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EPA Ground Water Issue

Steam Injection for Soil and Aquifer Remediation

Eva L. Davis

Background

Innovative technologies for subsurface remediation, including in situ techniques based on heating the subsurface to enhance the recovery of organic contaminants, are increasingly being evaluated for use at specific sites as the limitations to the conventionally-used techniques are recognized. The purpose of this Issue Paper is to provide to those involved in assessing remediation technologies for specific sites basic technical information on the use of steam injection for the remediation of soils and aquifers that are contaminated by volatile or semivolatile organic compounds. A related Issue Paper, entitled "How Heat Can Enhance In-Situ Soil and Aquifer Remediation: Important Chemical Properties and Guidance on Choosing the Appropriate Technique" (Davis, 1997), discusses the properties of some organic chemicals commonly found at contaminated sites, how these properties are affected by the presence of the chemical in a porous media, and how heat can enhance the recovery of these chemicals from the subsurface. The Issue Paper also provides information on three general types of heat-based remediation systems, and some guidance on which technique is most appropriate for different soil and aquifer conditions and for different organic chemicals.

This document contains more detailed information on how steam injection can be used to recover organic contaminants from the subsurface, the contaminant and subsurface conditions for which the process may be appropriate, and general design and equipment considerations. In addition, laboratory and field-scale experiments are described, and available treatment cost information is provided. This document is not meant to provide detailed information that would allow the design of a steam injection remediation project, but rather design considerations are provided to familiarize remediation workers with what is involved in the process.

* *U.S. Environmental Protection Agency*
National Risk Management Research Laboratory
Subsurface Protection and Remediation Division
P. O. Box 1198, Ada, OK 74820

Introduction

Steam injection was first developed by the petroleum industry for the enhanced recovery of oils from reservoirs. In petroleum industry applications, steam is injected to lower the viscosity of heavy oils and to increase the volatility of light oils. As much as 50 percent of the original oil in place may remain in the reservoir when the process becomes uneconomical and is discontinued. In the past several years, steam injection has been adapted for the recovery of organic contaminants from the subsurface, and extensive laboratory and field research has been done. When steam injection is used for subsurface remediation, the objective is to remove as much of the contamination as possible, thus reducing the residual to very low levels. The subsurface conditions dealt with by the petroleum industry versus remediation purposes are generally very different - the petroleum industry dealing with deep, confined reservoirs and the remediation industry with the shallow, generally unconfined subsurface. Thus, the petroleum industry technique and the technique for remediation purposes differ in significant ways.

Basic Principles

Consider the situation shown in Figure 1 where steam is injected surrounding a pool of a volatile contaminant in the subsurface. The figure illustrates steam injection above the water table, but steam injection for remediation purposes has also been successfully carried out below the water table (Newmark and Aines, 1995), and the basic principles described here are the same for either situation. Initially, the steam that is injected will heat the well bore, and the formation around the injection

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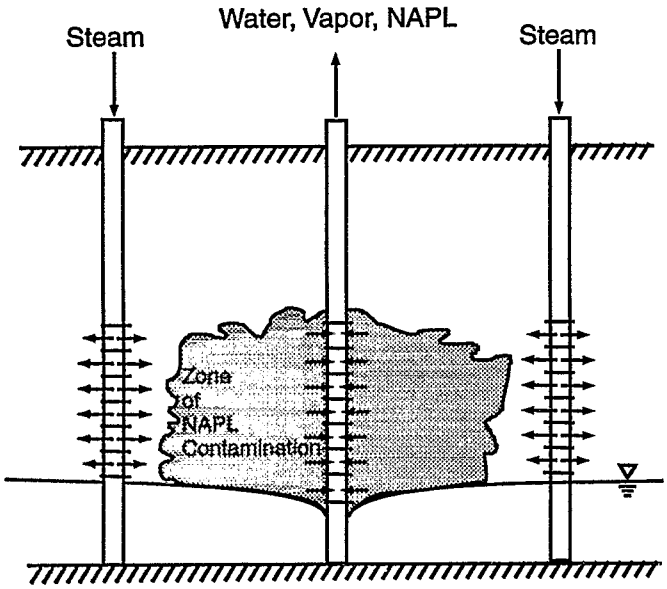

Figure 1. Diagram of a possible steam injection remediation system.

zone of the well. The steam condenses as the latent heat of vaporization of water is transferred from the steam to the well bore and the porous media where it enters the formation. As more steam is injected, the hot water moves into the formation, pushing the water initially in the formation (which is at ambient temperature) further into the porous media. When the porous media at the point of steam injection has absorbed enough heat to reach the temperature of the injected steam, steam itself actually enters the media, pushing the cold water and the bank of condensed steam (hot water) in front of it.

As these flowing fluids approach a region that contains the volatile contaminant at saturations greater than its residual saturation, the contaminant is displaced. First to come into contact with the contaminant is cold water, then the hot water bank, and finally the steam front. The cold water will flush the mobile contaminant (i.e., the contaminant saturation that is in excess of its residual saturation) from the pores. The hot water will reduce the viscosity of the contaminant, making it easier to be displaced by viscous forces, and may reduce the residual saturation of the contaminant. When the steam front reaches the contaminated area, no additional contaminant can be recovered by viscous forces. Additional recovery is achieved by volatilization, evaporation, and/or steam distillation of the volatile and semivolatile contaminants (Stewart and Udell, 1988).

Thus, when steam is injected into a porous media, three distinct zones can be considered to develop: the steam zone, the variable temperature zone, and the ambient temperature zone. These three temperature zones are shown in Figure 2. This figure also shows the relative concentrations of the contaminants in each of the zones. Closest to the injection point is the steam zone which, in the area close around the injection point, is at approximately the temperature of the steam. Further downstream within the steam zone, the temperature may decrease somewhat due to heat losses to the overburden and underburden. If the rate of steam injection is sufficiently high, the percentage of heat lost will not be great, and this zone can be considered essentially isothermal. In this zone, steam distillation and steam stripping are the main recovery mechanisms and these processes cause the formation of a contaminant bank just downstream of the steam front (Wu, 1977). Downstream of this is a variable temperature zone where condensation of the injected steam and evaporation of the contaminants takes place. The interface between the steam zone and the variable temperature zone is essentially the location of steam condensation, if the temperature gradient in the steam zone is not significant. At the front of this zone is the bank of contaminants that have been displaced by viscous forces, followed by the hot water bank. The zone furthest downstream is the ambient temperature zone which is saturated with water and the mobilized contaminant.

The amount of residual saturation remaining after the cold and hot water flush is dependent on the capillary properties of the porous media, the interfacial properties of the contaminant, and the pressure gradient in the water causing the displacement. Residual organic liquid saturations in unconsolidated sands are typically in the range of 14 to 30 percent (Wilson et al., 1990). The texture of the soil has been found to be the most important factor in determining the amount of residual organic contaminant left in a soil. Several researchers have found that increasing the temperature reduces the residual saturation of oils (Edmondson, 1965; Poston et al., 1970; Davis and Lien, 1993).

The residual contaminants are volatilized by the steam, and the volatilized contaminants are transported to the steam front, increasing the saturation of the contaminant in this zone and adding to the contaminant bank. The rate at which the contaminant bank formed by the evaporation and condensation processes moves downstream is inversely proportional to the saturation of the compound downstream, and directly proportional to the volatility of the contaminant (Yuan, 1990). Experimental work has shown that pure, separate, liquid-phase contaminants with boiling points less than that of water will be completely removed from the steam zone except for the small amount which is adsorbed to solid surfaces or dissolved in liquid water which may be present in the steam zone (Hunt et al., 1988). Theoretical studies have predicted that under certain conditions, liquid hydrocarbons having boiling points up to 175°C may also be completely removed directly behind the steam condensation front (Yuan, 1990; Falta et al., 1992b). This conclusion is supported by one-dimensional column experiments which

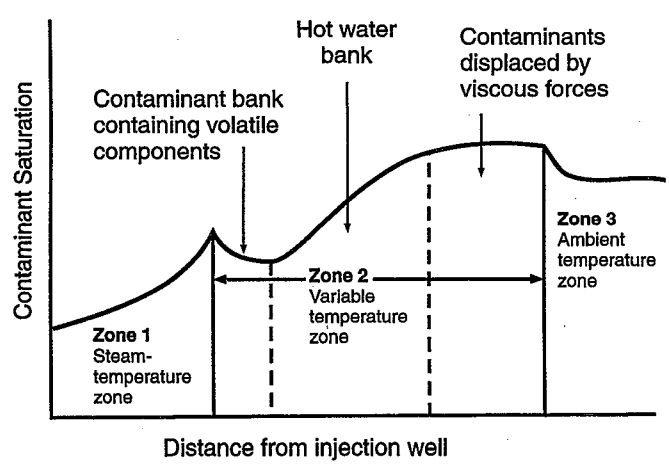

Figure 2. The three temperature zones that form during a steam flood (after Wu,1977).

showed essentially complete removal of toluene and gasoline (Hunt et al., 1988) and 96.8 to 99.8 percent recovery of No. 2 fuel oil and jet fuel (Hadim et al., 1993) by steam injection.

Recovery Mechanisms

The first recovery mechanism acting on contaminants during a steam injection is a physical displacement, first by the water originally in the subsurface, then by the hot water formed by the condensation of steam and finally by the steam itself. Physical displacement of the contaminant occurs when there is an immiscible organic liquid present at saturations greater than its residual saturation, and when there is a dissolved phase in the water that is displaced with the water. A physical displacement of soil air occurs when steam is injected into the unsaturated zone. When the initial contaminant concentration is significantly greater than residual saturation and its volatility is low, the greatest reduction in its saturation will be due to displacement by water (Herbeck et al., 1976).

The increased temperatures that accompany the steam injection process will cause decreases in the capillary and interfacial forces between fluids and the porous media which will reduce the residual saturation of the organic phase behind the hot water front. Also, thermal expansion of the organic phase can increase its saturation, increasing the mobile fraction and decreasing the residual. Another effect of the increased temperature is a decrease in the viscosity of the organic phase, which also increases its mobility. All of these factors contribute to the formation of a bank of the organic phase in front of the steam front that is displaced by physical forces.

The main recovery mechanisms for contaminants in the steam zone are steam distillation (also called co-distillation) and steam displacement (stripping). Steam distillation occurs when a liquid that is immiscible with water is present. The boiling point of the mixture is reached when the total vapor pressure of the system becomes equal to one atmosphere, rather than when the vapor pressure of the individual component becomes equal to one atmosphere. Since both liquids contribute to the total vapor pressure, this point is reached at a lower temperature than the normal boiling point of either of the liquids alone (Atkins, 1986). Thus, some immiscible contaminants that have a normal boiling point that is greater than 100°C may also be readily removed by the steam injection process. The steam distillation process is dependent on the composition of the liquids, as well as the temperature and pressure of the system. Steam stripping occurs as the injected steam sweeps the contaminant vapor to the condensation front, where the vapors condense, increasing the saturation of the liquid contaminant at the condensation front and allowing additional vaporization of the contaminant in the steam zone. When the saturation of the contaminant exceeds its solubility at ambient temperature, a contaminant bank is formed in front of the steam zone.

When the contaminant is a mixture of volatile and semivolatile components, such as gasoline or kerosene, the lower boiling components will vaporize first due to their larger vapor pressures. As a result of the removal of the volatile components, the liquid phase concentrations and thus the vapor pressures of the remaining "semi" and "nonvolatile" components in the liquid phase will increase, which leads to an increase in the evaporation rates of these components in the steam zone (Yuan, 1990). This sequential vaporization of compounds means that the contaminant bank which is recovered about the time of breakthrough of the steam will be enriched in the lighter, more volatile components of the contaminant (Weyland et al., 1991). By continuing steam injection after steam breakthrough, the less volatile components can be recovered at greater rates as their concentration in the remaining liquid, and thus in the vapor phase, increases. Udell and McCarter (1996) showed in one-dimensional laboratory experiments that compounds with boiling points up to approximately 300°C were removed by continuing injection of steam past breakthrough while the concentrations of compounds with boiling points up to 450°C were reduced by at least an order of magnitude by the injection of 100 pore volumes of steam. However, as the volume of remaining liquid decreases and it recedes into smaller pores, interfacial effects increase and the vapor pressure of the contaminants decreases, and this ultimately limits the amount of contaminants that can be recovered. The higher the temperature, the greater the vapor pressure (within the limits of the interfacial effects) and thus the greater the recovery (Lingineni and Dhir, 1992).

Cycling of steam injection and vacuum extraction after steam breakthrough at the extraction well has been found to be very effective during field demonstrations for the recovery of contaminants (Udell and Stewart, 1989; Newmark and Aines, 1995). Itamura and Udell (1995) have shown theoretically and numerically that depressurizing the steam zone by halting steam injection while continuing vapor extraction will cause a thermodynamically unstable system. To bring the temperature and pressure back into thermodynamic equilibrium, the temperature must be reduced to the point where it is in equilibrium with the reduced pressure of the system. Heat is lost by evaporation of the residual water and contaminants, which are then removed from the system by vacuum extraction. The injection of steam after equilibrium has been reached at the lower pressure allows a recharge of the heat necessary to drive the evaporation of contaminants, and the depressurization cycle can then be repeated. Itamura and Udell (1995) show that cycling of steam injection with continuous vacuum extration will always reduce the amount of steam required to meet a given clean-up level, and may also reduce the overall clean-up time.

Another mechanism that can enhance contaminant recovery during steam injection is enhanced desorption of contaminants from the porous solids. For a contaminant to desorb from a solid surface, it must absorb heat. The amount of heat that is required for desorption to occur is dependent on both the contaminant and the type of soil. Lighty et al. (1988) have found that essentially all of a semivolatile contaminant could be desorbed from glass beads and sands, but only about 80 percent of the contaminant was desorbed at the same temperature from porous clays and peat. The experimental results lead to the conclusion that a monolayer of adsorbate is strongly bound to the solid surface of a reactive soil such as a clay. The desorption of this monolayer is a long process (Tognotti et al., 1991), and likely requires temperatures significantly above the boiling point of the contaminant for complete removal (Lighty et al., 1988). Lighty et al. (1990) found that xylene, even at temperatures above its boiling point, can still adsorb from a gas stream onto a clay particle. The very slow desorption indicates that a very strong bond can be formed between reactive soils and organic contaminants.

Thus, contaminants can be recovered in the vapor phase, as a separate phase liquid, and dissolved in the aqueous phase. The relative amount of the contaminants in each phase will depend on the original concentration of the contaminant and its boiling point. Field demonstration projects of steam injection where gasoline and diesel fuel were recovered have found that most of the contaminant recovered was recovered in the vapor

phase (Newmark and Aines, 1995; EPA, 1995b), while a demonstration to recover JP-5 recovered most of the contaminant as a liquid (Udell et al., 1994).

Although it has been shown that steam injection can potentially recover a large percentage of volatile contaminants, it is expected that residual amounts of the contaminants will remain in the subsurface. These small amounts of contaminants can likely be remediated by natural attenuation or bioremediation. Thus, it is important to understand the effects of steam injection on microbial populations and their ability to degrade residual contaminants. Biological samples were taken at the Naval Air Station Lemoore after a steam injection demonstration to recover JP-5. These samples showed high numbers of active bacteria in the zones that reached 80°C to 100°C for extended periods during the demonstration and suggested enhanced biodegradation was occurring in the heated, oxygenated soil (Udell et al., 1994). Research carried out as part of the Dynamic Underground Stripping project showed that before steam injection a wide variety of microorganisms were actively degrading the BTEX components of gasoline. *Pseudomonas* was the dominant species originally, but *Flavobacter* was dominant after vacuum extraction. Above the water table, the largest populations were in areas where the contamination was at low concentrations. Below the water table, oxygen concentrations were low and there was effectively no microbial activity. After steam injection, extensive microbial communities were found in all samples, including those where the temperature had reached 90°C. The population, however, had shifted to yeasts and related organisms which had been observed in small numbers before heating. The community includes thermophiles previously identified from environments such as hot springs, and a number of organisms apparently represent previously unidentified species. The community includes the BTEX degrader *Rhodotorula* (Newmark and Aines, 1995).

Contaminant and Soil Type Considerations

The decision to use steam injection for remediation should be based on considerations of both the contaminant to be removed and the properties of the porous media to be remediated. The most important property of the contaminant in determining its receptiveness to remediation by steam is its volatility. If a contaminant is not volatile, a hot water displacement without the expense of steam injection can reduce the saturation of the contaminant to its residual saturation. For contaminants that have very low boiling points and a large Henry's constant, and which are above the water table, vacuum extraction may be able to adequately remove a significant portion of the contaminant from sandy, homogeneous soils. Steam injection is justified for removing trapped lenses or ganglia of a volatile or semivolatile contaminant that cannot be removed by viscous forces. Udell and Stewart (1990) feel that steam injection has perhaps the greatest potential to significantly decrease clean-up time and, therefore, offset the greater capitol costs of the system when semivolatile contaminants are to be removed. Semivolatile contaminants include the less volatile petroleum hydrocarbons, such as diesel or jet fuels, and some of the higher chlorinated solvents. However, temperatures significantly greater than ambient temperatures may be required to desorb even volatile contaminants, especially from clays or peat. Higher temperatures enhance the volatilization of liquid or adsorbed contaminants and allow greater recovery (Lingineni and Dhir, 1992). Thus, steam injection, along with vacuum extraction, may be necessary to achieve the desired clean-up levels for volatile contaminants when they are present in fine soils. Most of the volatile and semivolatile organics show very significant increases in volatility as the temperature increases, and most have very high vapor pressures at steam temperatures.

Stewart and Udell (1988) have shown theoretically that the viscosity of the contaminant is important in determining the size and saturation of the contaminant bank displaced by the steam front. Their calculations show that steam is capable of mobilizing any length of contaminant bank up to a contaminant/water viscosity ratio of three. For larger viscosity ratios, the displacement is unstable; i.e., fingering may occur, reducing the efficiency of the displacement. Their laboratory experiments support this theory, showing that low viscosity contaminants can be recovered in front of or just behind the steam front, while a mineral oil with a viscosity seven times that of liquid water at steam temperature was not recovered by steam injection.

Soil type has been found to have a strong effect on the rate of contaminant removal from soils (de Percin, 1991; Lighty et al., 1988). Adsorption onto glass beads and silica sands does not appear to form tight bonds; the adsorption is readily reversible even at low temperatures. Experiments performed by Lighty et al. (1988) showed that essentially all of the xylene adsorbed by silica sands was recovered rapidly. However, for reactive media, the desorption process is much slower, which may be caused by a strongly adsorbed monolayer on the particle surface (Lighty et al., 1988; Tognotti et al., 1991) or slow diffusion from small inner pores to the surface of the particle (Keyes and Silcox, 1994).

Laboratory studies by Hadim et al. (1993) have shown that remediation by steam injection can be achieved much more rapidly in coarser soils than in fine soils. Their experiments have also shown that soils which are poorly sorted (i.e., have a wider range of grain sizes) have a lower contaminant recovery efficiency when steam is injected. This effect is due in part to lower permeability in fine grained or poorly sorted soils, which causes a lower injection rate at a given injection pressure, and a greater residual saturation. For sands within a certain range of grain sizes, the same contaminant recoveries were achieved, but as the grain size decreased, longer treatment times were required to achieve the same recovery. As the grain size was decreased further, there was a reduction in the recovery efficiency.

Heterogeneity in the subsurface can have a very significant effect on the efficiency of steam injection. Small scale heterogeneities can cause fingering, especially at the higher flow rates (Basel and Udell, 1989). Channeling will occur when layered heterogeneity exists due to naturally occurring beds or to manmade disturbances of the subsurface such as highly permeable trenches containing buried utilities (EPA, 1995b). The degree of channeling that will occur increases as the differences in the permeabilities of the layers increases, as the ratio of the layer thicknesses (more permeable layer/less permeable layer) increases, and as the rate of steam injection increases (Basel and Udell, 1991). The occurrence of channeling can allow contaminants in the low permeability zones to be bypassed by the steam. However, there have been times when a relatively impermeable layer overlaid the target zone for steam injection, and the impermeable "cap" limited the vertical movement of the steam (i.e., steam override), and thus increased its horizontal spreading (Farouq Ali and Meldau, 1979; Aines et al., 1992). Thus, although lenses of less permeable soils that contain contaminants can reduce the efficiency of steam injection, full layers of this low-permeability medium overlying the permeable zone to be treated may actually improve the sweep efficiency of the injected steam through the permeable zones.

Many researchers have found that the recovery from steam injection is related closely to heating rates (Myhill and Stegemeier, 1978; Baker, 1969; EPA, 1995b). However, this dependence is more related to steam properties and injection rates; the thermal properties of soils and the liquid contaminants have generally not been found to vary enough to affect the recovery achieved by steam injection (Myhill and Stegemeier, 1978; Hadim et al., 1993). One property of the soil or aquifer to be treated that may significantly affect the process is the thickness of the target zone. In any steam injection process, some of the heat that is injected will be lost to the overlying and underlying strata. The thicker the target zone to be treated, the greater the percentage of the injected heat that stays within this zone.

Another property of the media that can affect the efficiency of the heating process is the permeability. When the permeability is low, the injection rate at a given pressure is low, which increases the time for heat to be lost to the overburden and underburden, and decreases the efficiency of the overall process. Thus, sandy media are more easily treated by steam injection than clays. Fan and Udell (1995) studied the movement of the evaporation front during steam injection from areas of high permeability into beds of lower permeability. They found that the lower the permeability of the less permeable zone, the higher the temperature must be in that zone for evaporation to occur. The reason for this is the decrease in vapor phase flux in the zone with decreasing permeability, creating a higher pressure in the zone and thus slowing evaporation.

Physical factors relating to the location and quantity of the contaminants in the subsurface are also important. Small volumes of contaminated soils may be more economically treated by excavation and incineration, especially if the contaminated soil is at or near the ground surface. The pressure of the injected steam is limited by the overburden pressure, which is a function of the depth of soil above the zone of injection. When the steam pressure is greater than the overburden pressure, fracturing of the overburden may occur, which could allow short-circuiting of the steam to the ground surface. Thus, shallow contamination may severelly limit the use of steam injection as it limits the injection pressure that can be used, again pointing to the use of excavation and incineration or thermal desorption for contaminants near the soil surface. The steam injection method may be a very efficient way to treat contaminated soil at significant depths, and can be used to depths greater than 100 feet. When the contamination is contained in a very narrow depth range, and there is no overlying and underlying confining layers to limit steam movement in the vertical direction, steam injection efficiency may decrease (EPA, 1995b). Steam injected into a fractured media would be expected to flow through the more permeable fractures and would be ineffective for displacing contaminants trapped in the porous matrix or in deadend fractures. However, conductive heating from the fractures into the matrix may effectively distill trapped volatile contaminants which could then flow in the vapor phase to recovery wells (Udell, 1997).

When liquid phase contaminants are displaced, they are concentrated in front of the steam zone as the steam displacement progresses. This concentrating of liquid phase contaminants may create a potential for downward migration of the liquid phase contaminant, particularly if the liquid phase contaminant is more dense than water. A confining layer beneath the zone to be treated may help in limiting liquid phase contaminant downward movement during steam injection (EPA, 1995b).

Design Considerations

One of the most important design considerations for a steam injection process is the steam injection rate. This factor, however, cannot be separated from considerations of the injection pressure, temperature, and steam quality. The injection pressure is limited by the depth of injection: when injection pressures greater than the overburden pressure are used, fracturing can occur in the overburden, allowing steam to escape to the surface. Udell et al. (1994) recommend that the injection pressure be as high as possible while not exceeding the soil fracture pressure which is estimated as 1.65 psi per meter of depth below the ground surface. Thus, the shallower the zone to be treated, the lower the injection pressure must be. There is a direct relationship between the injection pressure and injection rate, which are related by the permeability of the media. The more permeable the media, the greater the injection rate that can be achieved at a given limiting pressure. The greater the injection rate, the greater the heating rate of the subsurface. Newmark and Aines (1995) recommend large amounts of steam for establishing a complete steam zone in very permeable media. However, once the steam has reached the production well, the higher the steam injection rate the more steam (and therefore heat) that is produced. Thus, once steam breakthrough has occurred, greater thermal efficiency can be achieved by reducing the steam injection rate (Myhill and Stegemeier, 1978). Newmark and Aines (1995) found that repeated steam passes were effective for heating small impermeable layers in between steam zones. The optimum injection rate is dependent on many variables specific to a given system, such as distance between wells, sweep efficiency, and heat losses to over- and underburden, and may be best determined by field experimentation (Bursell et al., 1966).

Greater heating rates generally mean greater recoveries, and greater energy efficiency. Increasing the temperature of the injected steam, however, does not necessarily increase the rate of heating of the target area. Johnson et al. (1971), studying steam displacement of oil from a reservoir, found that when they increased the temperature of the steam they ultimately recovered more oil, but the greater temperature gradient between the steam injection zone and the over- and underburden increased the rate of heat loss, thus the steam front actually advanced more slowly. Longer times were required to achieve the increased recovery, and the additional oil recovered at the higher temperatures required a disproportionately larger amount of steam. Baker (1969) found that for a given steam injection rate, the rate of heat loss to the overburden and underburden increases with time as the area of contact with them grows. At some point, the rate of steam input will equal the rate of loss to the over and underburden, and the growth of the steam zone will stop. Thus, there is a maximum size to the steam zone for a given injection rate.

Several researchers have found a direct relationship between the steam quality and the oil/steam ratio at the producing well. Steam quality is defined as the proportion of the total water that is in the vapor phase; if liquid water is not present, the steam quality is 100 percent. Myhill and Stegemeier (1978) and Singhal (1980) found that as the quality of the steam at the injection point increases, the oil/steam ratio in the extraction well increases.

Pilot- and full-scale steam injection demonstration projects seem to indicate that greater efficiency is achieved by using continuous steam injection; i.e., 24 hours a day and at least 6

days per week, rather than intermittent injection (16 hours per day, 5 days per week). The intermittent injection schedule allows the soil to cool somewhat during the 8 hours when steam is not being injected, significantly slowing the overall heating rate and maximum temperatures in the target zone. Intermittent operation also was found to put additional stress on the boiler and other process equipment due to the frequent cooling and heating, and caused additional system down time (EPA, 1995b).

A physical characteristic of steam injection processes that must be considered is steam override due to gravitational forces. Gravity override is caused by the fact that steam is much less dense than liquids and therefore will tend to rise in the porous medium. At the same time, hot water produced by the condensation of steam is more dense than some contaminants, so may tend to underride the zone to be treated (Singhal, 1980). A frontal displacement mechanism with essentially pistonlike flow will displace more of the initial fluids by viscous forces. When steam override occurs, the effectiveness of the frontal displacement is reduced, and thus the vertical sweep efficiency of the steam displacement process is reduced. Various properties of the system determine the amount of override that occurs. When steam is injected into an unsaturated porous medium the steam front is essentially vertical. When there is a difference in density between the injected fluid and the fluid initially present, the slope of the interface between the fluids is equal to the difference between the vapor and liquid water phase viscous forces divided by the gravitational forces. The degree of gravity override increases as the difference in density between the liquid and vapor phases increases, as the permeability of the medium decreases, and as the viscosity of the liquid phase being displaced increases. One operational parameter that affects override is the steam injection rate. Steam override cannot be eliminated, but by increasing the injection rate of the steam, the difference between the vapor and liquid viscous forces is reduced and thus the amount of override can be decreased (Basel and Udell, 1989).

The major equipment requirements for a steam injection system are the steam generator, the distribution system to the wells, the extraction system, and the coolers/condensers for the extracted fluids. Means of treating the off gases, the water that is extracted, and any organic phase that is recovered will be required, but these systems are beyond the scope of this paper and will not be discussed further. Mobile steam plants are available (Newmark, 1992) that are powered by natural gas, propane, or another available fuel. Steam generators require a high quality feed water to avoid scale buildup in the generator (Schumacher, 1980), so often the generator feed water must be treated before use. Normally, operation of a steam injection system will require that the boiler be operated and manned continuously during the injection process (Newmark, 1992).

Pneumatic air lift pumps (Newmark, 1992) and jackpumps (Udell and Stewart, 1989) have been used in the extraction wells to remove liquid water and contaminants. Blowers are used to remove steam and contaminants in the vapor phase. Heat exchangers are used to condense the extracted vapors and to preheat the steam generator feed water.

Special consideration must be given to the construction of the steam injection wells due to the high temperatures and pressures they must withstand. PVC or fiberglass wells that are commonly used for ground-water monitoring are not adequate for steam injection processes. Steel casing is commonly used for both injection and extraction wells, but the installation must allow for the expected expansion of the casing with temperature. Experience in the oil industry has shown that pipe failures in steam injection projects occur at the couplings, due to repeated expansion and contraction during the heating and cooling processes (Gates and Holmes, 1967). Cement used for conventional wells will frequently fail when exposed to the high temperatures associated with the steam injection process (Schumacher, 1980). The addition of 30 to 60 percent by weight of quartz silica or silica flour to conventional cements will provide temperature stability, and the addition of sodium chloride will allow the cement to expand linearly with temperature (Gates and Holmes, 1967). Information on well construction casing materials and cements that have worked for steam injection wells is available from both the oil industry (Gates and Holmes, 1967; Hall and Bowman, 1973; Farouq Ali and Meldau, 1979; Chu, 1985) and from pilot-scale contaminant recovery operations (Newmark, 1992).

The placement of steam injection and extraction wells is critical to the efficiency of the remediation system. Determining well placement and injection zones should be based on a thorough knowledge of the subsurface characteristics, including delineation of zones of high permeability and high contaminant concentration. If the target area to be remediated is not too large, injection wells may circle the contaminated zone with one or more extraction wells in the center. When the area to be remediated is large enough that the desired injection rates cannot be achieved by peripheral injection wells, injection and production wells are usually arranged in a pattern. The 5-spot pattern (see Figure 3) alternates injection and extraction wells so that all wells are surrounded by four wells of the opposite type. Patterns using two injectors per producer (7-spot pattern, see Figure 3) have also been used by the oil industry to recover viscous oils (Boberg, 1988). Patterns such as these may be effective when the subsurface and contaminant distribution is essentially homogeneous. When significant heterogeneity exits, well placement must take this into account. When a pronounced directional permeability trend exists, this will control well placement. Edge or peripheral drives may be more appropriate when there is significant geologic structure (Willhite, 1986). Farouq Ali and Meldau (1979) recommend close well spacings and an ample number of production wells, and Udell et al. (1994) found at a field demonstration that 5 to 6 meter well spacings appeared to work better than 12 meter well spacings. Based on

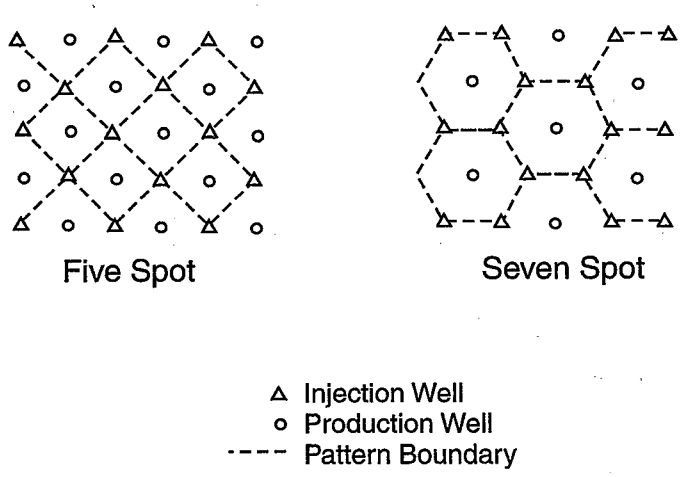

Figure 3. Five spot and seven spot well patterns used for steamflooding.

the results of this demonstration, they also recommended that flexibility be built into the system by installing wells that can be used for either steam injection or fluid extraction. The heat losses observed by Baker (1969) would suggest that there is a maximum radial area that can be heated by a given steam injection rate, and this would set an upper limit on distance between wells in order to heat the entire area. Pilot studies for contaminant recovery have used well spacings as low as 1.5 meters, but full scale operations have used well spacings on the order of 18 meters (Aines et al., 1992; Newmark, 1992; EPA, 1995b).

The sweep efficiency of the injection process is the areal and vertical amount of the formation targeted for treatment that is actually contacted by the steam. Sweep efficiency can be reduced by areas of lower permeability that are bypassed by the steam. When large areas of the formation contain lower permeability materials, steam may essentially miss the whole area. One technique that has been used successfully to increase sweep efficiency is to shut down the production wells which have a good connection to the injection well once those areas are clean (i.e., are no longer producing contaminants), and to continue producing from wells that are in the direction in which steam penetration is desired (Powers et al., 1985; EPA, 1995b). Where a high viscosity fluid is to be recovered it may be desirable to heat a large portion of it early on to reduce its viscosity. This has been accomplished by injecting steam into a lower more permeable layer, and allowing heat to transfer upward to the oil and increasing its mobility (Hall and Bowman, 1973). In a case where a viscous oil was floating on top of the water table, steam injection below the water table was found to conduct heat into the oil layer to increase its mobility (Farrington and Sword, 1994). Gravity override may also aid in distributing heat to fluids of low mobility. Steam may spread evenly on top of a contaminant layer and conduct heat downward to heat the contaminant and increase its mobility through viscosity reduction and/or distillation (Farouq Ali and Meldau, 1979).

Effluent stream monitoring is required to monitor the progress of the remediation process. Vapor and aqueous phase samples are normally collected at regular intervals during the course of a remediation and analyzed to determine the amount of contaminants being removed. Sample intervals of one hour have been used on a small-scale demonstration project, while a one-day sampling interval was used on a full-scale demonstration. However, the time required to analyze these samples by techniques such as gas chromatography limits their usefulness for process control and optimization purposes. Also, it has been found that effluent streams, particularly the vapor effluent stream, can vary significantly over short periods of time, and these variations cannot be monitored with the one-day or even one-hour periods between samples that are generally used for grab samples. Flame ionization detectors have been used with some steam injection systems for real time monitoring of the contaminants being recovered in the vapor phase (de Percin, 1991; EPA, 1995b). Fourier transform infrared radiation (FTIR) (Langry and Kulp, 1994) and differential ultraviolet absorption spectroscopy (DUVAS) (Barber et al., 1994) have both been evaluated for real time monitoring of effluent vapors. FTIR measures alkane components in the vapor stream, while DUVAS measures aromatic compounds. To date, the concentration information from these on-line monitors has been more qualitative than quantitative, but these monitors have been shown to provide a real time estimation of the amount of hydrocarbons being recovered by the system. In order to correctly interpret the effluent concentration data, it must be kept in mind that a lag time between injection and the effect on the extraction well is to be expected. Also, mass transfer limitations can occur within the subsurface, which reduces effluent concentrations and makes it appear that the concentration remaining in the subsurface is at lower levels than it actually is. Thus when the extraction system is shut down for a period of time and then restarted, effluent concentrations are higher than they were before the shutdown.

Tracking the movement of the steam injection front in the subsurface is also desirable for monitoring the progress of the process, and to aid in understanding the processes that are occurring as a result of steam injection. Temperature measurements, either at intermediate observation wells or at the producing wells, provide a direct means of tracking steam front movement (Hall and Bowman, 1973; Powers et al., 1985; Newmark, 1992). However, when additional steam passes are used after the subsurface is heated to approximately steam temperature, the small differences in temperature produced by the passage of an additional steam front may be hard to detect. Thus, other means of tracking steam front movement may be needed (Newmark and Aines, 1995). Powers et al. (1985) also monitored the chloride concentration in the naturally occurring brine that was produced, and found measurable decreases in its chloride content due to dilution by condensed steam before a thermal response was detected. Neutron logs will indicate the presence of vapor saturation and, thus can be used to monitor the steam front movement (Hall and Bowman, 1973). Radioactive tracers have also been used to determine which injection wells are influencing each of the various producers and to what extent (Powers et al., 1985).

The Dynamic Underground Stripping Project (Newmark, 1992; Newmark and Aines, 1995) used a wide variety of geophysical techniques both before steam injection to establish baseline information and to help characterize the subsurface, and during steam injection to test their ability to monitor the movement of the steam front. Geophysical logs were compared to the temperature records obtained from monitoring wells to provide additional insight into the results from the geophysical logs. Low permeability, clay-rich zones have relatively large amounts of exchangeable cations, giving them a relatively lower electrical resistivity than more coarse-grained soils. Electrical resistance tomography (ERT) provides cross-sections of subsurface resistivity and can identify the higher permeability zones where steam flow is likely to occur. Temperature increases may increase the mobility of exchangeable cations and thus decrease resistivity, or in areas where the steam has caused desaturation, the resistivity may increase (Vaughan et al., 1993). Thus, changes in resistivity were found to be useful for mapping the movement of the steam front (Ramirez et al., 1993). Induction resistivity logs measure the resistivity of the pore fluids near the boreholes providing a more detailed vertical view of steam in the subsurface, and were found to delineate the vertical temperature distribution. Tiltmeters, which measure deformations in the ground surface that result from a pressure transient in terms of tilt, also showed potential for determining the movement of the steam front. Tiltmeters were found to be more useful after the ground was already heated to approximately steam temperature to map the movement of additional steam passes (Newmark and Aines, 1995).

Numerical models may be useful as an aid to designing clean-up operations using steam injection, and to provide estimates of the time required to achieve different levels of contaminant removal (Newmark, 1992). Many models of heat flow (Spillette, 1965; Marx and Langenheim, 1969; Prats, 1969) and oil recovery from a reservoir due to steam injection (Willman et al., 1961;

Vinsome, 1974; van Lookeren, 1983; Rubin and Buchanan, 1985) have been developed. Because there are significant differences between steam injection for oil recovery and for contaminant removal, numerical models developed for oil recovery processes would not necessarily include all of the processes that are important in the contaminant remediation process. Partitioning processes between the air, water, and solid phases that occur at the pore level are not generally important in oil recovery operations, but may be very important when considering removing contaminants down to the parts per million and parts per billion level (Falta et al., 1992a). The thermal model developed by Rubin and Buchanan (1985) is general in its formulation and may be adequate to model some aspects of a steam injection process for subsurface remediation. A finite-difference simulator called the Multicomponent Multiphase Nonisothermal Organics Transport Simulator (M^2NOTS) has been developed by the University of California at Berkeley to simulate the steam injection process for the purpose of subsurface remediation. This simulator was used to aid in the design of the Dynamic Underground Stripping Project, however, comparisons between simulations and the field trial at the gasoline spill site are not currently available.

Laboratory Experiments

Two-dimensional laboratory experiments on steam injection have also been done. When steam was injected into a two-dimensional homogeneous sand pack containing *o*-xylene, the xylene was displaced as a free product bank ahead of the steam condensation front. Essentially complete recovery of the contaminant was achieved with the injection of approximately 350 pore volumes of steam. However, when steam was injected into a layered sand pack containing diesel fuel, there was not a significant physical displacement of the diesel by the steam condensation front. Instead, the volume of the initial mobile pool decreased as it was displaced by the steam front, and residual hydrocarbon liquid was observed in all regions that had contained the diesel. Continued steam injection and vacuum extraction then produces a fractional distillation of the diesel fuel components with the most volatile components being removed first (Udell, 1994).

Itamura and Udell (1993) studied the recovery of tetrachloroethylene (PCE), a dense, semivolatile contaminant, from a two-dimensional sand pack that contained mainly layered heterogeneity. Near the top of the model and above the water table was a layer containing diamond-shaped lenses of varying permeability sands. The contaminant was introduced at the top of the model and the contaminant that reached the zone of variable permeability lenses preferentially migrated to the lowest permeability zones in this region and then along the boundaries between the different permeability sands. Steam was injected over most of the vertical depth of the model, invading the most permeable layer first, and then the variable permeable layer containing most of the contaminant. When the injected steam reached the contaminant, it was displaced both downward and horizontally towards the recovery well. The mobile contaminant in front of the condensation front moved along the boundary between different permeability sands. After the mobile, separate-phase contaminant had been displaced, the contaminant continued to be recovered in the vapor phase. The highest recovery rate of PCE occurs just before steam breakthrough in the regions containing the majority of the contaminant. Visually it could be determined that some of the contaminant remained in the model, but the percent of the contaminant recovered was not reported.

Field Trials

Table 1 contains a compilation of some of the details of steam injection field trials that have been carried out. In The Netherlands, steam stripping has been used to remediate contaminated soils since at least 1983. However, only limited information on the applications of steam stripping could be found in the literature. Hilberts (1985) describes a vacuum bell structure that is placed on top of the soil and is commonly used for the steam injection process. The 2 meter by 2 meter box contains 4 lances for steam injection, and has been used to treat contaminated soils as deep as 4.5 meters. Contaminants are drawn off from the center of the bell, which creates a vertical flow of the steam up through the soil. At the Broomchenie site which contained organic bromides, reductions of 97 percent in the most heavily contaminated soil were found, but further analysis showed that most of the organic bromide had been converted to inorganic bromide which remained in the soil. Only a small amount of bromide was present in the condensate removed from the soil (Hilberts, 1985).

A small-scale pilot demonstration project was undertaken at the Solvent Services, Inc. site (San Jose, California) in August 1988 (Udell and Stewart, 1989). Surface spills and leaking underground storage tanks at this industrial facility had released a variety of volatile organic compounds to the subsurface. Extensive temperature monitoring showed that the movement of the steam zone was controlled. Cycling of vacuum extraction and steam injection was then carried out sporadically after steam breakthrough and significantly greater recovery rates were achieved at the beginning of the second vacuum extraction period. Comparison of soil core analysis done before and after the pilot remediation study indicates that there was some downward migration of contaminants in solution in the condensate. Low permeability zones isolated contaminants, and the post-treatment concentrations in some of these zones was higher than the initial concentrations. The authors postulated that high water saturations containing high concentrations of contaminants which were pushed in front of the steam front were imbibed into the low permeability areas and caused the observed increases in the more highly water-soluble contaminants. Overall, the pilot study demonstrated the potential for steam injection in conjunction with vapor extraction as a rapid and effective remediation technique.

de Percin (1991) reported on a demonstration project for the "Detoxifier" system made by NovaTerra, Inc. This system is similar to that used in The Netherlands in that it is a shroud or bell placed on the soil surface in which a vacuum is maintained to remove the contaminant vapors. In this case, instead of lances to inject steam, the steam, along with hot air, is injected through augers that are rotating in opposite directions to break up the soil. The steam and hot gases carry the contaminants to the surface. The augers can treat 2.5 m^3 of soil to a depth of 8.2 meters. Blocks of soil are treated sequentially, and treatment time is varied dependent on the soil type and contaminant concentration. A flame ionization detector measures the organic concentration of the gases in the shroud, which are roughly correlated to the concentration of organics remaining in the soil, and can indicate when a desired level of treatment has been achieved. A tracer study showed that the mixing action of the Detoxifier auger does not produce a homogeneous treatment area, thus all of the soil may not receive adequate treatment.

Basile and Smith (1994) reported on a combined anaerobic degradation/steam injection/vacuum extraction system being used to remediate separate and aqueous phase chlorinated hydrocarbons. Laboratory data showed that elevated bioactivity

Table 1. Summary of Steam Injection Projects for Subsurface Remediation.

Site/ Reference	Contaminant Concentration/ Volume	Description of Geology	Treatment System Design	Removal Efficiency or Volume	Comments
Utrecht's Griftpark, Netherlands (Hilberts, 1985)	BTEX, naphthalene, PAH, phenol	layered sands, slags, clay and bog		BTEX: 99.5% (sand), 20% (clay); naphthalene: 99.9% (sand), 60% (clay); PAH: 97% (sand), 35% (bog); phenol: 80% (sand), 20% (clay)	Vacuum bell
Broomchenie, Wierdin, Netherlands (Hilberts, 1985)	Organic bromide compounds, 3 -7700 mg/kg	Sand, ground-water at 5 m depth	Treatment to depth of 4.5 m	97%	Vacuum bell Converted to inorganic bromide
Mannheim, Netherlands former gas works (Hilberts, 1985)	Benzene 55 mg/kg Toluene 15 mg/kg Xylene & Ethylbenzene 2-4 mg/kg phenol 30 mg/kg	Rough sand material	Treatment at depth of 1.8 to 2.6 m	All contaminants reduced to below detection limits	Vacuum bell and steam drive
Solvent Services, Inc. (Udell and Stewart, 1989)	VOCs and nonvolatile organic contaminants at concentrations greater than 1000 ppm	Silts and clays, continuous poorly sorted sand layer at bottom, 0.61 to 1.5 m	7.3 m^2 area treated by 6 injection wells, 1 extraction well, 1.5 m between wells, 111.6 kg/hr of steam injected for 120 hrs, then 67 kg/hr for 20 hrs	Vacuum Extraction: 99 kg in 40 hrs Steam extraction: 146 kg in 140 hrs Followed by intermittent operations	Pilot scale demonstration

Continued

Table 1. (continued)

Site/ Reference	Contaminant Concentration/ Volume	Description of Geology	Treatment System Design	Removal Efficiency or Volume	Comments
Solvent Services, Inc. (Udell and Stewart, 1989)	VOCs and nonvolatile organic contaminants at concentrations greater than 1000 ppm	Silts and clays, continuous poorly sorted sand layer at bottom, 0.61 to 1.5 m	7.3 m^2 area treated by 6 injection wells, 1 extraction well, 1.5 m between wells, 111.6 kg/hr of steam injected for 120 hrs, then 67 kg/hr for 20 hrs	Vacuum Extraction: 99 kg in 40 hrs Steam extraction: 146 kg in 140 hrs Followed by intermittent operations	Pilot scale demonstration
Annex Terminal Port of Los Angeles, San Pedro, CA (de Percin, 1991; EPA, 1991)	Major contaminants were TCE, PCE, chlorobenzene Initial average concentration of 466 ppm VOCs		33 m^3 area treated to 1.5 m depth by steam (200 °C) and compressed air (135 °C)	84.7% VOCs, 55% SVOCs Treatment time was 1 month	Detoxifier system devoloped by NovaTerra, Inc.
AT&T New York (Basile and Smith, 1994)	Chlorinated solvents, TCE & 1,1,1-TCA, DNAPL (separate and dissolved aqueous phase)	Tight, heterogeneous		4,500 kg of hydrocarbons recovered in 2 years	Nutrients injected at 40 °C, vacuum extraction of 7.8 m^3/min, maximum vacuum of 41 cm Hg

Continued

Table 1. (continued)

Site/ Reference	Contaminant Concentration/ Volume	Description of Geology	Treatment System Design	Removal Efficiency or Volume	Comments
Yorktown Naval Shipyards (Farrington and Sword, 1994)	Naval Special Fuel Oil, estimated 8000 l[1]	Upper 6 m was homogeneous fine to coarse sand, below that was interbedded sands and clays. Water table 3.8 to 4.1 m below ground. Hydraulic conductivity 2.0 to 5.2 x 10^{-3} cm/s	83.6 m^2 treated with 5 spot pattern of 4 injection wells, 1 extraction well, 9.1 m between injection wells. Injected at 6.1 to 7.6 m depth, extracted from 3 to 9.1 m depth. Injection rate of 272 kg/hr	617 l recovered Steam injected over 2 month period	Hot water may be more appropriate for this nonvolatile, viscous oil
Naval Air Station Lemoore, CA (Udell et al., 1994; EPA, 1995a)	JP-5, estimated 757,000 l	Sands and silts with hydraulic conductivity of 3.9 x 10^{-3} to 1.4 x 10^{-2} cm/s. Water table at 4.9 m	12,140 m^2 treated with 2 injection wells at the center, 8 vapor/ground-water extraction wells. Injection depth of 6m	Approximately 976,000 l recovered in 3 months of operation. Final vadose zone concentration of 20 to 50 ppm TPH. 20,000 ppm remains at water table	Demonstration project
Pinellas Plant Northeast Site, Largo, FL (DOE, 1997)	Volatile Organic Compounds including BTEX and chlorinated solvents	Silty sands, water table at 1 m below ground surface	1566 m^3 treated by 48 holes to a depth of 9.8 m	Approximately 544 kg recovered	Dual Auger Rotary Steam Stripping Demonstration project

1 - The pilot study report does not contain an estimate of the amount of oil contained in the area treated by the pilot study. This estimate was made using the same assumptions as made in the report to estimate the oil contained within the entire contaminated region, with an estimate of the contamination extending over a 1.5 m depth.

occurred at temperatures between 30°C and 40°C, so nutrients are injected at 40°C to promote biological dechlorination of the contaminants. The authors claim that the degradation products are more easily extracted than the chlorinated solvents, and are then steam stripped and removed from the subsurface via shallow vacuum extraction wells. They claim that the in situ remediation was favored over excavation and off-site disposal by local residents because it eliminated the need to transport contaminated soil through the neighborhood.

The Dynamic Underground Stripping Project is a joint venture between the University of California-Berkeley and Lawrence Livermore Laboratory. The process combines steam stripping in permeable layers and electrical resistance heating of clay layers to heat the subsurface. Characterization of the site before steam injection indicated that about half of the contaminants were above, and half were below the water table. The highest gasoline concentrations were found in the capillary fringe (Newmark and Aines, 1995). Electrical resistance heating of the clay layers was initiated at night (to limit interference with construction activities going on during the day) for 12 weeks prior to steam injection, raising the temperature in the clays from 20°C to 50°C. Steam was injected both above and below the water table, and during 5 weeks of continuous steam injection over 6,400 liters of gasoline was recovered, most of it in the vapor phase.

After about 3 months, the second phase of steam injection was begun. During this phase, steam was injected intermittently, so that the treatment zone was kept desaturated and periodically depressurized. Cycle times were 5 to 6 days, and this phase was continued for 6 weeks. Extraction of gasoline was found to be particularly vigorous when the treatment zone was maintained in a depressurized condition at elevated temperatures, and a total of 18,500 liters of gasoline were recovered. Soil cores taken after the second phase of steam injection showed that most of the gasoline remaining in the subsurface was trapped in the low permeability zone between the two steam zones. A final phase of vapor extraction with limited electrical heating and periodic fluid extraction was conducted for 3 months, which recovered an additional 3,800 liters of gasoline (Yow et al., 1995). It is believed that no additional free gasoline remains in the treatment zone, but benzene and toluene remained in the ground-water at concentrations above their maximum contaminant limits. Maximum contaminant limits had also been set for 1,2-dichloroethane and xylenes, and these levels had been met. Biological sampling at the conclusion of the project showed that BTEX degraders had survived the heating and could rapidly remove the remaining contaminants from ground-water (Newmark and Aines, 1995).

As part of EPA's SITE demonstration program (EPA, 1995b), a steam injection demonstration was carried out at the Rainbow Disposal site in Huntington Beach, California, between August 1991 and August 1993. The soils treated by this system were under and around existing facilities at the transfer facility, and transfer activities continued during the remediation efforts. The discontinuous clay layers at this site created a nonuniform distribution of the contaminant in the subsurface. The spilled diesel flowed downward through the sand layers, and when it reached a sand/clay interface, it flowed laterally along the interface until it reached a break in the clay layer which allowed it to flow downward by gravity again. This caused large variations in concentrations even over small vertical distances.

Maintenance of the boilers, the oxidizing unit to treat offgases, and the steam distribution system caused considerable downtime, and operating logs from the project showed the system had an online factor of 50 percent. Initially the steam injection system was operated 16 hours per day, 5 days per week. This led to inefficient heating of the soil and maintenance problems with the boilers due to the thermal stress associated with frequent startups and shutdowns. An increase in the soil heating efficiency and diesel recovery was noted when a 24 hours per day, 6 days per week schedule was adopted, and the operation of the boilers improved.

The clean-up criteria set by the California Regional Water Quality Control Board was 1,000 mg/kg of total petroleum hydrocarbons (TPH). It appears that this criteria was not met, as 45 percent of the post-treatment samples inside the treatment zone were above this level. For the small number of soil cores available for which there is pre- and post-treatment data, it appears that the diesel fuel moved downward in the time between coring and steam injection. The post-treatment soils data shows the majority of the contamination is in the range of 8 to 12.2 meters in depth. This could have been caused by the loss of a perched water table due to the very dry conditions in the region. Steam was injected at 10.7 to 12.2 meters below ground surface, and the 7.6 meter long screens on the extraction wells pulled vapor and liquids from the 3 to 10.7 meter depth range. Thus, the steam had a vertical component of flow, caused by the vertical positions of the screens on the injection and extraction wells. The growth of the steam zone was monitored by a limited number of temperature wells, and this data shows that the region from 6.1 to 9.1 meters below ground surface was generally heated to steam temperature. At the bottom of the wells (12.2 meters), the temperature generally did not rise above 70°C. Some of the highest concentrations of TPH were in an area where underground storage tanks existed, and this area only received steam for a short period of time at the end of the project. Thus, it appears that a majority of the remaining contamination (but not all) was in areas that did not reach steam temperature. Also, cycling of steam injection and vacuum extraction, which was found to be very effective at other field sites for recovering contaminants, was not used at this site.

A more thorough understanding of the subsurface conditions, a better designed injection/extraction system to heat the lowest zones where contaminants occurred, more temperature monitoring wells throughout the treatment area and monitoring of the steam injection rate at individual injection wells to monitor the growth of the steam zone, and more effective operation may have improved the overall effectiveness of this system.

A pilot steam injection study was carried out at the Yorktown Naval Shipyards in Yorktown, Virginia (Farrington and Sword, 1994), where Naval special fuel oil had leaked from underground storage tanks. This oil is slightly less dense than water, with a specific gravity in the range of 0.94 to 0.99 at ambient temperatures, and is essentially insoluble in water and nonvolatile. The viscosity of this oil, measured on two different samples, ranged from 137 to 50 centipoise at 38°C. Thus, the oil at this site is floating on top of the shallow water table and moves only slowly at ambient temperatures. Steam was injected below the water table to heat the oil, and oil began to be recovered from the system when the average temperature reached about 60°C. The viscosity of the oil at this temperature is in the range of 20 to 40 centipoise, a substantial reduction from the ambient temperature viscosity. For an oil which is nonvolatile, and where the injected fluid is not being used to physically displace the free phase liquid, hot water injection, if implemented correctly, may be capable of recovering as much of the free-phase oil as steam injection without the associated difficulties and extra costs of generating and injecting steam.

A pilot scale demonstration project was carried out at Naval Air Station Lemoore in Lemoore, California, in 1994 to recover JP-5 (Udell et al., 1994). The system consisted of two injection wells surrounded by 8 extraction wells within the contaminated zone. Thus, much of the recovered fluids, including an estimated 80 percent of the recovered JP-5, was from outside of the targeted treatment area enclosed by the extraction wells. Concentration of TPH inside the treatment area in the vadose zone was reduced from as high as 100,000 ppm to 20 to 50 ppm. At and below the water table, however, TPH concentrations remained around 20,000 ppm. Soil samples taken after 35 days of steam injection showed high TPH concentrations at the interface of the surface clay layer and the underlying silty sand which had previously appeared to be uncontaminated. Continued steam injection reduced these concentrations. Recommendations for reducing or eliminating the upward spreading of contaminated vapors included control of the ground-water elevation to avoid mounding during steam injection, higher JP-5 extraction rates in both the liquid and vapor phases, and greater energy input rates to avoid condensation. These recommendations could be achieved by installing wells made for both steam injection and extraction of liquids and vapors, allowing greater system flexibility and by continuous monitoring of ground-water elevations to optimize fluid removal rates.

A demonstration of a Dual Auger Rotary Steam Stripping system by In-Situ Fixation, Inc., (DOE, 1997) was carried out at the Pinellas Plant Northeast Site at Largo, Florida, starting in December 1996. The system used was similar to the previously described "Detoxifier" system. The remediation goal of this demonstration project was to reduce high contaminant concentrations (500 to 5000 ppm) to levels which are more amenable to anaerobic bioremediation, which was the chosen remedial technique for this site. Although 75 to 95 percent removals of contaminants from soil and ground water were generally achieved, the treatment goal of 100 to 200 ppm remaining was not generally met. In the more highly contaminated areas, the system was severely limited by the vapor treatment system which could not treat the large quantities of volatile organics that were released. Thus, it is difficult to fully assess the effectiveness of the auger/steam injection system for releasing contaminants from soil and ground water because of the limitations placed on system operation from the undersized vapor destruction system.

Cost Information

Cost information on innovative remediation methods is sparse because of the limited experience with applying these methods in the field. Because each site is unique in terms of the subsurface geology, the types and quantities of contaminants, and in terms of other site characteristics that may affect an in situ treatment technology such as steam injection, costs incurred during the application of this technology at one site are not directly applicable to the use of the same technology at another site. Also, much of the available cost data were collected during demonstration tests, and clearly some of the costs incurred during research and development of the technology will not be incurred again as the technology is applied at other sites (Evans, 1990).

Often cost information for in situ remediation is put in terms of a cost per unit of soil treated, and the terms of cost per cubic meter of soil treated will be used in this Issue Paper. However, the limitation of reporting cost data in this manner must be understood. Some costs associated with the technology, for example, mobilization, startup, and demobilization, are fixed costs and are not dependent on the volume of soil to be treated. Other costs, such as utilities for steam generation, are very dependent on the volume of soil to be treated. Thus, the cost in terms of per cubic meter of soil to be treated are going to decrease as the fixed costs are spread over a greater volume of soil to be treated. Also, consider the question of depth of the contaminated zone to be treated. The deeper the zone of contamination, the greater the drilling and well installation costs, but this may not significantly increase the cost per unit of soil treated. However, as the zone of contamination gets deeper, costs for excavation will increase significantly, and the relative costs of an ex situ treatment which relies on excavation of the soil versus an in situ treatment such as steam injection are going to change.

The costs associated with the "Detoxifier" demonstration at the Annex Terminal Port of Los Angeles have been estimated to be \$330/m^3 to \$415/m^3, based on a volume of 6,824 m^3 to be treated. The range in costs is related to the percent time on line that is used to make the estimate. Forty-four percent of the total costs were labor costs. Based on the company's operations to that time with the Detoxifier, they estimate the costs to treat 9,175 m^3 of material to be \$425/m^3 at the treatment rate of 3.8 m^3/hour, \$260/m^3 at the treatment rate of 7.7 m^3/hour, and \$165/m^3 at a treatment rate of 15 m^3/hour. They expect the costs to reduce as they gain additional experience and make modifications to their equipment. These numbers show that unit costs are very sensitive to the treatment rate, which is determined by site characteristics, contaminants present, and the clean-up criteria (EPA, 1991).

For the steam enhanced remediation project at the Rainbow Disposal site, the costs associated with the project were approximately \$4.4 million. The total amount of soil that was considered to have undergone treatment was 72,600 m^3, which gives a cost per cubic meter of approximately \$60. Labor accounted for about one-third of the total cost, and utilities accounted for another large portion. For this project, mechanical problems reduced the on-line factor to about 50 percent, which drove up the total costs, especially labor costs. It is reasonable to expect higher on-line factors at commercial remediation sites. Cost estimates were developed based on this project using on-line factors of 75 and 100 percent, and the associated costs were estimated to be \$47 and \$38/m^3, respectively.

In the Dynamic Underground Stripping demonstration project, steam injection heating costs were approximately \$2.0/m^3 (Udell, 1997), while electrical resistance heating costs were \$6.5/m^3 (Newmark, 1992). Overall costs to clean up the gasoline spill site were \$11 million, which works out to a unit cost of about \$78/m^3 to \$92/m^3, and they expect the costs to drop by at least one-half as experience with the process is gained. These costs were also inflated due to the fact that this was a research project that involved a large number of researchers, and several experimental techniques were investigated which, while adding to the overall costs, did little or nothing to improve the efficiency of the project. Despite the inflated costs of this project, the total costs compare very favorably with estimated costs of \$25 million for vacuum extraction and water table lowering without steam injection, and \$30 million for excavation and backfilling (Yow et al., 1995).

Costs of the Dual Auger Rotary Steam Stripping demonstration project totaled \$919,650 and a total of 1566 m^3 of soil were treated, giving overall treatment costs for this demonstration of \$587/m^3. However, significant downtime was experienced during the early part of this demonstration due to equipment problems and, as mentioned previously, the rate of treatment in some

areas was slowed significantly due to the undersized vapor treatment system. With improved on-line times and when higher treatment rates can be achieved, it is estimated that treatment costs as low as $88/m³ may be possible.

Conclusions

Laboratory studies and field demonstrations have demonstrated the ability of steam injection to effectively recover volatile and semivolatile contaminants from the subsurface. However, in order to effectively and efficiently apply this process, it is important to characterize the site adequately to determine the horizontal and vertical distribution of the contaminant, and the preferred flow paths for the injected steam. This information is critical to the design of the steam injection and extraction system. Effective operation of the system will likely include cyclic operation of steam injection and vacuum extraction after steam breakthrough at the extraction well has occurred. Advantages of steam injection over other remediation techniques include the fact that excavation is not required, potential contaminants are not injected to the subsurface, and potentially much more rapid remediations are possible. Without a doubt, the initial capital costs for steam injection are higher than those for a system that relies on removal of soil gases without heating, such as vacuum extraction. However, the accelerated removal rates can lower the total cost of cleanup by reducing the time required for the remediation, thus reducing the overall operating costs (Udell and Stewart, 1989). In addition, the higher temperatures can increase the amount of semivolatile organics that are recovered and the removal efficiencies from clay soils by increasing the volatilization and desorption from soil surfaces. In systems where the volatilization is limited by a low volatility of the contaminant or strong adsorption onto a solid phase, the temperature of the system may actually determine the clean-up level that can be attained. There will undoubtedly be trade offs between the efficiency of the cleanup and the cost of the treatment process.

Notice

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