to the no-flow boundary condition along the bottom boundary, which represents the water table. This gradient causes flow below the well along its axis so that some contaminant removal occurs below the well. This effect was found to be even more pronounced when the numerical grid was enlarged, suggesting that it is not an artifact of the no-flow, boundary condition along the side.

Role of Plume Geometry ("Realistic" Plumes)

In this first set of simulations, two realistically shaped plumes generated by a point-source and a line-source are each remediated by single vertical wells at capped and uncapped sites, and by a single horizontal well. The results of these six simulations are discussed in this section and presented in Figs. 3 through 9. The air pressure fields for these simulations are as shown in Fig. 2.

Point-Source Plume. Figure 3 shows the residual contaminant mass fraction (mass left in ground/original mass) for the point-source plume as a function of time for the three cleanup scenarios. The vertical well with surface capping cleans the soil the most successfully, followed by the horizontal well and finally the vertical well without surface capping. Remediation by the horizontal well initially lags behind that by the vertical wells but eventually slightly surpasses that by the uncapped vertical well. This lag occurs because the horizontal well is located in a lower region of the plume, which initially has a low concentration. The vertical well is centered in the most concentrated region of the plume.

Figures 4 through 6 show the contaminant plumes at various times through the cleanup for the vertical wells at a capped and an uncapped site, and the horizontal well, respectively. (Note the change in scales.) During remediation by the vertical well at the capped site (Fig. 4), the upper portion of the plume is swept horizontally with fresh air, thus drawing the plume closer to the extraction well. The extended low pressure region developed by the cap also remediates the lower portion of the plume more effectively than for the uncapped vertical well (Fig. 5). Short circuiting between the upper boundary and the uncapped vertical well is evident in Fig. 5. The plume is drawn downward along the well axis rather than horizontally toward the well as in the capped scenario. The horizontal sweeping pattern is much more efficient for removing the contaminant plume. These results agree qualitatively with simulations of the remediation of a gasoline spill using vertical wells at both capped and uncapped sites (Benson et al. 1993).

The horizontal well (Fig. 6) cleans the plume from the upper surface, as expected. It also cleans the plume along the well axis, which helps to remediate the portion of the plume located below the well. Note that the plume shape becomes quite asymmetric, and the region below the horizontal well that is not aligned with the well axis is difficult to remediate. Also note that the plume is drawn downward before remediation starts. This leads to an initial spreading of the plume which accounts for the lag shown in Fig. 3.

Line-Source Plume. Figure 7 shows the residual contaminant mass fraction for the linear plume as a function of time for the three well configurations. After 30 days, residual levels are very similar between the vertical well at a capped site and the horizontal well. The simulation was extended to 60 days to more clearly differentiate between the two scenarios. The extended simulation shows the horizontal well reaching slightly better, cleanup levels after 60 days. In this comparison, however, the level of cleanup is so high that an actual remediation effort would be stopped before the simulated 60 day results were reached. If a residual mass balance of 10^{-6} is satisfactory, the vertical well with surface capping would be the winner in this case because it achieves that value sooner than the horizontal well. Figures 8 and 9 show the contaminant plumes at various times for the vertical well at a capped site and the horizontal well, respectively. The lag in cleanup at early times for the horizontal well is again evident as the well pulls the more highly concentrated region of the plume downward.

Two observations are noted concerning this set of simulations. First, although the plume was generated by a line source, the resulting plume shape is not particularly linear because of high capillarity in the medium. This prompted the study of plume aspect ratio that follows. Also, a region of high concentration is evident at 30 days directly below the sink region for the horizontal well. This region makes a large contribution to the residual contaminant mass fraction but is probably an artifact of the no-flow boundaries that are close to the extraction region for the horizontal well. This was confirmed by running the horizontal well simulation with an extended numerical grid, and better cleanup levels were achieved below the extraction region. This problem is not present in the sensitivity studies that follow because the horizontal well is placed at the lower edge of the plume.

Role of Plume Geometry (Block-shaped Plumes)

In this next set of simulations, block-shaped plumes with a uniform concentration (0.5 ppm) are remediated by a single vertical well with surface capping and a single horizontal well. A sensitivity study was run to examine the effects that the plume volume and the aspect ratio have on the relative performance of vertical vs. horizontal wells. A total of 15 plume geometries were examined (Table 1). Note that the aspect ratio is given as $x:y:z$, where x is aligned with the axis of the horizontal well, y is perpendicular to the axis of the horizontal well, and z is the depth. Also, the aspect ratio, plume volume, and plume dimensions are for the entire plume, rather than for just the quarter of the plume that was modeled. Figure 10 shows sample figures of the various plumes for Cases A, B, C and D with both the vertical and horizontal wells placed appropriately within the plumes. The numerical grid is much larger than the plume in each case. The results of these simulations are discussed in this section and presented in Figs. 11 through 15.

Preliminary simulations were performed with block-shaped plumes to determine the effects that screen length and well placement have on the remediation efficiency of the vertical well and the horizontal well. The results showed that the optimum screen length extends the entire length of the plume, but no longer. A horizontal well should be placed at the bottom edge of the plume. Locating the well higher in the plume decreases efficiency because the region below the well is more difficult to flush. Locating the well below the plume unnecessarily spreads the plume downward, thus increasing the duration of the cleanup effort. These results were used to optimize the screen length and well placement for the simulations presented in this section.

The performance of each well was optimized by fully screening over the depth of the plume for the vertical well or the width of the plume for the horizontal well. The vertical well was placed at the center of the plume and capped over the entire plume in all cases. The horizontal well was placed at the bottom edge of the plume. The lag experienced in the residual mass fraction curves for horizontal wells discussed above does not occur when the concentration is uniform because the well is not located in a region of low concentration.

Table 1. Summary of Simulations with Block-Shaped Plumes

<u>Case</u>	<u>Aspect Ratio</u>	<u>Total Volume (m³)</u>	<u>Plume Dimensions (m)*</u>
A-1	1:1:1/2	6912	24 (H) x 24 x 12 (V)
A-2	1:1:1/2	23328	36 (H) x 36 x 18 (V)
A-3	1:1:1/2	39753	43 (H) x 43 x 21.5 (V)
B-1	1:1:1	6912	19 (H) x 19 x 19 (V)
B-2	1:1:1	23328	28.6 (H) x 28.6 x 28.6 (V)
B-3	1:1:1	39753	34.1 (H) x 34.1 x 34.1 (V)
C-1	2:1:1/2	6912	38 (H) x 19 x 9.5 (V)
C-2	2:1:1/2	23328	57.2 (H) x 28.6 x 14.3 (V)
C-3	2:1:1/2	39753	68.2 (H) x 34.1 x 17 (V)
D-1	1.5:1:1/2	6912	31.5 (H) x 21 x 10.5 (V)
D-2	1.5:1:1/2	23328	47.2 (H) x 31.4 x 15.7 (V)
D-3	1.5:1:1/2	39753	56.3 (H) x 37.6 x 18.8 (V)
E-1	2:1:1/2	23328	57.2 (H) x 28.6 x 14.3 (V)
E-2	2:1/2:1/2	12678	57.2 (H) x 15.5 x 14.3 (V)
E-3	2:1/4:1/2	6135	57.2 (H) x 7.5 x 14.3 (V)

*The V and H show the approximate length of the vertical (V) and horizontal (H) wells used for the simulation. All vertical wells were capped over the entire plume.

Plume Volume. Figure 11 shows the residual contaminant mass fraction as a function of time for a plume with aspect ratio 2:1:1/2 (Case C) for the three total volumes listed above. Results for the vertical well (capped) and the horizontal well are shown. As expected, the efficiency of a given remediation strategy decreases as the size of the plume increases. In other words, a single well can more completely remediate a smaller plume (Case C-1) than it can larger plumes (Cases C-2 and C-3). However, for a given plume shape, the difference in the efficiencies of the two strategies increases as the plume size increases. For this particular aspect ratio, the horizontal well is more efficient by about a factor of 10, after 30 days, than the vertical well regardless of the plume size. As the plume size increases, the absolute difference in the residual mass fraction increases from $O(10^{-8})$ for the C-1 (smallest) plume to $O(10^{-1})$ for the C-3 (largest) plume. This means that the winning horizontal well configuration wins by a greater margin as the plume volume increases. For Cases A, B, and D, the vertical well with surface capping outperforms the horizontal well and also wins by a greater margin as the plume volume increases.

Aspect Ratio. Figure 12 compares the results for the simulations run with the largest plume volume, Cases A-3, B-3, C-3, and D-3. In (a), it becomes evident that a vertical well at a capped site best remediates plumes that are elongated along the vertical well axis (in the z direction). As the plumes become more linear and less centered about the z-axis, the efficiency of the vertical well decreases quite rapidly. The results for the horizontal well shown in (b) are not as clear as for the vertical well, but the horizontal well does perform slightly better as the plume becomes more linear. In (c) through (f), the relative performances for the horizontal and vertical wells for each of the four cases are compared. The vertical well outperforms the horizontal well in Cases A-3, B-3 and D-3, with the biggest difference for the plume in Case B-3 (d) (aspect ratio 1:1:1) which has the greatest portion of the plume along the vertical well axis. The Case D plumes are best remediated by the vertical well. However, the performance of the vertical wells is only slightly better than that of the horizontal wells for this plume configuration, leading us to conclude that this is close to a crossover point in the comparison between the single vertical and single horizontal wells. Case D-3 (f) was run to 60 days to be sure that the curves did not cross, and the vertical well remained the winner. The winners for the smaller volume plumes (Cases A-1, A-2, B-1, B-2, C-1, C-2, D-1, and D-2) are the same as for the cases shown in Fig. 12, but with better remediation efficiency as the plume size decreases as discussed above.

Although the Case C plumes are the most linear of the cases discussed above, they are still quite wide in the y direction. This prompted us to run another set of simulations (Case E) to study the effect that the plume width has on plume remediation. The base case plume, Case E-1, has the same dimensions as the Case C-2 plume. This plume was halved and quartered in the y direction (perpendicular to the axis of the horizontal well) producing two narrower plumes, Cases E-2 and E-3. For these simulations, the horizontal well is four times longer than the vertical well (see Table 1). Figure 13 shows the residual mass fraction curves for these six cases. Remediation by the horizontal well becomes much more effective as the plume width, perpendicular to the axis of the horizontal well, decreases. Remediation by the vertical well does not improve much with decreasing plume width because the radius of influence of the well is not large enough to effectively sweep the extremities of this long linear plume.

Some other test calculations were run on the Case B-2 plume. This plume is best remediated by using a vertical well at a capped site and has an aspect ratio such that the horizontal and vertical wells are the same length. This plume was also halved and quartered in the y direction (perpendicular to the axis of the horizontal well) to produce narrower plumes as in Case E. Similar improvements in cleanup were shown for both the vertical and horizontal wells as the plume width decreased. In this case, the radius of influence of the vertical well is large enough to reach the extremities of the plume, and the horizontal well does not show a distinct advantage as the plume becomes more linear. By comparing these results to those for Case E (Fig. 13), we see that the horizontal well wins for a long linear plume, where "long" means that it is beyond the radius of influence of the vertical well, and that as the plume becomes more linear (narrower in the y direction), the advantage that the horizontal well has over the vertical well becomes greater.

However, if the plume is linear but not long (not beyond the radius of influence of the vertical well), the vertical well (with surface capping) wins over the horizontal well, even for very narrow plumes.

Some test calculations were run with extraction rates of 200 and 400 scfm for plume E-3 using the vertical well with surface capping. These were run to determine whether the vertical well could reach the same performance level as the horizontal well by increasing the extraction rate within a normal range. The results, shown in Fig. 14, show that by increasing the flow rate to 400 scfm, the vertical well outperforms the horizontal well. Here the extraction rate is four times that used by the horizontal well, but the vertical well length is only 1/4 that of the horizontal well. For this example, a cost-benefit analysis could be used to determine which configuration to use in a true field situation.

Multiple Vertical Wells

A very limited study was performed to compare the performance of two vertical wells to a single horizontal well. Two vertical wells were placed along the center line of the Case E-3 plume. This plume was chosen because it resulted in the clearest win for the horizontal well. The vertical wells extend the full depth of the plume and dissect it such that 1/4 of the plume is outside each of the two wells and half of the plume is between the two wells. (Here again only 1/4 of the domain is actually modeled with a single well placed in the plume. The effects of the other well are obtained through symmetry.) Both wells are pumped at 100 scfm or twice the total pumping rate used by the horizontal well. However, the total length of vertical wells is still only half that of the horizontal well.

Figure 15 shows the residual mass fraction curves for the Case E-3 plume when remediated by the vertical well, the horizontal well, and the two vertical wells. The site is again capped for the vertical well simulations. The two vertical wells essentially reach the same cleanup level as the horizontal well after 30 days. From the slope of the curves, it appears that the performance of the two vertical wells will quickly surpass that of the horizontal well. By adding an extra well, the radius of influence of the two wells is now large enough to reach the extremities of this long linear plume and remediate the plume at least as well as the horizontal well. Here again a cost-benefit analysis could be used to determine which configuration to use in a true field situation. The costs associated with installing the different wells, purchasing and operating blowers, and treating different quantities of contaminated air would all need to be considered.

REMEDIATING A PLUME IN A HETEROGENEOUS MEDIUM

General Comments

Two-dimensional calculations were run using a single low permeability lens located within a homogeneous high permeability medium to illustrate the effect that a clay lens might have on the flow field and on the contaminant removal during vapor extraction. For these runs, the vertical well runs over the full depth of the right edge with extraction occurring in the top cell. The horizontal well runs over the entire bottom edge with extraction from the right, bottom cell. The permeability of the clay lens was varied to study its effect on remediation.

Note that the two-dimensional configuration eliminates radial flow to the vertical well. It also effectively makes the plume width the same as the vertical well, so that the plume is perfectly linear, and it assumes that the clay lens extends infinitely in the third (y) dimension so that no flow occurs around the lens in that dimension. All of these factors contribute to the winning of the horizontal well in the two-dimensional case. Despite this edge to the horizontal well, two-dimensional calculations can be used to examine the effect that a clay lens and that clay permeability have on contaminant removal rates in a heterogeneous system.

Three-dimensional calculations were also run using both a single low permeability lens and a pair of low permeability lenses. These simulations were run mainly to determine whether significant trapping of contaminant occurs between lenses. A plume with aspect ratio 2:1:1 was used. This plume is best remediated by a horizontal well in an isotropic, homogeneous medium, but the single and double set of clay lenses were added to see if contaminant trapped between the double lenses changes the results. The lenses were offset in the y dimension so that they are not located directly above the horizontal well.

Flow Fields for Horizontal and Vertical Wells

Figure 16 contrasts the two-dimensional velocity vector plots for runs in a homogeneous sand to those for a sand with a clay lens. These plots show the mid-range velocity vectors. The largest and smallest valued vectors are not shown. The fastest velocities occur along the well axis in each case, and also in the upper left corner (below the uncapped portion of the upper boundary) for the vertical well at a capped site and the upper right corner for the vertical well at an uncapped site. The slowest velocities occur in the clay lenses, which show up as the rectangular shape in the center of the lower set of plots. The lower valued vectors run diagonally through the clay lens for the vertical well configurations and nearly vertical through the clay lens for the horizontal well configuration.

For the vertical well at a capped site, the air enters the domain through the uncapped portion of the upper boundary. The clay lens deflects a portion of the flow resulting in higher, air-phase velocities above the clay and lower velocities below the clay than for the homogeneous case. For the vertical well at an uncapped site, the air enters along the entire upper boundary with the majority entering very close to the well. The clay lens again deflects a portion of the flow, but since the majority of the air flow short circuits directly to the top of the well, the lens has a much weaker effect on the flow field than with the capped scenario. The plots show that the higher vacuum maintained by the vertical well with site capping (see Fig. 2) results in higher velocities throughout the entire region than without capping.

For the horizontal well, the air enters uniformly along the entire upper boundary and travels to the bottom of the domain. The air flow is diverted around the clay lens causing very slow flow at the midpoint of the clay on both the upstream and downstream sides. These areas become points of stagnation as the clay permeability decreases relative to the sand permeability. This is also true at the upper left and lower right corners of the clay lens with the vertical wells.

This figure illustrates that the uniform, radial flow assumption used to calculate vapor extraction by most models does not hold in any case for a vertical well at an uncapped site. The assumption is more appropriate for a vertical well at a capped site or at a site with an upper confining layer. The underlying condition of a confined aquifer holds when the cap or confining layer is large compared to the radius of influence of the well or at least compared to the radius of the plume. The assumption of uniform radial flow is appropriate in many cases for modeling saturated, groundwater flow where water flows into the system through side boundaries. Its use should not be extended for general use in modeling vapor extraction where the air often enters from the surface or from an air injection well.

Role of Permeability Ratios

Two-dimensional calculations were used to study the effect of clay permeability on contaminant removal during vapor extraction. First a single low permeability (or clay) lens with a fairly high saturated permeability was used: anisotropic with 0.1 darcy horizontally and 0.03 darcy vertically compared to isotropic 20 darcys in the sand. More calculations with lower clay, saturated permeabilities (isotropic 10^{-3} darcy and 10^{-5} darcy) were also run.

Figure 17 shows contours for the two-dimensional calculations of the contaminant plume when remediated by vertical wells at capped and uncapped sites and a horizontal well at 2 days and 30 days. In each case, a contaminant shadow develops due to the clay lens. For the capped site, the shadow develops below the clay lens in the corner opposite the air entry region. For the uncapped site, the shadow is even more pronounced and extends above the lens due to short circuiting of the air flow. Here again, surface capping helps to increase the remediation efficiency. For both vertical well configurations, the contaminant distributions show that the plume is being swept diagonally through the clay lens. With the horizontal well, the contaminant shadow develops below the clay lens, with the highest concentration at the center point where the velocity is the lowest. The clay lens is swept vertically. Remediation is more effective because the lens is swept through its narrowest dimension rather than across the diagonal as with the vertical well scenarios. These conclusions are confirmed by the flow fields presented in Fig. 16.

The results for the three runs in Fig. 17 show that the horizontal well is the most effective because it sweeps the high, permeability clay. The sands are swept quickly by both the vertical well with surface capping and the horizontal well reaching essentially the same residual mass fraction value. This is followed by a slow sweeping of the clay, with the horizontal well performing a better sweep. The results are very similar for the simulations with the low permeability clay lenses except that the time scale for sweeping the clay lens increases. The velocities in the clay lens decrease as the clay permeability decreases. The horizontal well continues to outperform both vertical wells but by a smaller margin as the clay permeability decreases. However, since clays are often highly anisotropic with larger horizontal permeabilities, the sweep efficiency by the horizontal well will decrease with increasing anisotropy.

Role of Multiple Lenses

Three-dimensional calculations were used to look at the effect that multiple clay lenses might have on vapor extraction. A block-shaped plume was remediated by both a vertical well with surface capping and a horizontal well in a medium containing either a single clay lens or two, closely-spaced, clay lenses. The calculations show that contaminant shadows develop due to the lenses and have similar patterns to those shown in the two-dimensional calculations (Fig. 17). The shadow develops below the clay lens in the corner opposite the air entry region for the vertical well at a capped site. The shadow develops below the clay lens for the horizontal well. The shadows are enlarged when two clay lenses are present simply because the additional lens causes more flow diversion. Some trapping of contaminant occurs in the sand layer between the lenses. However,

further calculations show that contaminant removal in the clay lenses is diffusion limited. The region between the clays would be swept so much more quickly than the surrounding clay lenses that trapping between the lenses would not significantly slow down remediation, at least for the placement and limited number of lenses used in this study.

The plume geometry (aspect ratio of 2:1:1) used for this calculation is best remediated by a horizontal well in a homogeneous medium. In these simulations, where the single and double clay lenses are added, the horizontal well still beats the vertical well for this particular plume geometry. The simulation is run for only 60 days. Over this time period, the sand is swept very effectively while the contaminant in the clay lenses is basically untouched. These results indicate that with relatively few clay lenses, the plume geometry still dictates the winning well orientation for remediating the high permeability sands. This may not be true as additional lenses in a system divert air flowing toward the well. Preliminary calculations show that very little air can reach a horizontal well placed below a large clay layer. In this case, the winning well orientation is controlled by the stratigraphy rather than the plume geometry.

For heterogeneous systems, a site specific simulation is required to determine the most effective remediation strategy. The contrast between the clay and sand permeability will dictate whether clay lenses can be flushed with air or if diffusion limitations control removal of contaminants from the clays. Ho and Udell (1992) conclude that a system with permeability ratios above 100:1 is diffusion limited. In this case, horizontal flow induced by a vertical well would better sweep contaminant out of the area surrounding thin clay lenses thus speeding diffusion out of the clay lenses. For lower permeability ratios, vertical flow through thin clay lenses induced by a horizontal well may be more effective for flushing the hard-to-reach contaminant in the clay lenses. In any case, we predict that in general the horizontal well would only provide an advantage for long linear plumes, and that this advantage may be negated by using a vertical well with site capping operating at a higher extraction rate or multiple vertical wells.

CONCLUSIONS

In these calculations, we assume perfect knowledge of the plume. This is never true for a real situation. However, knowledge of the plume can be gathered through sampling, from information about the original contaminant source, and by modeling plume generation. This knowledge can be used in conjunction with the results of this study to make a decision as to the orientation, placement, and screen length of a vapor extraction well that will give the best performance during environmental remediation.

The most significant conclusions that can be drawn from this study are the following:

- In an accessible, homogeneous medium, a single horizontal, vapor extraction well outperforms (i.e., achieves a lower level of residual contamination in a shorter amount of time) a single vertical, vapor extraction well at a capped site only for a long linear plume. Here, "long" means that the plume extends beyond the radius of influence of the vertical well. However, the radius of influence of a vertical well can often be increased so that it beats the horizontal well by increasing its extraction rate. Also, two vertical wells with site capping may outperform a single horizontal well if the plume extends beyond the radius of influence of the single vertical well. A horizontal well often outperforms a vertical well in the absence of site capping.
- For heterogeneous systems, site-specific simulations are required to determine the most effective remediation strategy. However, we believe that the above conclusions are generally true for an accessible, heterogeneous medium (e.g., low permeability clay lenses in a relatively high permeability sand) as well. Clay lenses can produce significant contaminant shadows by diverting flow. These shadows can be predicted given information about the properties and location of the clay lenses and the location and orientation of the extraction well.
- Given that horizontal wells are generally more expensive to install than vertical wells, vertical vapor extraction wells used in conjunction with site capping are recommended over horizontal vapor extraction wells with a few exceptions. These exceptions are for long (see above) contaminant plumes, at sites where vertical access is a problem, or in cases where surface capping is difficult. For long linear plumes, a site-specific, cost-benefit analysis to balance relative performance with costs (e.g., installing the different wells, purchasing and operating blowers, and treating different quantities of contaminated air), contaminant levels and cleanup goals is suggested.
- For maximum removal efficiencies during vapor extraction the following guidelines are suggested. Surface capping should be used with vertical extraction wells. Both horizontal and vertical wells should be screened over the entire length of the plume. A horizontal well should be placed at the lower edge of the plume (perpendicular to flow direction) and aligned with the plume's major axis in the horizontal plane. A vertical well should be placed in the center of the plume.

This study did not consider the relative performance of horizontal versus vertical vapor extraction wells for fractured media. Horizontal wells may provide an advantage for remediating areas with contaminant located in vertical fractures by intercepting a greater number of fractures than possible with a vertical well. Also, this study considered only vapor extraction. It could be extended to include groundwater pumping and air sparging wells.

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Vertical Well with Surface Cap

Horizontal Well

Fig. 1. Geometric configurations for the vertical well at a capped site and the horizontal well.

Capped Vertical Well

Uncapped Vertical Well

Horizontal Well

Fig. 2. Pressure fields for a vertical well at a capped site, a vertical well at an uncapped site, and a horizontal well, all in a homogeneous medium ($\text{max}=1.003 \times 10^5 \text{ Pa}$, $\text{min}=0.994 \times 10^5 \text{ Pa}$).

Fig. 3. Residual contaminant mass fraction vs. time for remediation of a point-source plume in a homogeneous medium.

Initial Concentration

2 Days

5 Days

max=1.e-6, min=1.e-15

10 Days

20 Days

30 Days

max=1.e-8, min=1.e-15

Fig. 4. Contours of TCE plume at various times during remediation of a point-source plume -- vertical well with surface capping.

Initial Concentration

2 Days

max=1.e-6, min=1.e-15

5 Days

10 Days

20 Days

max=1.e-8, min=1.e-15

30 Days

Fig. 5. Contours of TCE plume at various times during remediation of a point-source plume -- vertical well without surface capping.

Initial Concentration

2 Days

5 Days

max=1.e-6, min=1.e-15

10 Days

20 Days

30 Days

max=1.e-8, min=1.e-15

Fig. 6. Contours of TCE plume at various times during remediation of a point-source plume -- horizontal well.

Fig. 7. Residual contaminant mass fraction vs. time for remediation of a line-source plume in a homogeneous medium.

Initial Concentration

2 Days

5 Days

max=1.e-6, min=1.e-15

10 Days

20 Days

30 Days

max=1.e-11, min=1.e-20

Fig. 8. Contours of TCE plume at various times during remediation of a line-source plume -- vertical well with surface capping.

Initial Concentration

2 Days

max=1.e-6, min=1.e-15

5 Days

10 Days

20 Days

max=1.e-11, min=1.e-20

30 Days

Fig. 9. Contours of TCE plume at various times during remediation of a line-source plume -- horizontal well.

Case A 1:1:1/2

Case B 1:1:1

Case C 2:1:1/2

Case D 1.5:1:1/2

Fig. 10. Sample block-shaped plumes for Cases A, B, C, and D.

Fig. 11. Residual contaminant mass fraction vs. time for remediation of block-shaped plumes C-1, C-2, C-3, vertical well with surface capping and horizontal well.

Fig. 12. Residual contaminant mass fraction vs. time for remediation of block-shaped plumes A-3, B-3, C-3 and D-3. (All vertical wells are at capped sites.) Results for (a) all vertical wells, (b) all horizontal wells, (c) vertical vs. horizontal for A-3, (d) vertical vs. horizontal for B-3, (e) vertical vs. horizontal for C-3, (f) vertical vs. horizontal for D-3.

Fig. 13. Residual contaminant mass fraction vs. time for remediation of block-shaped plumes E-1, E-2 and E-3 in a homogeneous medium.

Fig. 14. Residual contaminant mass fraction vs. time for remediation of block-shaped plume E-3 with variable extraction rate (100, 200 and 400 scfm) for the vertical well at a capped site.

Fig. 15. Residual contaminant mass fraction vs. time for remediation of block-shaped plume E-3 comparing a single vertical well, a horizontal well, and two vertical wells.

Fig. 16. Two-dimensional vector plots in homogeneous and heterogeneous (sand with a single clay lens) media for a vertical well at a capped site, a vertical well at an uncapped site, and a horizontal well.

Fig. 17. Contours of TCE plume at various times during remediation in a heterogeneous (sand with a single clay lens) medium for a vertical well at a capped site, a vertical well at an uncapped site, and a horizontal well.

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