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SUMMARY PERFORMANCE ASSESSMENT OF *IN SITU* REMEDIATION TECHNOLOGIES DEMONSTRATED AT SAVANNAH RIVER

by

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ABSTRACT

The Office of Technology Development (OTD) in the Department of Energy's (DOE) Office of Environmental Restoration and Waste Management is investigating new technologies for "better, faster, cheaper, safer" environmental remediation. A program at DOE's Savannah River site was designed to demonstrate innovative technologies for the remediation of volatile organic compounds (VOCs) at nonarid sites. Two remediation technologies, *in situ* air stripping and *in situ* bioremediation—both using horizontal wells, were demonstrated at the site between 1990-1993. This brief report summarizes the conclusions from three separate modeling studies on the performance of these technologies.

Volatile organic compounds (VOCs) including chlorinated solvents such as trichloroethylene (C_2HCl_3, TCE) are among the most common contaminants in groundwater and soils. A common remediation approach has been to pump the contaminated groundwater to the surface where the water is treated to remove the contaminants. This pump-and-treat approach has been successful in containing contamination and removing much of the contaminant mass at many sites. It has been less successful at remediating sites to the low levels of residual contamination required by regulatory agencies. Moreover, cleanup efforts based on pump-and-treat are often costly and slow, and they do nothing to remediate VOCs in the vadose zone which may be a long-term source of groundwater contamination.

The Office of Technology Development (OTD) in the Department of Energy's (DOE) Office of Environmental Restoration and Waste Management is investigating new technologies for "better, faster, cheaper, safer" environmental remediation. A program at DOE's Savannah River site was designed to demonstrate innovative technologies for the remediation of sites contaminated with VOCs in nonarid environments. The Savannah River Integrated Demonstration (SRID) focused on two *in situ* remediation technologies aimed at remediating VOC contamination in both the groundwater and the vadose zone at one location at Savannah River facility.

The first technology, *in situ* air stripping, was demonstrated during a field test in 1990 (Looney et al. 1991). *In situ* air stripping is a combination of air injection below the water table and vacuum extraction in the vadose zone. A second technology, *in situ* bioremediation, was demonstrated using the same wells during a field test in 1992-1993 (Hazen 1992). The goal of the *in situ* bioremediation demonstration was to stimulate naturally occurring methanotrophic bacteria at the site with injection of various amounts of methane, air and air-phase nutrients (nitrogen and phosphate) such that significant amounts of the chlorinated solvents present in the subsurface would be degraded.

Both the *in situ* air stripping and *in situ* bioremediation demonstrations used a pair of horizontal wells. Wells used for site remediation are typically vertical. 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, such as under buildings or waste sites, horizontal wells are clearly advantageous. In cases where access is not an issue, the advantage of horizontal over vertical wells is less clear.

We assessed the performance of the remediation technologies demonstrated at the SRID site using numerical simulation as a tool. We believe that significant value is added to the technology demonstrations through the assessment and evaluation of field data combined with flow and transport modeling. Field demonstrations of *in situ* remediation technologies are complex and expensive. Moreover, a field demonstration provides data on only one particular design implementation at one particular place and time. We have used modeling to learn more about the fundamental flow, transport and chemical processes involved in technology performance. We also suggest possible improvements to the technology design, predict technology performance over longer time and at different sites, and compare the performance of these and other remediation technologies.

We divided our performance assessment work into three separate studies. The first study is based on the construction of a history-match model of the *in situ* air stripping demonstration using the FEHM computer code. The second study is based on site-specific simulations of the *in situ* bioremediation demonstration using the TRAMP code. The third study is more general. It focuses on the relative performance of horizontal versus vertical vapor extraction wells in highly simplified systems using the code TRACR3D The main conclusions from these studies are give below. For details about these modeling studies, see Robinson et al. (1994), Birdsell et al. (1994) and Travis and Rosenberg (1994). Information about the computer codes is given in Travis and Birdsell (1991), Zyvoloski (1992) and Travis (1993).

In Situ Air Stripping

- The TCE concentration at the extraction well versus time can be simulated very well using a relatively, simple model with a dual porosity formulation. The model assumes a mass transfer limitation between liquid-phase TCE held up in clay lenses and the moving air, which travels mainly in the surrounding sandy zones of higher permeability.
- Cyclic operation of the system may offer substantial cost savings for only a marginal performance cost. Similarly, operating the system at lower flow rates may offer substantial cost savings for only a marginal performance cost.
- The injection of heated air through the lower well is unlikely to result in increased TCE removal. This is because only a small region is heated at any one time and as soon as air travels from a heated region to one at ambient temperature, any "extra" TCE in the air phase will redissolve.
- Aligning the injection and extraction wells at any particular angle to one another is probably not necessary. Heterogeneities in the medium are likely to be the dominant factor in governing the spreading of air in the saturated zone and for any reasonable configuration, it is very unlikely that TCE stripped from the saturated zone would not be captured by the extraction well. The injection well should be directly aligned with the major axis of the plume in the horizontal plane for the greatest likelihood of adequate air sweep through the plume.
- The TCE removal curve is asymptotic.
- The main characteristic in assessing the performance of this technology at another site is the heterogeneity of the site. For a site with 10 times less heterogeneity (as measured by the

average effective clay lens size) than the Savannah River site but otherwise identical, removing 95% of contamination would take about half the time.

- Replacing the lower air injection well with a groundwater pumping well (also horizontal) results in more TCE being extracted from the groundwater, but the amount of TCE below the water table that is removed in both cases is small.
- Time required for remediation is decreased dramatically if *in situ* destruction methods can be successfully employed in the field.

In Situ Bioremediation

- A successful strategy should include pulsing of methane. It is important to remember, however, that the diffusivity of methane in air is about 10,000 times larger than in water. Therefore, pulsing in the unsaturated zone is less effective at saturated zone pulsing rates because discrete pulses of methane will not remain as spatially separated.
- Addition of nutrients significantly accelerates the biodegradation process by allowing the methanotroph population to grow rapidly. However, nutrient injection must be controlled to prevent explosive growth of bacteria near the injection wells, resulting in pore clogging and consumption of all the food substrate (methane) before it has a chance to spread throughout the system.
- If the methane and nutrients have the same transport properties (e.g., Henry's Law coefficient), then one should inject them together. If the methane and nutrients have significantly different transport properties, as in the Savannah River demonstration, then pulsing nutrients out of phase with the methane injection and systematically varying the phase lag would allow a larger region to be remediated efficiently and effectively.
- The goal in pulsing should be to maintain discrete pulses, without creating regions where methane and nutrient levels are too low (the bacteria will die) or too high (the bacteria will grow too much). To achieve this goal, several smaller wells may be more effective than a single pair of wells in some cases.
- The total amount of TCE extracted or biodegraded by *in situ* bioremediation is significantly (~40%) higher than the amount that would have been extracted in an otherwise identical remediation without microbial degradation (*in situ* air stripping).
- In addition to removing a greater total amount of TCE from the system, *in situ* bioremediation results in lower residual levels of TCE than *in situ* air stripping—in places by a factor of three to six lower.
- Many of these same limitations of *in situ* air stripping apply to *in situ* bioremediation (e.g., long remediation times due mainly to VOCs in lower permeability clays), but *in situ* bioremediation can reduce remediation times and residual contaminant levels substantially.
- The main requirement for success is that methanotrophic bacteria exist at the site. Since methanotrophs are fairly common bacteria, this should not be a problem.
- *In situ* bioremediation with methanotrophs is not very dependent on site-specific factors at Savannah River, so the basic design of this technology should work at other sites.
- The details of technology implementation (e.g., injection strategy, well placement) which are key to its success, however, must be carefully evaluated for each new site. Site-specific scoping calculations will be necessary at each new site to determine the optimal number of wells, injection/extraction strategy, and so forth. Site-specific testing to obtain biokinetic rates to support these scoping calculations (i.e., laboratory tests on samples from the site which cover the range of nutrient, food and contaminant concentrations likely to be used or encountered) is strongly recommended.

- If VOC concentrations are much higher than at the SRID site, *in situ* bioremediation may not be effective. This is because at high concentrations, the contaminants can be poisonous to bacteria. In this case, *in situ* air stripping should be used to reduce the levels of VOCs to more moderate values before *in situ* bioremediation is attempted.

Horizontal versus Vertical Vacuum Extraction Wells

- Horizontal wells have the advantage only for long, linear plumes or if surface capping or vertical access is problematic. Often several vertical wells with site capping outperforms a single horizontal well (and may be less expensive).
- A system consisting of a horizontal air injection well and vertical extraction well(s) in the vadose zone with surface capping may be an optimal *in situ* air stripping system, provided access is not an issue and capping is possible.
- Intuition and modeling assumptions that commonly hold for saturated flow must be reexamined for vapor extraction. Also, the success of horizontal wells in the oil industry is not directly relevant to the success of horizontal vapor extraction wells—the economics and hydrological environment are significantly different.
- 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 and aligned with the plume's major axis in the horizontal plane. A vertical well should be placed in the center of the plume.

Both *in situ* air stripping and *in situ* bioremediation as demonstrated at Savannah River, while not a panacea for VOC remediation, are valuable additions to the existing "toolkit" of technologies available for environmental remediation. Details are contained in Robinson et al. (1994), Birdsell et al. (1994) and Travis and Rosenberg (1994).

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