Verification of an Improved Approach for Implementing In-Situ Thermal Desorption for the Remediation of Chlorinated Solvents

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ABSTRACT: The traditional approach for implementing ISTD for the remediation of organic compounds in the subsurface involves the installation of a combination of heater-only and heater-vacuum wells throughout the treatment area. This approach was originally developed for the treatment of sites with high-boiling point semi-volatile organic compounds (SVOCs, e.g., PCBs) where a tight well spacing (e.g., 2-3 m) is used to achieve the high temperatures (300 to 400°C) necessary to volatize and desorb the contaminants and to capture the formed vapors via the creation of enhanced air permeability due to desiccation of the soils. The high temperatures immediately surrounding the heater-vacuum wells also ensures high rates of in-situ destruction of the SVOCs, thereby minimizing the mass loading to the off-gas treatment system and ensuring attainment of the required destruction and removal efficiencies (e.g., 99.9999% DRE for PCBs).

The much lower treatment temperatures (i.e., 100°C) required for the remediation of sites contaminated with chlorinated volatile organic compounds (CVOCs), allows for the use of much wider spacings between the heaters (e.g., 5 to 8 m). These wider spacings significantly reduce the overall cost of remediation by reducing installation, material, and construction costs. In low hydraulic conductivity soils (e.g., silts and clays), however, these wider spacings can result in the delayed capture and removal of vapors and steam, thereby prolonging treatment, due to the slow drying of the soil immediately adjacent to the heater-only wells and the associated lag in establishing vapor pathways between the widely spaced heater-only and heater-vacuum wells.

A full-scale field application of a new approach for ISTD treatment of CVOCs in saturated low permeability soils (i.e., 10^{-8} cm/s) was recently completed at the Terminal One Site in Richmond, CA. The new approach utilized heater-only wells installed with a small sand pack to facilitate drying and heating of the soil and horizontal SVE wells for the capture of steam and contaminant vapors. The sand pack provided a pathway for vapors to move upwards along the heater-only wells into an overlying unsaturated high permeability layer of fill where the vapors were readily removed by the horizontal SVE wells. These improvements significantly reduced the cost and improved the performance of the ISTD system and minimized the potential for DNAPL banking and downward mobilization. Thorough heating to the ground surface also prevented condensing and translocation of contaminants in the vadose zone.

INTRODUCTION

The traditional approach for implementing ISTD for the remediation of organic compounds in the subsurface involves the installation of a combination of heater-only and heater-vacuum wells throughout and surrounding the treatment area (Figure 1). Heat flows from the 1200-1500°F (650-800°C) heating elements through the soil by thermal conduction, and in permeable soils, by convection. As the soil is heated, VOCs and

SVOCs in the soil are vaporized and/or destroyed by a number of mechanisms, including: (1) evaporation into the subsurface air stream; (2) steam distillation; (3) boiling; (4) hydrolysis; (5) oxidation; and (6) pyrolysis (high-temperature chemical decomposition in the absence of oxygen). The vaporized water and contaminants are removed from the subsurface via the heater-vacuum wells. For traditional applications of ISTD, the ratio of heater-only to heater-vacuum wells range between 2:1 and 3:1 (i.e., 2 or 3 heater-only wells for every heater-vacuum well).

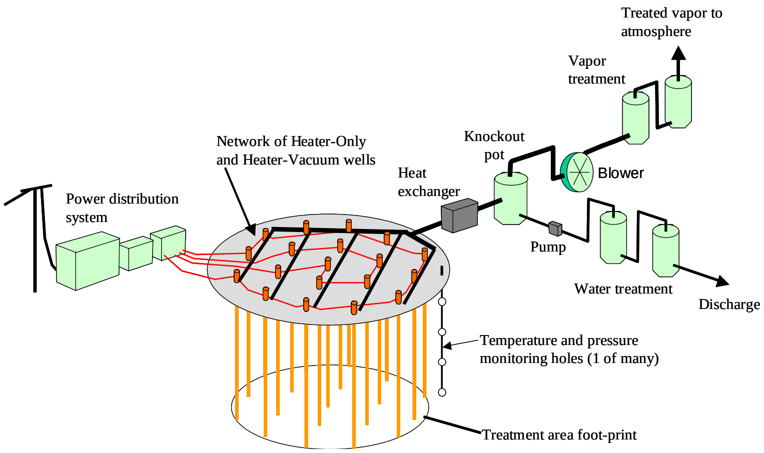


FIGURE 1. Example layout and setup of a typical ISTD system.

This approach was originally developed for the treatment of sites with high-boiling point semi-volatile organic compounds (SVOCs, e.g., PCBs). The tight well spacing (e.g., 2-3 m) is used to efficiently achieve the high in-situ soil temperatures (300 to 400 °C) necessary to volatize and desorb the contaminants and to capture the formed vapors via the creation of enhanced air permeability due to desiccation of the soils. The close well spacing also ensures good vapor capture and high rates of in-situ destruction.

The high temperatures necessary for treatment of SVOCs, requires that all of the water within the treatment zone be removed and/or boiled-off. For treatment zones located below the water table, some form of hydraulic control is typically required to prevent ongoing migration of water into the treatment zone and to ensure efficient heat-up. If water migration into the treatment zone is controlled, the rate of heat-up is governed by the thermal conductivity of the soil and the thermal gradient. Large thermal gradients are possible for dry soil with close well spacings because of the absence of a steam/boiling zone soon after the start of heating (Figure 2).

Figure 2 represents a conceptualization of subsurface temperatures and soil moisture conditions between 2 heaters at three different times during heating and remediation of a site with high boiling point compounds (e.g., PCBs). A typical target temperature and well spacing for such a site is 350oC and 2.5m, respectively. Midway through heating (t_1), approximately 2/3 of the water has been removed and 2/3 of site has been heated to >100oC. Since heat migrates radially outward from the heaters and the surface area of the dry and hot soil zone surrounding the heaters is large, the rate of heat transfer is high and the remaining water is quickly boiled-off and the soil is super heated (t_2). Once the water has been removed from the soil, heating is dominated by thermal conduction under high thermal gradients and heating to the target temperature progresses rapidly.

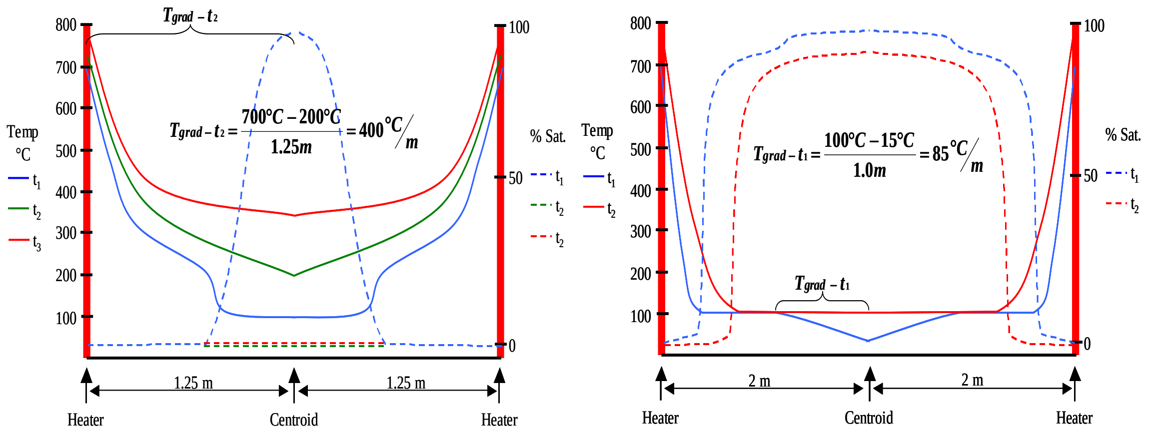


FIGURE 2. Temperature and soil moisture distributions during high - 350°C (left) and low - 100°C (right) temperature ISTD applications.

For sites contaminated with volatile organic compounds (VOCs) or chlorinated volatile organic compounds (CVOCs), complete remediation (e.g., >99.99% reduction) can be achieved with a much lower treatment temperature of just 100°C. This is because VOCs and CVOCs are readily steam-stripped and volatilized at 100°C. Further, mixtures of chlorinated solvents and water boil at temperatures less than the boiling point of individual constituents. For example, a mixture of PCE and water will boil at 88°C at 1 atm pressure, more than 30°C less than the 121°C boiling point of pure PCE. Thus, higher treatment temperatures and complete removal of the water are not required to achieve very low cleanup up levels. Experience and laboratory studies (LaChance et al. 2004; Udell 1996, Heron et al. 1998a; Heron et al. 2005) suggest that removal or boiling-off between 20% and 30% of the water present in the treatment zone is sufficient to achieve low cleanup levels (e.g., <100 μg/kg). This represents a significant cost savings, as vaporization of water or boiling is responsible for the majority of the power consumed at a site. For VOC/CVOC sites, the primary factor affecting the rate of heat-up and the time required to achieve treatment is thermal conduction under low temperature gradients and in permeable soil, convection of steam. (Figure 2)

The lower target treatment temperature of CVOCs, allows for the use of much wider spacings between the heaters (e.g., 5 to 8 m). These wider spacings significantly reduce the overall cost of remediation by reducing installation, material, and construction costs. In low hydraulic conductivity soils (e.g., silts and clays), however, these wider spacings can result in the delayed capture and removal of vapors and steam, thereby prolonging treatment, due to the slow drying and super heating of the soil immediately adjacent to the heater-only wells and the associated lag in establishing vapor pathways between the widely spaced heater-only and heater-vacuum wells.

MATERIALS AND METHODS

A full-scale field application of a new approach for ISTD treatment of CVOCs in saturated low permeability soils (i.e., 10^{-8} cm/s) was recently completed at the Terminal One Site in Richmond, CA. Figure 3 provides a plan view of the site showing the extent of the treatment zone, the heater well layout, and the locations of the horizontal SVE wells. The 126 heaters were placed at 4-m spacing. Figure 4 shows a generalized cross-section of the subsurface conditions at the Richmond site and a conceptualization of the ISTD design.

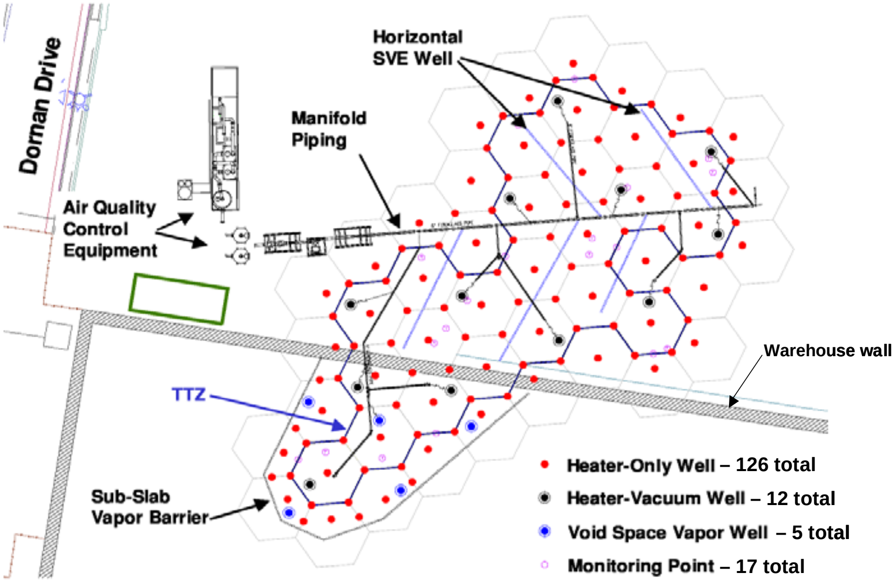


FIGURE 3. ISTD system layout.

The new approach used at the Richmond site utilized heater-only wells in-stalled with a small sand pack to facilitate drying and heating of the low permeability (10^{-8} cm/s) Bay Mud and horizontal SVE wells for the capture of steam and contaminant vapors. The sand pack provided a pathway for vapors produced during heating to move upwards along the heater-only wells into an overlying unsaturated high permeability layer of fill where the vapors were readily removed by the horizontal SVE wells (Figure 4). These improvements significantly reduced the cost and improved the performance of the ISTD system and minimized the potential for DNAPL banking and downward mobilization.

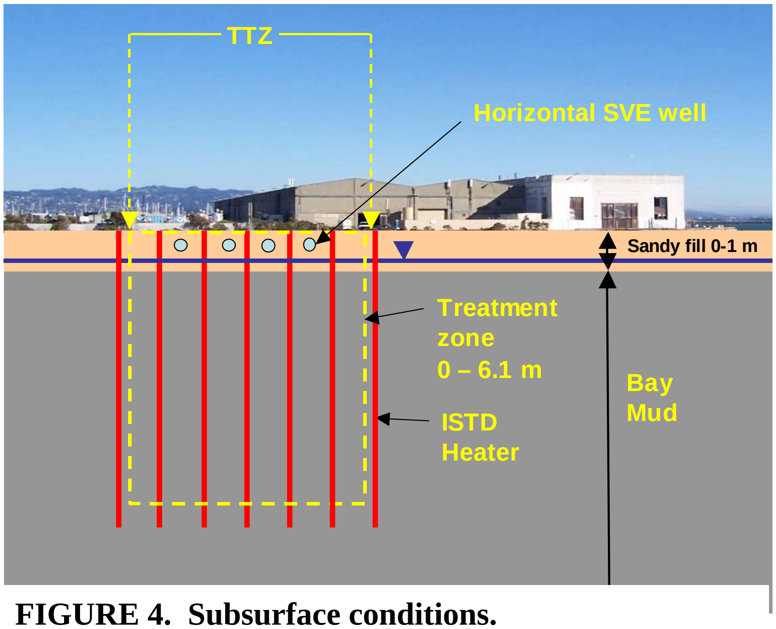
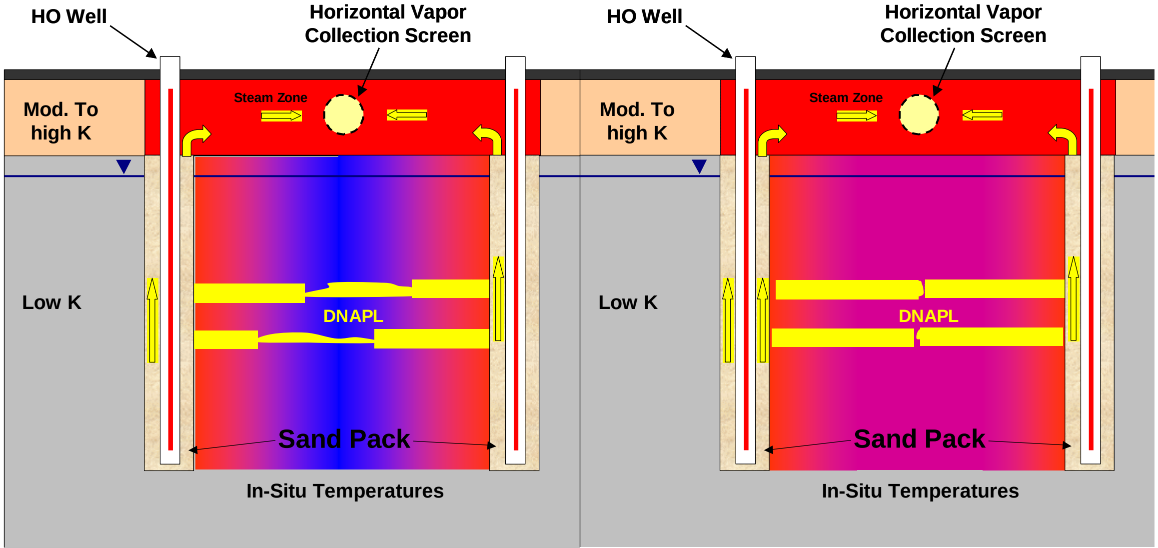


FIGURE 4. Subsurface conditions.

Figure 5 presents a conceptualization of how heating progresses during ISTD in low permeable deposits and the affects of heating on DNAPL present in the treatment zone. An insulated vapor barrier was installed across the surface of the treatment zone to ensure thorough heating to the ground surface, thereby, preventing condensing and translocation of contaminants in the vadose zone.



Imposing a vacuum on hot/dry zones immediately surrounding the heater wells encourages mass and vapor to flow to and up sand packs

Progressive heating (1-2 ^{0}C per day) ensures controlled mass depletion and minimizes condensation and threat of mobilization

FIGURE 5. Conceptualization of impacts of progressive heating and mass removal on DNAPL mobilization when using ISTD in low permeability deposits.

During operation, the zone immediately adjacent to the heater wells heats to above 100^{o}C, as the soil there dries. The pores of this zone are filled with vapor, predominantly steam. Due to the drying, the soils have increased vapor phase permeability, enabling this zone to serve as a preferred pathway through which the generated steam and VOC vapors escape to shallower depth, without a significant pressure build-up. As water and DNAPL are heated and vaporize, a volume increase of about 1,600-fold occurs (expansion from liquid to vapor). The path of least resistance for this large volume of vapor to escape is towards the boring, then up along it to the shallow permeable soil and the vapor collection system. Figure 6 shows a close-up of this process, but with a shallow vapor collection point in place of the horizontal SVE wells used at the Richmond site.

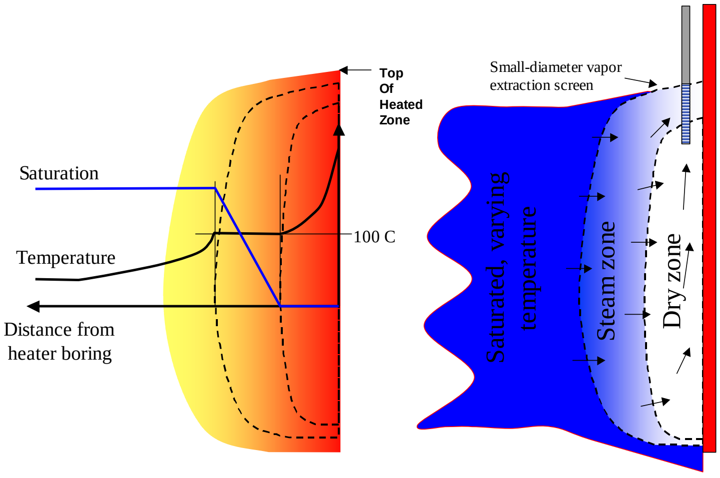


FIGURE 6: Schematic of TCH boring design and vapor recovery method (the arrows on the right side indicate vapor flow directions).

It is crucial to understand that the boiling of liquids in the steam zone leads to production of several hundred pore-volumes of vapor. Since these vapors are extracted at each heater location, they do not migrate horizontally away from the heaters, as would happen during steam injection. The vapors are constantly extracted, meaning that the mass of VOCs in the subsurface decreases immediately after onset of heating. In addition, any contaminant vapors that are not removed and are pushed outwards, encounter cooler regions immediately adjacent to the region at steam temperature and condense just a short distance away. As the heat front steadily advances, these regions are subsequently heated and the condensed contaminants are re-vaporized, with a portion or all of the contaminant mass removed. This depletion process occurs progressively and on a small scale, not all of a sudden over large portions of the subsurface as in a steam drive. Therefore, DNAPL saturations decrease immediately upon the start of heating, and significant banks of condensate are not formed. This is key to minimizing the risk of DNAPL mobilization.

RESULTS and DISCUSSION

Figure 7 presents a plot of temperature within the permeable fill for centroid locations in between the heater wells (i.e., locations within the well field farthest from a heater) and Figure 8 presents temperature data from the centroid locations at various depths within the Bay Mud underlying the permeable fill. Figure 7 indicates that the permeable shallow zone heated up quickly and much faster than the Bay Mud. This was due to convective transport of steam and heat throughout the permeable fill. Steam generated around the heaters readily moved up the sand packs and into the permeable material where it was extracted by the horizontal vapor collection wells. The establishment of a dry hot zone surrounding the heater wells (0.3 m) facilitated the steady heat-up of the interwell regions through out the vertical extent of heating. The target temperature of 100°C was generally reached after 110 days of heating.

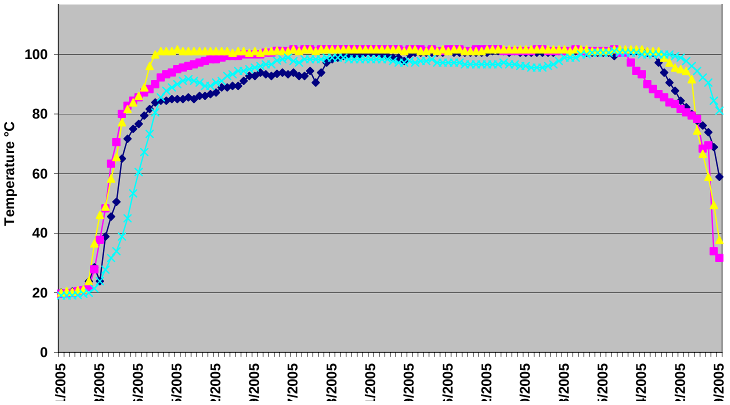


FIGURE 7. Temperatures within permeable fill at centroid locations in between heater wells.

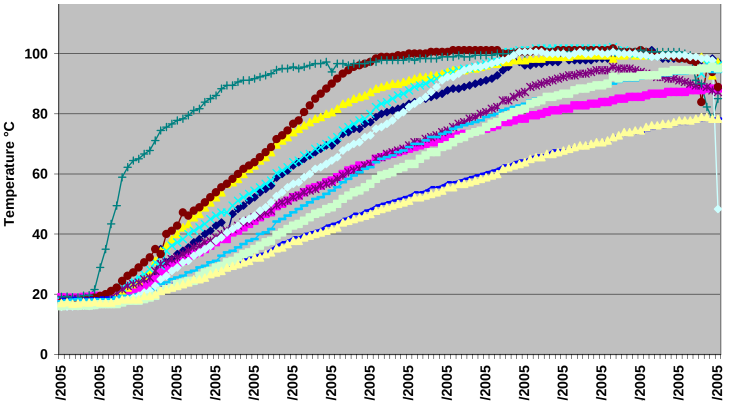


FIGURE 8. Temperatures at various depths within Bay Mud at centroid locations in between heater wells.

Over the course of heating, approximately 660,000 liter or 30% of the water present in the treatment zone was boiled off and recovered as steam. This volume of water is equivalent to approximately 500 pore volumes of steam generated and removed from the treatment zone during the 110 days of heating, or ~5 pore volumes per day. Thus, even in very low permeable soils stream stripping is the primary removal mechanism.

Figure 9 presents a comparison of pre- and post-treatment average soil concentrations relative to the remedial goals for the target CVOCs. These data indicate that the new ISTD approach was very effective at removing the target CVOCs from the treatment zone. Greater than 99% reduction in concentration was achieved for all constituents after 110 days of heating.

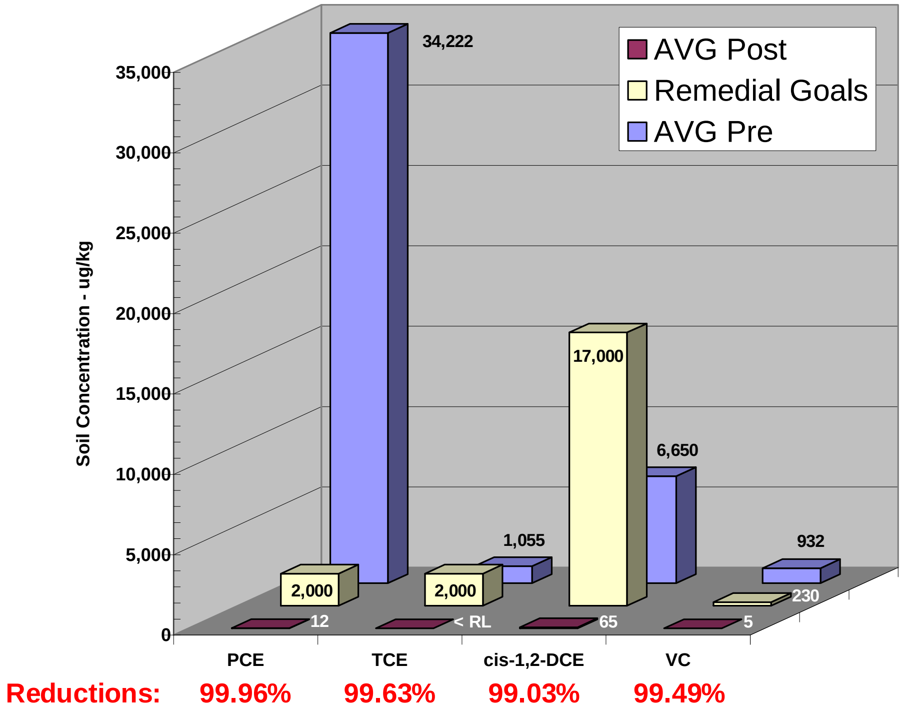


Figure 9. Comparison of pre- and post-treatment soil concentrations.

These results are based on 17 pre-treatment samples and 64 post-treatment samples. Post-treatment samples were collected from centroids (i.e., coolest locations) at random and biased depths throughout the treatment interval. 15 samples, or 23%, were collected between 18 and 20 ft bgs (i.e., the bottom of the treatment zone). These data did not show any evidence of vertical mobilization of contaminants or DNAPL.

CONCLUSIONS

An improved approach for the use of ISTD for the remediation of VOCs and/or CVOCs in low permeability soils has been developed, tested in the field, and verified to be successful and cost-effective. The improved approach relies on the installation of a sandpack around each heater well and the extraction of vapors from each well either directly or indirectly via a soil vapor collection system. This approach allows for the creation of a hot, dry zone and preferential pathway for vapor migration around each heater. As the steam zone progressively builds around a heater well, steam and contaminant vapors are steadily removed toward and along the heater wells, thus preventing the rapid buildup of high pressures and outward lateral migration of steam and contaminant vapors into cooler regions where condensation and DNAPL banks could form. This approach prevents or minimizes the risk for lateral migration of contaminants and reduces the risk of downward migration by progressively depleting DNAPL pools as the site slowly heats up.

Traditional approaches using a network consisting of combinations of heater-only and heater-vacuum wells are not as efficient at treating VOCs and CVOCs in low permeability soils because the target temperature is only 100°C and only a fraction of the water need be removed for effective treatment. Thus, the low permeability soil does not dry out and the relative air permeability remains low and vapor recovery limited.

Even in low permeability sites, steam stripping is the dominant removal mechanism. At VOC/CVOC sites where 30% of the pore water is boiled off, ~500 pore volumes of steam will be generated and removed from the treatment zone over the duration of heating/treatment. This has been proven to be sufficient to achieve very high removal rates (e.g., >99% reduction in concentration) and very low, residential soil cleanup standards (e.g., <100 μg/kg).

Finally, the replacement of heater-vacuum wells with either horizontal or vertical soil vapor extraction wells that result in the removal of vapors from each heater well, results in a significant reduction in installation and material costs, thus reducing, the overall costs of ISTD for the remediation of VOCs and CVOCs.

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