Data Compilation Regarding Geotechnical and Structural Effects of Subsurface Heating

This report is a compilation of information from representative past In Situ Thermal Remediation (ISTR) projects related to geotechnical and structural effects of in situ heating. Information related to changes in soil moisture content near heater wells before operation and directly after operation including depth of soil samples, distance of soil samples to heater wells, and soil geology is included. We have included observations related to soil consolidation near heater wells, particularly beneath or adjacent to buildings or concrete structures.

With the exception of the Fargo, ND ERH entry, most of the following observations are from projects that utilized In Situ Thermal Desorption (ISTD). Note that these observations include both higher-temperature applications of ISTD (those with target temperatures ≥ 300°C), and moderate-temperature applications of ISTD (those with target temperatures close to 100°C). Accordingly, projects treating SVOCs are considered higher-temperature applications, while those treating VOCs are moderate temperature applications. Each entry is identified as up-front as either higher- or moderate temperature. The entries are in chronological order, oldest project first.

Cape Girardeau, MO (higher temperature). In 1997, Shell-TerraTherm performed a demonstration-scale ISTD project to treat PCBs at the Missouri Electric Works (MEW) CERCLA site in Cape Girardeau, MO (Vinegar et al. 1997; France-Isetts 1998). There, PCBs (Aroclor 1260) were the contaminants of concern in massive clay soil. Both thermal blankets and thermal wells (Figure 1) were tested at the site.

Fig. 1. ISTD of PCBs using thermal wells at MEW Site, Cape Girardeau, MO.

The soil temperatures achieved within interwell regions of the target treatment zone (TTZ) were >500°C, much higher than is now considered necessary. The post-treatment soil exhibited increased porosity (from 30 to 40%) and increased air permeability (from 3×10^{-9} to 5×10^{-5} cm/s). It was reported that mechanisms for increased permeability and porosity included fracturing, clay desiccation, and removal of organic material. Additional air permeability resulted from evaporation of soil moisture. Samples of the post-treatment soil were also analyzed by scanning electron microscopy and x-ray diffraction. The soil texture was altered from a plastic silty clay to a rigid porous material that was likened to a siltstone, but which was described as breakable in the hand. The clay plasticity was not retained, and the x-ray diffraction showed a shift from an illite clay to an amorphous clay (no illite x-ray peak). The work was not performed near a structure.

Portland, IN (moderate temperature). In 1997, Shell-TerraTherm performed the first full-scale ISTD project to treat CVOCs at a site in Portland, IN (Vinegar et al. 1999; USEPA 2003). The site geology included fill, a combination of sand, clayey sand and construction debris, to a depth of about 7 ft., over silty-clay till. Twenty-five of the 130 heater wells in the larger of the two treatment areas were drilled through a concrete loading dock at a spacing of 7.5 ft. Maximum soil temperatures attained at a depth of 4 ft BGS at the loading dock were no higher than the boiling point of water. Dr. Kirk Hansen, Shell Oil Co. structural geologist recalls that there was no damage to the concrete. Eldon Ronning of Lawhon & Associates, Westerville, OH, who served as oversight consultant on the project while with Metcalf & Eddy, concurred with this characterization (Personal Communications, 3/2008). The loading dock remained in use by another owner in 2002, the last time we inquired. The first photo in Figure 2 was taken in 1997 during the ISTD project, while the second photo was taken by Dan Stiehl, a manager at the facility in Nov., 2002, nearly five years later.

Fig. 2. ISTD and post-ISTD photos of concrete loading dock (at right), Portland, IN site.

Eugene, OR (moderate to higher-temperature). In 1998, Shell-TerraTherm performed a full-scale ISTD project to treat petroleum hydrocarbons and VOCs including BTEX at a former bulk fuel terminal in Eugene, OR (Conley et al. 2000). The site geology included gravel over silt and silty sand / silty gravel. 102 of the total of 761 heater wells were drilled inside a building through the concrete floor, at a spacing of 7 ft (Figure 3). The

Fig. 3. ISTD wellfield being installed inside a building on slab, Eugene, OR site.

wells were installed to a depth of 14 ft. Within the 0-4 ft vadose zone, pre-treatment water saturation at the site was characterized as 0.5. Since the target temperature was above the boiling point of water, it can be assumed that the post-treatment water saturation was very low. Nevertheless, according to Shell's Dr. Kirk Hansen (personal communication, 3/2008), there was only minor, cosmetic cracking of the concrete floor around the heaters, nothing structural. Based on aerial photography available on Google Earth, the building appeared to remain in active use as of 2008.

Ferndale, CA (higher-temperature). In 1998, Shell-TerraTherm performed a full-scale ISTD project to treat PCBs (Aroclor 1254) at the former Naval Facility Centerville Beach, Ferndale, CA (Conley and Lonie 2000). A total of 1000 cy of soil were treated using thermal wells installed to a depth of 20 ft. A portion of the wellfield was located within a former transformer building (Figure 4). Some subsidence that was observed under one corner of the building was later attributed to the fact that the silty-clay soil had not been properly consolidated beneath the footing.

Fig. 4. ISTD wellfield being installed adjacent to and inside a small building at the Ferndale, CA site.

Confidential Midwest Site (moderate-temperature). In 2004 at a Confidential manufacturing site in the Midwest, TerraTherm completed a full-scale ISTD project to treat CVOCs (LaChance et al. 2004). The site consisted of a silty-clay till, with heater wells installed at a 17-ft spacing. To examine the effect of heating on the nearby slab-on-grade manufacturing plant structure, (see Fig. 5), TerraTherm placed one thermocouple ("TC-A") just outside the thermal well field, which was under an asphalt parking lot. Specifically, TC-A was located 5 ft horizontally from the outer ring of heater-only wells and 4 ft below ground surface (bgs). Note that at that time we had been heating over a depth interval from 2 to 17 ft bgs at that location for six months, with operating temperature of the heaters ranging from 1400-1600°F, and a target temperature within the treatment zone of 210°F (which was the boiling point of water at the 1000 ft elevation of the site). The maximum temperature observed at TC-A was 114°F, while the well field was still operating, and it declined afterward. We placed a second thermocouple, "TC-B", 10 ft from the edge (outermost) heaters and to a depth of 8 ft bgs, and it registered a steady temperature of 85°F during heating. The combined data are presented in Figure 6.

Figure 5. ISTD wellfield adjacent to slab-on-grade building at Midwest site.

Note that these temperatures were measured during the operational period, which by the time the data were collected had lasted nearly 6 months at that location. TerraTherm

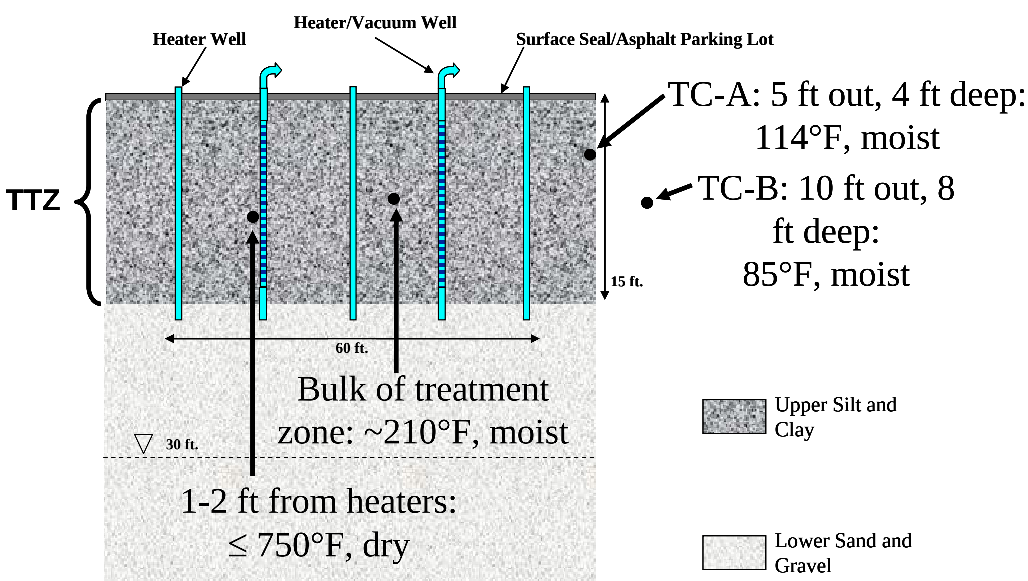

Figure 6. Adjacent temperature data collected at Midwest ISTD site.

also collected soil moisture content data during an interim soil sampling event after 130 days of heating (Figure 7). Although pre-treatment moisture content data had not been collected, the data from a distance of 7 ft from heater wells may be assumed to approximate pre-treatment conditions.

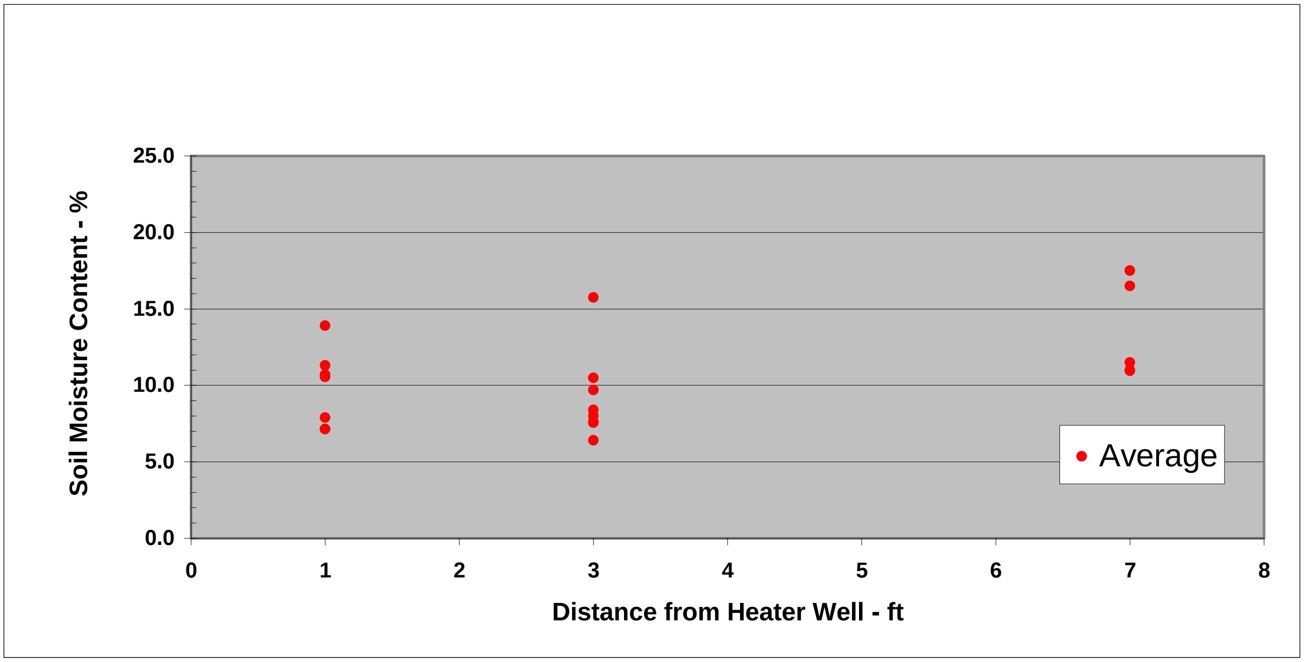

Figure 7. Average of Soil Moisture Contents at Midwest Site at Various Distances from ISTD Heater Wells after 130 Days of Heating, Soil Temperature: 90 to 100°C.

Moisture contents closer to the heater wells are somewhat lower, but illustrate that the soil was not desiccated. Such temperatures and moisture contents as those we measured would not be expected to have a significant effect on soil geotechnical properties affecting nearby or overlying structures, any more than seasonal temperature changes would affect them. Within the treatment zone, we saw very limited indications of subsidence, and only within about 1 ft of each of the heater wells, none further from them. This would be from localized desiccation of clayey soils immediately adjacent to the heater wells. The large energy demand represented by the latent heat of vaporization (i.e., to boil off water) means that most of the soil volume (97-99%) will sit at the boiling point of water for weeks. Thus, with moderate-temperature applications of ISTD it's fairly easy to avoid drying out the bulk of the soil volume when heating only to the boiling point of water.

Richmond, CA (moderate-temperature). In 2005, TerraTherm completed a full-scale ISTD project to treat CVOCs both beneath and outside of a large warehouse building on the shores of San Francisco Bay in Richmond, CA (LaChance et al. 2006) (see Fig. 8). The soils treated consisted of about 0-3 ft of a granular fill over saturated clayey Bay Mud. The southerly edge of the building, which was supported by pilings, was built directly on top of the Bay Mud, while within the northerly portion of the treatment zone there was a space of 1 to 3 ft between the floor and the Bay Mud surface. TerraTherm did not observe significant effects on the building or its concrete floor. Outside the building, small amounts of subsidence were evident within a foot of so of heater wells, but not within the bulk of the treatment zone. Over 95% of the soil cores collected from within the heated treatment zone for confirmation of cleanup (Sept. 2005) were observed to be moist (Figure 9).

Figure 8. ISTD wellfield adjacent to (above) and inside building, Richmond, CA.

Figure 9. Example of soil core collected during confirmatory soil sampling event, Sept. 2005, when soil had achieved target temperature of 100°C. Desiccation of the clayey soil was not observed.

This observation was consistent with what we reported above for the Midwest site. At both sites, we achieved the target treatment temperature of the boiling point of water.

Fargo, ND (moderate-temperature): The most serious case of subsidence that has been reported during an In-Situ Thermal Remediation project occurred during Electrical Resistance Heating (ERH) at USEPA's removal action at the Camelot Cleaners site in Fargo, ND. That soil was an expansive, smectite (2:1, expanding lattice-type) clay, and apparently shrunk due to drying during implementation of ERH there (Smith et al. 2006).

Odense, Denmark (moderate-temperature): At a site in Denmark, ISTD and steam were utilized by NIRAS, Krüger and TerraTherm to treat PCE-contaminated clay till over a sandy aquifer, inside an active dry-cleaning facility in operation (Figures 10 through 12)(Nielsen et al. 2008). The site is located in an area of Denmark consolidated by the ice cap during the last glacial period.

Detailed measurements of the vertical movement at selected monitoring points were taken prior, during and after thermal treatment to document the potential subsidence. All measurements were conducted by a professional surveyor.

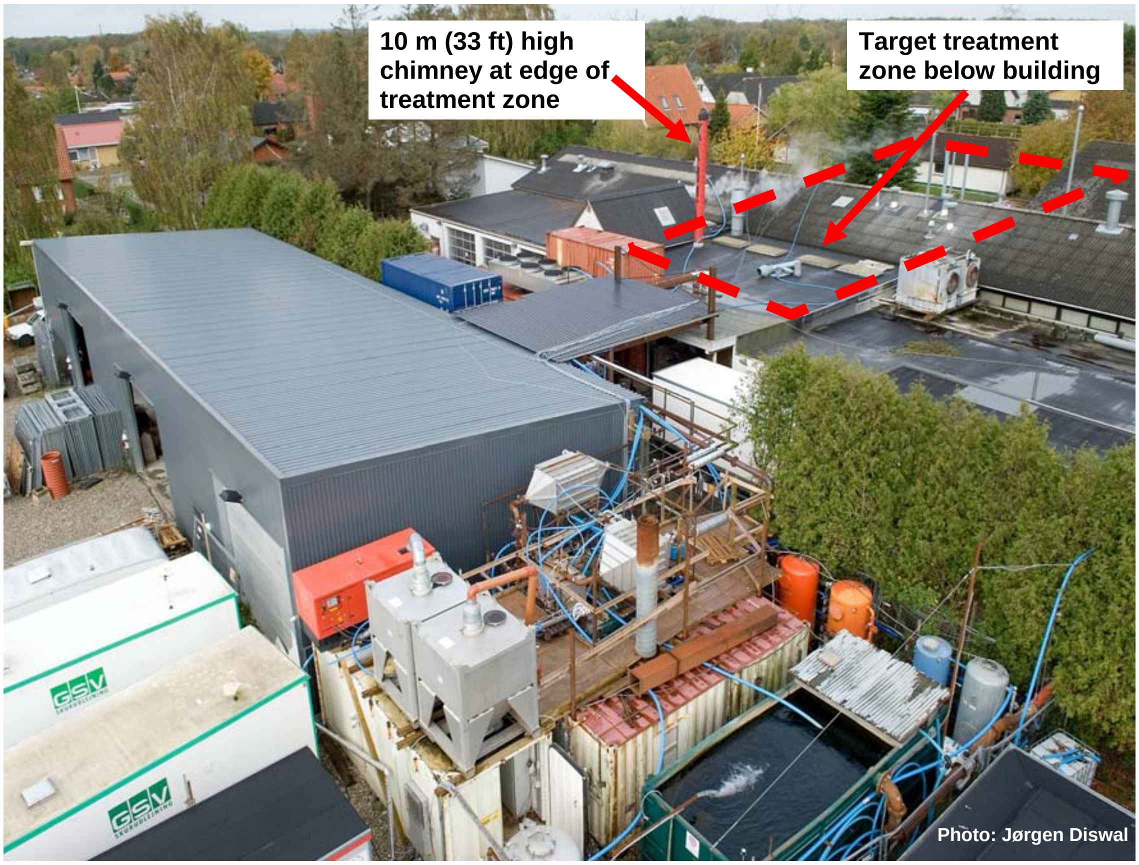

Figure 10. Aerial photo of the site showing the location of the treatment area below a building.

45 ISTD heater wells and 9 steam injection wells heated up the treatment zone extending 14 m (46 ft) below the floor in the facility. The upper 11 m (36 ft) was clay till heated by ISTD and the lower 4 m (14 ft) was sand heated by steam.

39 out of the ISTD heater wells were placed inside the dry cleaning facility with an average heater spacing at approximately 4.2 m (14 ft). Due to the limited space in the treatment area between dry cleaning machines, cables and other obstacles some of the heaters had to be placed in rows (hot walls) with an even closer spacing to cover the treatment area.

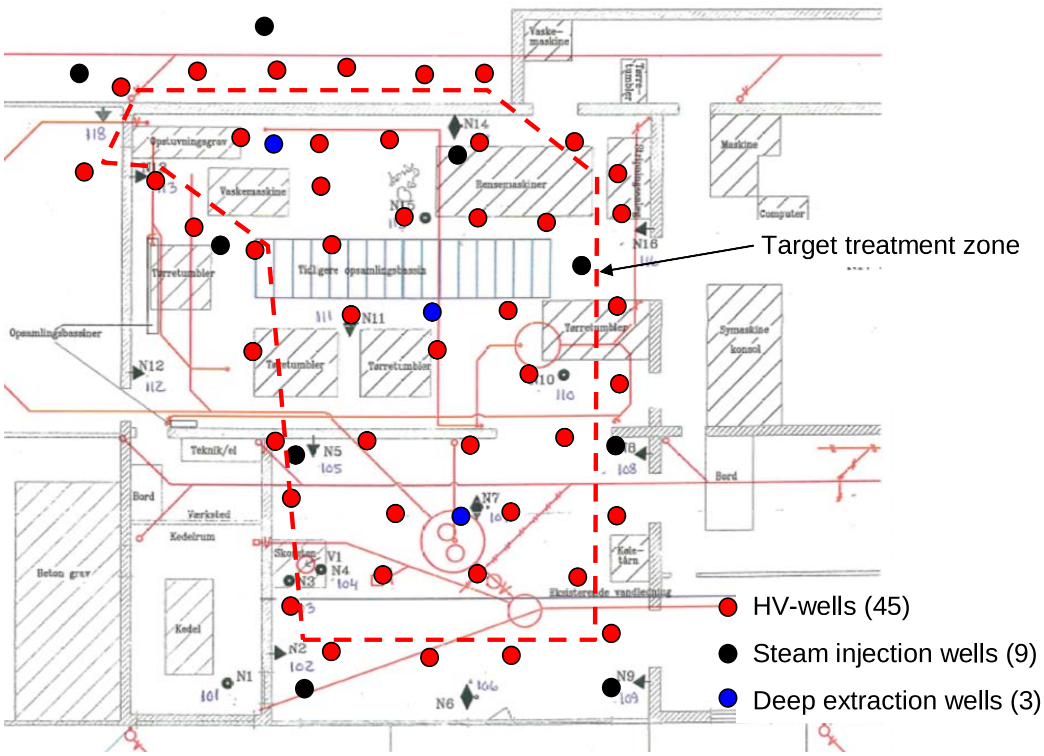

Figure 11. Well layout showing heaters inside the dry cleaning facility between machines walls and cables.

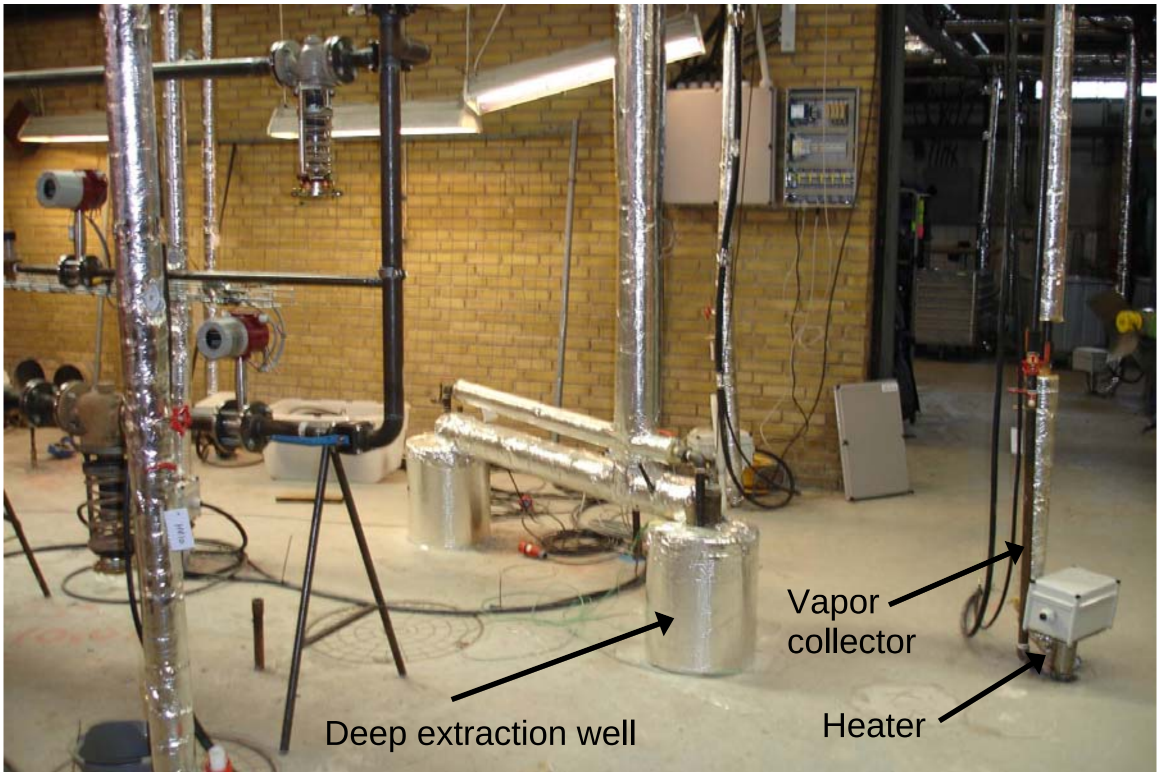

Figure 12: Picture showing wells installed inside the dry cleaning facility

18 subsidence monitoring points were placed in and around the treatment area. Three (3) points were placed directly on the concrete floor, five (5) points were established through the concrete floor and 1 m (3 ft) into the soil supporting the building, seven (7) points were put on the walls and one (1) point was located on a pillar supporting the roof. Furthermore two (2) monitoring points were located on the base to and one (1) on the top of a 10 m (33 ft) high chimney located directly at the edge of the treatment zone. The 18 monitoring points were placed in the well field in a random distance to the individual heater well – some close to heaters and some farther away from heaters. The location of each of the 18 monitoring points appears in Figure 13.

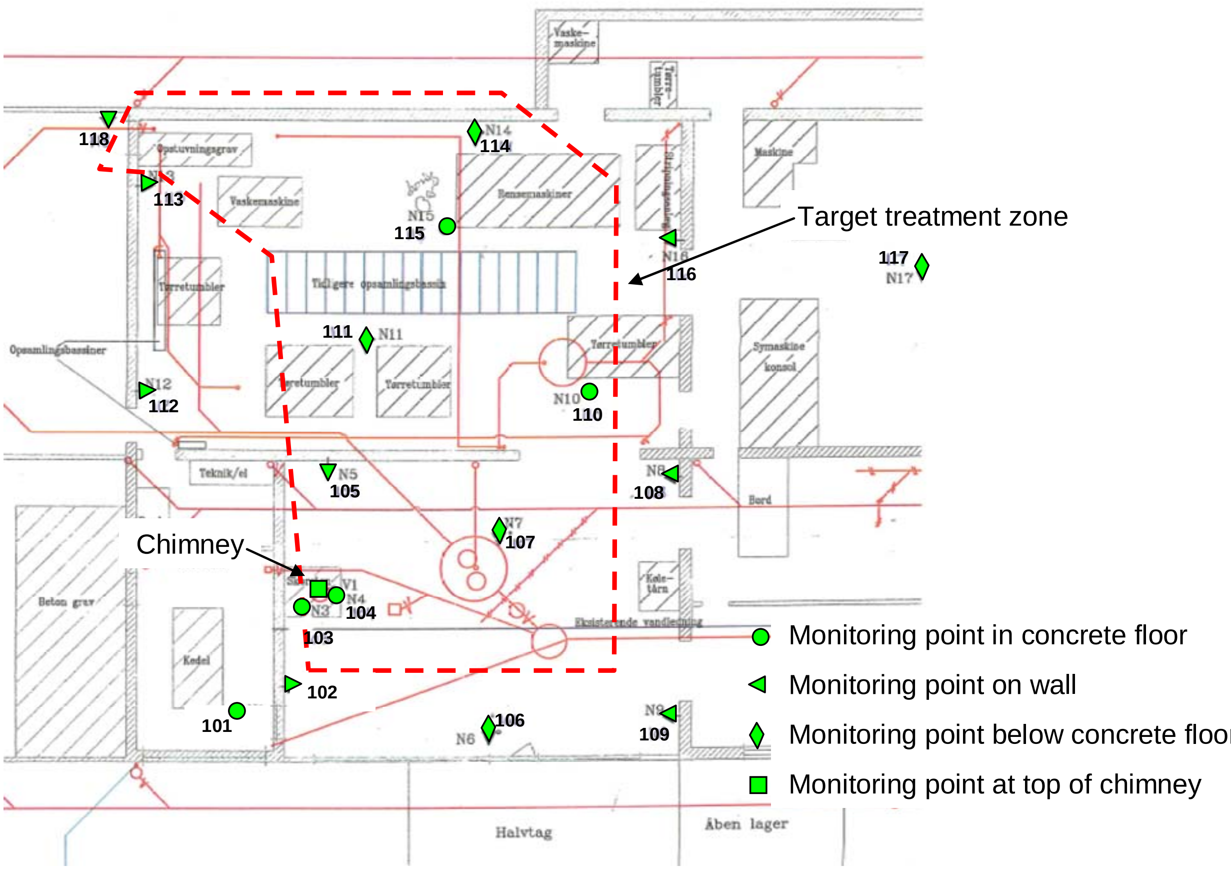

Figure 13. Map showing the location of the 18 subsidence monitoring points

The monitoring points were measured 11 times prior to, during and after treatment. One (1) round was conducted prior to, four (4) rounds during and six (6) rounds after treatment. The last round of measurements is scheduled to be completed in December 2009 at which time the water content in the treatment area is expected to have returned to its original level. At each monitoring round the level of each monitoring point was measured with a 1/10 mm (1/250 inch) accuracy.

Figure 14 shows the movement (upwards is positive, downwards is negative) of each of the 18 monitoring points. A monitoring round conducted in February 2008 more than 4 months prior to start of operation was used to establish a baseline for the calculations.

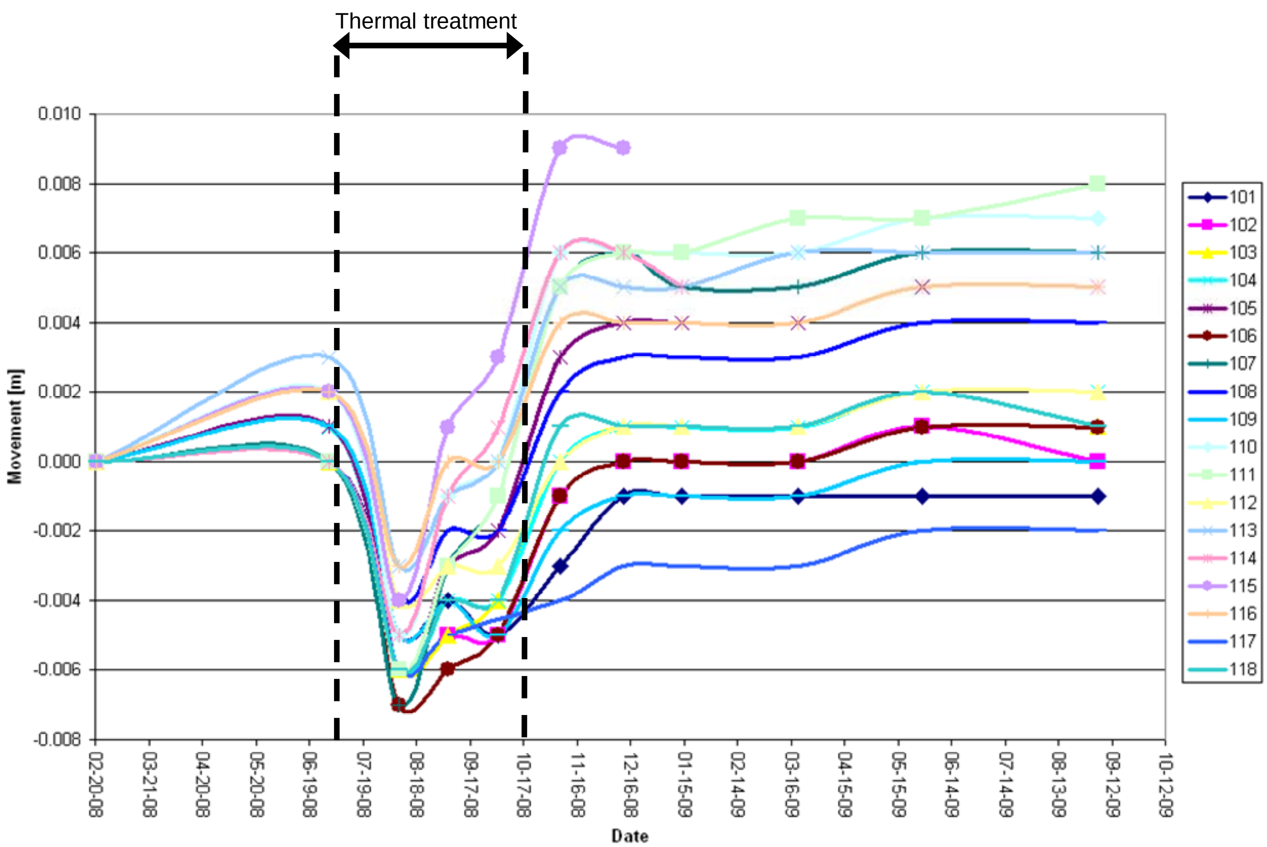

Figure 14. Measurements of vertical movement prior to, during and after thermal treatment at the Odense site.

Generally the typical movement (subsidence/lift) measured at the site was less than 4 mm (0.16 inch), but a lift as great as 9 mm (0.35 inch) was measured at a point located on the concrete floor (point 115) immediate after treatment.

The biggest subsidence was measured in two monitoring points (point 106 and 107) established in the soil 3 ft below the concrete floor with a subsidence recorded up to 7 mm (0.27 inch). Point 106 is now slightly above its original level (1 mm – 0.04 inch), while point 107 at the last monitoring round was measured to be 6 mm (0.23 inch) above its original level.

Overall the measurements indicate that the building at the site actually has risen as a result of the heating, since only two of the 18 points have been below their original level the past two measurement rounds.

Furthermore results from the measurements conducted to the control point on the top of the chimney show that the tilting of the chimney during and after operation was less than 8 mm (0.31 inch) in each direction.

During and after treatment, the building was inspected for any damage potentially caused by the small movements. No cracks or chinks were found.

Conclusions:

It is difficult to generalize when speaking about structural effects of heating the subsurface since they are site specific. Nevertheless, it can be concluded that indications of concern observed to date were under very specific circumstances:

1. Sites with expansive clay minerals such as smectite (e.g., Fargo, ND)
2. Sites with clayey soil that was desiccated by higher-temperature heating (e.g., Cape Girardeau, MO)
3. Sites with underconsolidated soil that were dewatered, then desiccated by higher-temperature heating (e.g., Ferndale, CA; N. Adams, MA)

Sites lacking any of these three conditions (e.g., Portland, IN; Eugene, OR; Confidential Midwest site; Richmond, CA; Odense, Denmark) did not show indications of subsidence or ill effects on concrete slabs or footings.

In summary, TerraTherm has not seen geotechnical changes such as subsidence associated with subsurface heating to be a problem in most cases. Precautions can certainly be made to help prevent subsidence. Positioning the heaters at least several feet away from sensitive utility lines would be advisable. Installing thermocouples adjacent to such lines may be appropriate to enable temperatures to be monitored there and the power applied to nearby heaters modulated to keep the utility lines from getting hotter than desirable. That is something that can be accomplished readily with ISTD. Thermal conduction heating is a very uniform and predictable process. TerraTherm can control individual heaters if desired and if we design the system to operate that way, we can keep the temperature at any sensitive location from rising above whatever limit you set, such as the boiling point of water. With SEE, there is not likely to be an issue with sensitive site features getting too hot.

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Thermal Treatment – How Close Can You Go, and Is It Safe to Humans?

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ABSTRACT: Thermal remediation is often chosen for delicate urban sites due to its ability to remediate to stringent goals in a fast and predictable way. But the delicate surroundings often pose a number of challenges in the way of obstructions, risk of settlement, and a need for stringent health and safety precautions. Three recent full-scale thermal remediation projects carried out in Denmark using in situ thermal desorption (ISTD) all posed challenges due to relatively stringent cleanup criteria and delicate surroundings.

Heating contaminated soils to 100ºC or more is a very aggressive remedy, and the effectiveness of the treatment is widely documented and accepted. The use of these aggressive technologies, however, often raise concerns regarding how close you can go to different objectives and general health and safety issues when used in urban sites and active industries where workers are present daily. The use of thermal treatment is not only a matter of effectiveness but also about the ability to implement the technology in a safe and sound way.

This paper presents some reflections based on three full-scale remedies carried out in Denmark in 2008 and 2009.

CONDUCTIVE HEATING - PRINCIPLE

The main principle in conductive heating is introducing a temperature gradient in the soil and, due to thermal conduction, the soil heats up in a uniform way. The thermal conduction technology used at these sites is developed and patented by Shell and commercialized through TerraTherm Inc. The technology consists of installing numerous vertical heater wells. The heater wells are all equipped with an electrical heater element, and by increasing the temperature on the heater element up to 500ºC to 800ºC a temperature gradient in the soil is introduced. Since the thermal conductivity of different soil types vary very little, it is possible to get a very uniform heating in all types of soil even with substantial heterogeneity. A few examples of thermal conductivity for different soils types are listed in Table 1.

TABLE 1. Thermal conductivity in different types of soil.

Soiltype	Thermal conductivity W/(m·K)
Gravel/stone	2.5
Sand	1.2
Clay	0.6

By raising the temperature in the soil the contaminants vaporize and are subsequently collected by capturing the produced steam and gas. In the close proximity of the heater wells, in-situ destruction can take place due to the high temperatures. Target temperature in the soil typically range between the boiling point of water and 325ºC depending on the contaminants to be treated and cleanup criteria to be reached.

CASE 1 – KNULLEN, ODENSE

The first case study regards a contamination underneath an industrial dry cleaner site. The dry cleaner facility is in operation and has to stay so without any restriction in the use of the work area while the remedy is ongoing.

The geological profile at the site consists of a permeable fill layer 0–3 m bgs. From 3–10 m.bgs. an impermeable clay/till body is present. Underneath this, a high yielding sandy/gravel aquifer is found. This aquifer is confined with a hydraulic head 5 m. bgs. The PCE contamination is spread through a leaking water/chemical separator and starts from 4.0 m. bgs. down to approximately 13.0 m. bgs.

Due to the complex hydrogeology steam was used to create a hot floor Underneath the clay and till body that was heated by the use of in situ thermal desorption (ISTD). The following will focus on the ISTD part of the remedy.

Primary concerns in the ISTD setup were as follows:

- Collection of vaporized contamination underneath the workspace
- Elevated floor and workspace temperature when heating Underneath the building
- Electrical safety and other issues when workers without any knowledge of the process are to use the workspace without restrictions during remediation
- Possible settling due to the aggressive heating

With extremely limited access and confined space, 45 ISTD heater wells and 9 steam injection wells were installed together with a comprehensive extraction system.

Target zone of the ISTD heating was 4 to 10 m. bgs. In this formation the soil was heated to a minimum of 100ºC. To address the issue of vaporizing the contaminants under the building and also to prevent condensation in the cooler upper 3 meters of the formation, a 1” extraction screen was installed in the gravel pack around each heater well.

Vaporization starts at the heater well and this is also where the in-situ produced steam would tend to go because of the permeability created when pore water is boiled off. As an extra safety regarding vapor intrusion to the workspace area, a sub slab venting system was installed. The system consisted of 22 one inch screens placed in the permeable fill layer right beneath the concrete floor. Vacuum was monitored, and smoke tests were done at visible cracks to see downward gradient while operating the system. During the remedy, 4 tons of chlorinated solvents were recovered successfully without any indications of vapor intrusion or complaints from the workers inside the building.

Heating underneath the building raised issues regarding possible temperature rise in the concrete floor and subsequently the workspace area. Another mean off the sub slab venting system was to provide cooling if necessary. Temperatures inside the building were fairly high before heating due to the lack of insulation of all the old steam pipes to the steam cleaner. As mentioned earlier, a comprehensive temperature monitoring system was installed. In the central location of the workspace, a monitoring point was installed 2 cm into the concrete floor and one 1.5 m above. Figure 1 illustrates the observed temperatures in the workspace area 1.5 m above the floor, in the concrete floor and 0.5 – 1 – 2 and 2.5 meter underneath the floor. As seen, the maximum temperature inside the building was 34ºC. It also seems that the increase in temperature in the floor and above it was not entirely dependent on the soil temperature since it decreased, while the soil temperature from 0.5–2.5 was steady or increasing. July 2008 was an extremely warm month in Denmark and has a significant impact on the fairly high temperatures measured inside the building.

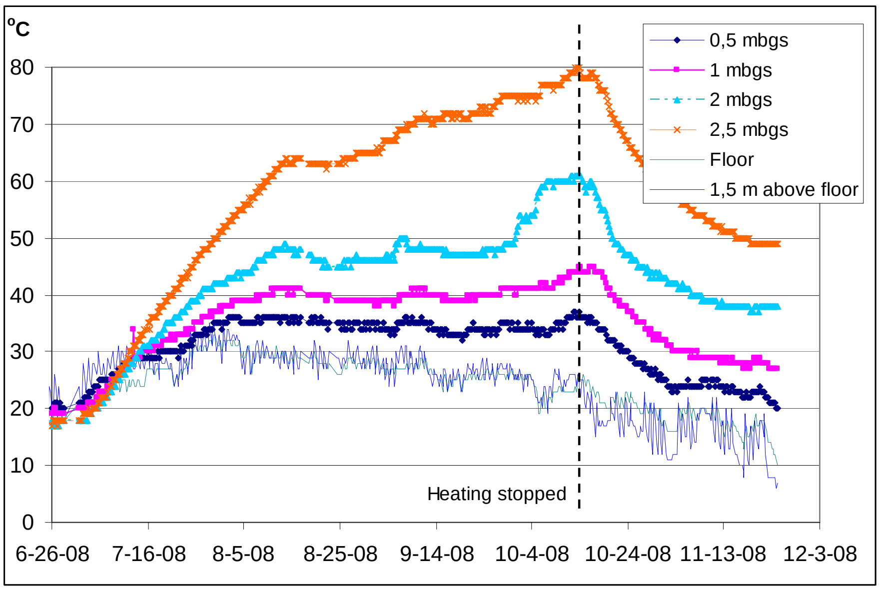

FIGURE 1. Soil temperature distribution.

The major health and safety issue at this site was the fact that 45 heater wells were connected with power cables, grounding cables and communication cables inside the working area. 67 extraction wells were assembled in a manifold carrying off gas at temperatures up to 250ºC. Normally the heated area is fenced but at this site, the laundry workers were to use the area without restrictions, e.g., pushing trolleys around heater wells, filling and emptying laundry machinery.

All piping was insulated and protected against accidental contact. All electrical equipment and installations of course comply with the national code, but to understand the safety a few issues will be discussed in the following.

Heater circuits are supplied with standard low voltage 220–240 V and not high voltage. The current, however, is run at approximately 200 A. The heater can and liners are all grounded with dedicated grounding circuits. Power cables to the heater circuits are over-current protected by fuses and a circuit breaker. On top of that every circuit has its own residual current circuit breaker (RCCB) that detects any leaking current in the circuits. At this site, the RCCB was set and tested at 30 mA equal to any private installation. No short circuiting, trigging of RCCBs occurred during the remediation.

The possibility of geological settling and subsidence when heating underneath a building was investigated. Dewatering and evaporation of pore water while heating can change the geotechnical properties of the heated soil. When treating contaminants at 100ºC, a pore water reduction of approximately 20% to 40% is common. This is an average reduction and one will see extremely dry soil in the proximity of the heater wells. When heating to 100ºC, these dry zones typically extend less than 40–60 cm from the heater well and typically will not exceed 10% of the total heated area.

Before the remediation started, an insurance coverage regarding structural building damage due to settlement was obtained. Concerns were especially focused on a chimney and its foundation. 19 leveling monitoring points were installed and measured before, during and after heating. The monitoring will continue 5 years after the end of the remedy.

The leveling data are shown in Figure 2. As seen, a general rise is observed during the beginning of the heating followed by level lowering below the starting point. Change in levels is a maximum of 9 mm and does not raise any geotechnical worries. Inspection during heating and subsequently one year after has not shown any signs of cracks in walls, floor or foundation.

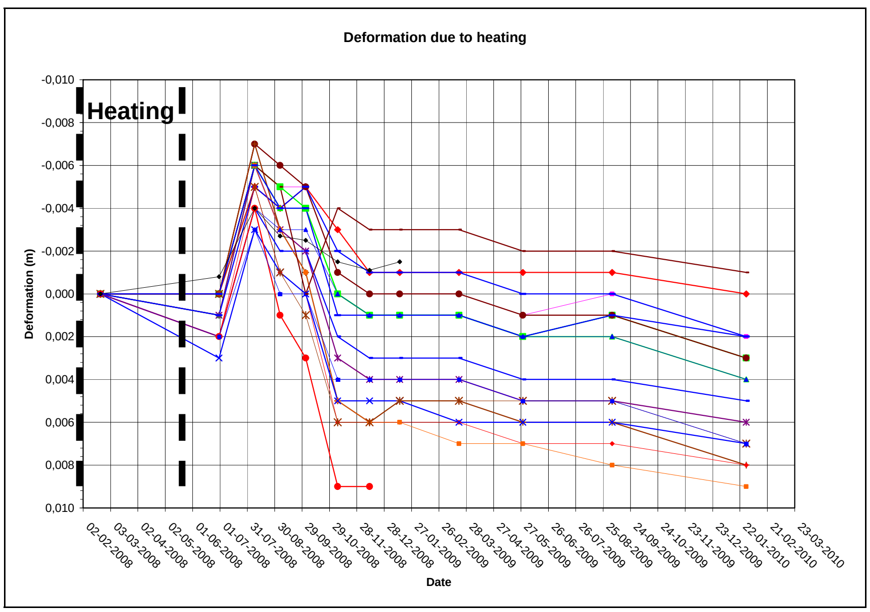

Figure 2. Leveling data. Heating period shown with black lines. /4/

After a successful ISTD remediation, four tons of chlorinated solvent were recovered and a mass reduction of 99+ percent was achieved within 105 days of heating. Non-educated people have been working in a work area packed with heater wells, manifolds extracting extremely hot off gas etc. without any incidents. This shows that it is possible to remediate using thermal methods underneath an active site in operation and do it in a safe and sound way.

CASE 2 – SKULDELEV

The second case study is a 7 m deep PCE hot spot located directly adjacent to a poorly constructed building and extending beneath the local fire pond. Due to a shallow water table and high hydraulic conductivity, the treatment volume was isolated with sheet piles, allowing for partial dewatering during treatment. Due to the topography, the treatment area was divided into terraces.

Placed in a very scenic residential area, the major concerns were human safety during heating, odor, and managing severe settlement when heating a 2.3 m thick peat layer.

At this site, the treatment area was fenced and blocked to public access.

Figure 3 shows the heated area. The double line illustrates the sheet pile, and the yellow lines illustrate the different terraces. The heating took place approximately 1 m from the old factory building. The sheet pile at this point was anchored in the soil underneath the factory building. The part of the sheet pile close to the building will stay permanently.

On the other side of the heated area, a private garden was located separated by a fence only. During the remediation, people stayed there and used the garden.

Especially the middle terrace was impacted by a thick peat layer. The layer was up to 2.3 m thick. During heating, especially the area where monitoring well T6 is located severe subsidence was seen.

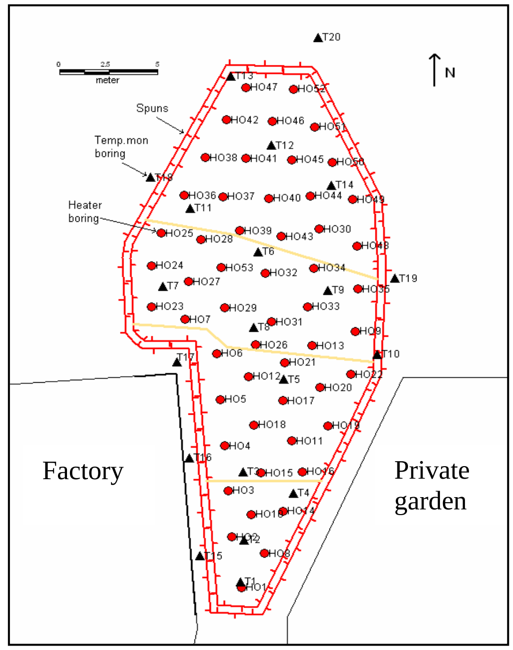

FIGURE 3. Treatment area.

Figure 4 illustrates the temperature in T6 at 0.5 and 1.5 m.bgs. The vapor cap settled more than 0.5 meters and eventually the thermocouple originally placed 0.5 m. bgs. was exposed. This subsidence resulted in damage to the vapor cap and inflow of cold air in large cracks. This challenged the pneumatic control and also heating of the top layer of soil underneath the vapor cap. In the last period of the remediation a polishing phase with cyclic ventilation was done to secure remediation of the top layer. At this time, steam was observed in the area, and outdoor air sampling was done both on the heated area and at the borders to the private gardens, etc.

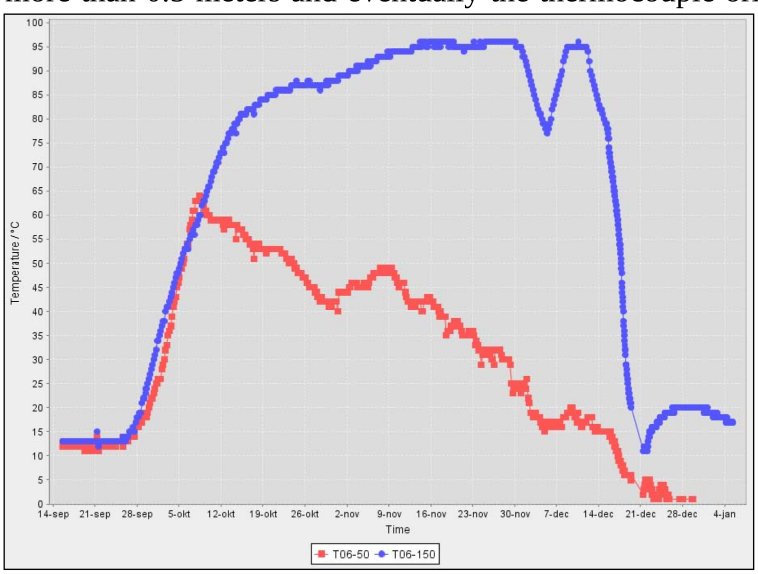

FIGURE 4. Temperature profile 0.5 and 1.5 m below surface

None of the air samples showed contaminants at a level raising any health issues. One thing observed though was the smell of peat being burned. Even with pneumatic control, cleaning of gas with activated carbon etc. this odor is very distinct and absolutely an issue to be aware of.

The thermal treatment lasted 83 days, and mass reduction of 99+ % was seen. Even the peat layer was remediated to the cleanup criteria of 5 mg PCE/kg. The odors, health and safety issues were handled. A vapor cap holding itself in place without any damages due to subsidence would be preferable when heating in areas with high subsidence./1,2,3/

CASE 3 – REERSLEV

The third case study represents a 10 m deep PCE contaminated clay body divided into 2 areas, with a total treatment volume of 11,100 m^3. One area included part of a graveyard, a listed graveyard wall, and a playground in a recreational area. The other area was located partly in the front yard and straight up to a residential house. The risk assessment called for cleanup criteria of 1 mg PCE/kg. Only excavation and ISTD were chosen as realistic remedies. Based on price, practicability and LCA, the ISTD technology was chosen for this site.

Primary concerns in the remedy were as follows:

- Handling the graveyard, graveyard wall and graves both ethically and practically,
- Heating close to residential houses – heat distribution.

Approximately 250 m^2 of the graveyard was contaminated. Excavation in this area would be very problematic since 5 graves were placed in the area, and also removal of the listed graveyard wall would be a significant challenge. Excavation using sheet piles was not an option due to a layer of rocks and boulders 8 m.bgs. Excavation with a 45º slope would extend the excavation all the way to the church. Part of this is a middle age graveyard,

FIGURE 5. Vapor cap touching the wall of the house (the purpose of the vapor cap is to insulate and prevent heat loss, capture vapors and prevent infiltration of rainwater).

and because of that it would be almost impracticable to dig in this area. Instead, 24 heater wells were installed 12 m down, 5 gravestones were temporarily moved and the area was covered with light weight concrete (vapor cap). This approach was evaluated as the most ethical and practical solution and it was accepted by the relatives and by the church.

Based on the experience from earlier cases, settling of the graveyard wall was evaluated to be of minor risk. The graveyard wall itself was covered while installing the vapor cap.

After the remedy, the vapor cap and wells were removed, leaving the graveyard wall untouched.

The other issue on this site was the fact that the heating extended all the way to a residential house with the vapor cap touching the wall of the building (Figure 5)

During the heating period, the temperature in the soil was monitored online at 240 monitoring points. Also, the temperatures of the heater wells were monitored. Just on the edge of the treatment zone, monitoring wells T17 and T16 were located (Figure 5). After 116 days of heating, the temperature in these exceeded 800ºC and 90ºC. At that time, it was decided to decrease the heater temperature from 425ºC to 225ºC on the outer heater circuits facing the house. An instant effect is seen in T16 and T17. The development in temperatures is shown in Figure 6.

At the time the heater well temperature was decreased, a temperature monitoring point just inside the house was established and the mean temperature in the point from 0.25 – 1.0 m was measured to 40ºC. Later, when the heat was turned off completely, three other monitoring points were established. These were all measured in February 2010.

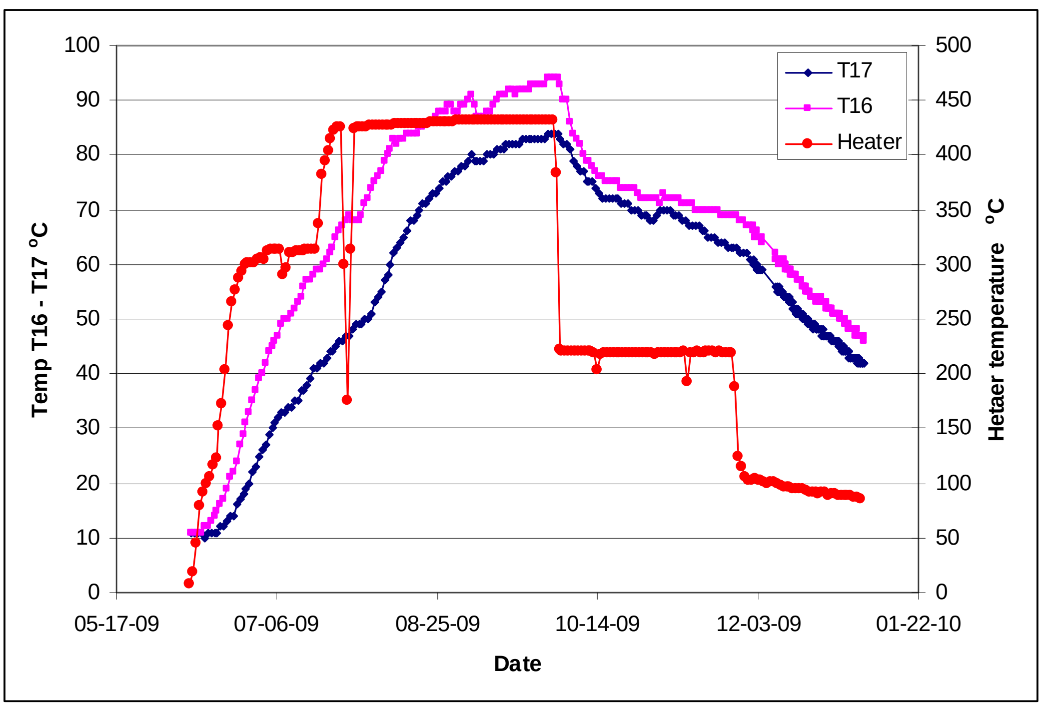

FIGURE 6. Temperature in T16 and T17 is mean temperature from the depths 0.25 – 1.0 and 2.0 m.

Calculations done by TerraTherm Inc. and presented in Figure 7 show the predicted temperature with time in different distances from the treatment zone. The output temperatures are modeled in a three layer numerical model. The heat distributions in different distances from the TTZ are modeled based on the mean temperature in the layers in the entire treatment zone. The grid size is 1 m in the vertical direction and 0.5 m in the horizontal direction.

The temperature predicted fits the measured temperatures within 15ºC although it seems the model has some difficulty regarding the observed temperature in T17. The calculations predict almost no temperature increase 6.5 m away from the treatment zone although the temperature measured was 15ºC and 20ºC. Since there are no time series on the temperature measured, it is difficult to evaluate if the increase might be due to thermal conduction from the house itself and/or better insulation Underneath the house compared to the vapor cap used on the treated area.

After 169 days of heating the cleanup criteria (1 mg PCE/kg) was achieved with a good margin. Highest post treatment soil concentration was 0.057 mg PCE/kg and a 99+ percent reduction was seen at the site.

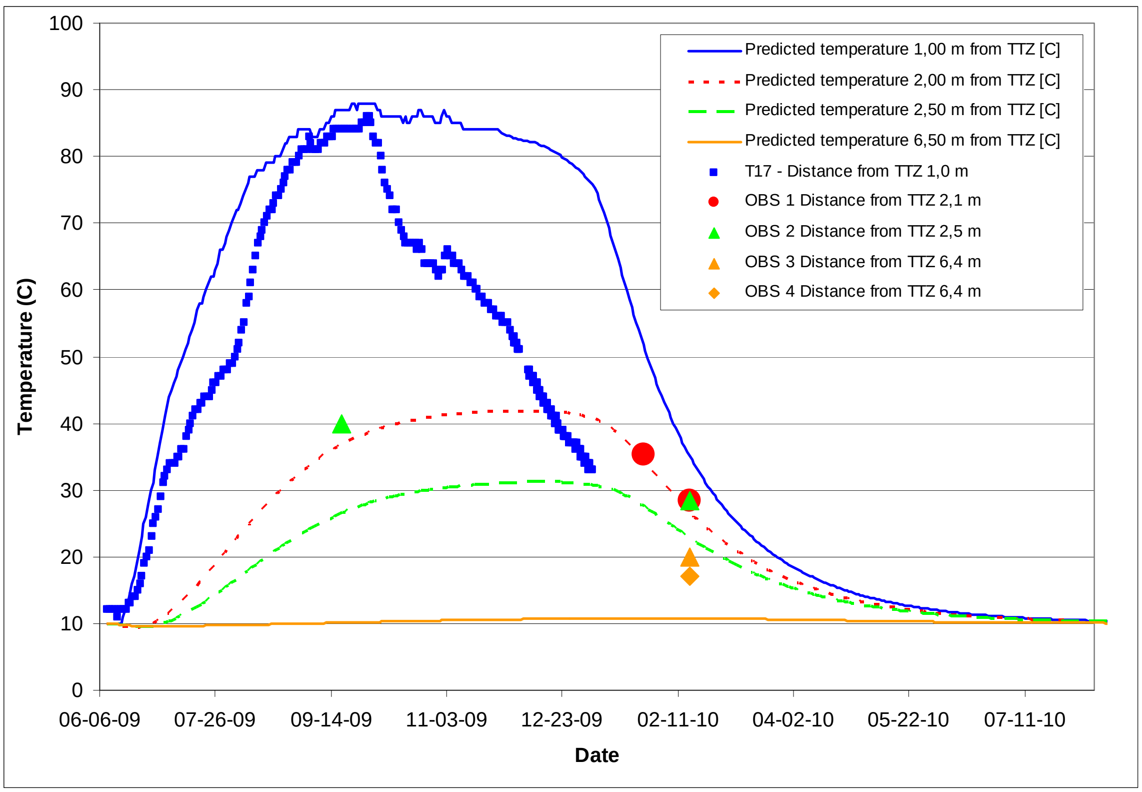

FIGURE 7. Predicted temperatures outside the treatment zone. Calculation done by TerraTherm Inc.

DISCUSSION

The three case studies have shown that it is possible to use thermal remediation not only in abandoned industrial sites but also in delicate urban surroundings where health and safety issues are very important. One of the important things when using aggressive remedies at such sites is the ability to monitor these sites closely and also share relevant information with different stakeholders. Before starting the remediation, people closely connected to the site e.g. workers in a building to be remediated must understand how the technology works and what safety precautions are built into the system. A thorough test of all these precautions should be conducted.

A key parameter to monitor is temperature. Fortunately, it is an easy parameter to monitor. Understanding the thermal distribution is essential to evaluate the ongoing remedy. Thermal conduction is a "slow" process, and with the necessary monitoring points it is possible to work with temperature distribution even in areas with temperature sensitive installations.

Working in areas with high content of e.g. peat, severe subsidence may occur. The risk of subsidence must be evaluated, especially regarding structural damage to nearby buildings and also to the construction of the vapor cap. Damage to the vapor cap may challenge heating due to inflow of cold air and can also complicate pneumatic control.

CONCLUSION

The three case studies showed that with the proper engineering thermal remediation running 200 amps heater circuits, elevated soil temperatures at 100 ºC or above and the removal of significant amounts of chlorinated solvents can occur in a safe and sound way even underneath buildings housing active industries.

The studies also show that subsidence must be evaluated closely when heating in areas with high organic content, but also that heating, e.g., consolidated clay even underneath buildings can be done without any damage.

The "slow" nature of thermal conduction is beneficial because of the ability to heat closely to temperature sensitive installations.

ENDNOTES

1. Krüger. 2007. "Capital Region of Denmark, ISTD Pilot Test, Vestergade 5, Skuldelev", February 2007 (Report in Danish).
2. NIRAS A/S. 2005. "Frederiksborg County. Vestergade 5, Skuldelev. Evaluation and Clean-Up of DNAPL at Well KB15". Minute October 24 2005. (Minute in Danish).
3. Nielsen, S.G., Heron, G., Jensen, P., Riis, C., Heron, T., Johansen, P., Ploug, N., Holm, J. 2010. "Thermal Treatment of Thick Peat Layers – DNAPL Removal and Shrinkage" Paper in: Remediation of Chlorinated and Recalcitrant Compounds—2010. Proceedings of the seventh International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2010).
4. Skou, H., Just, N., Steffensen, H., Heron, G. and Griepke Nielsen, S. "Remediation of PCE Contamination by a Combination of ISTD and Steam Enhanced Extraction, Knullen 8, Odense, Denmark" Paper in *"Proceedings for Winter meeting 2009, ATV Committee for Soil and Groundwater (9.-11. March 2009)"* (Paper in Danish)

Elenco interventi bonifica mediante ISTD

Sito	Luogo	Data completamento	Volume	Profondità	Principali contaminanti	Litologia suolo	Temperatura di processo	Concentrazioni prima (terreni)	Concentrazioni obiettivo (terreni)	Concentrazioni dopo (terreni)
			mc	m			°C	mg/kg	mg/kg	mg/kg
Missouri Electric Works	Cape Girardeau, MO	mag/97	50	3,6	PCB 1260	Argilla limosa	~370	Max.: 19,900 Media: 649	2	< 0.033
US Navy Former Mare Is. Naval Shipyard	Vallejo, CA	dic/97	130	4,2	PCB 1254/1260	Argilla limosa	~370	Max.: 2,200 Media: 53.5	2	< 0.033
Tanapag Village Site Remediation	Saipan, NMI	ago/98	750		PCB 1254/1260	Limo sabbioso	~370	Max: 10,000 Media: 500	10	< 10
US Navy Centerville Beach	Ferndale, CA	dic/98	400	5,1	PCB 1254/1260	Limo e argilla	316	Max: 860 Media: 302	1	< 0.17
Confidential Midwest Site	-	feb/04	8.700	0 to 15 (14.1)	TCE	limo sabbioso	100	Max: 99.7 Probabile presenza DNAPL	1,0	0,070
National Grid Former MGP Site	North Adams, MA	mar/05	1.500	5,4	Benzene, PAHs, Peci carbone	Riporti e rifiuti	Strato intermedio: 325 Fondo: 120	Porzione intermedia Benzene: 2,068 Naphthalene: 679 Benzo(a)pyrene: 20 TPH: 4,000 Fondo Coal Tar DNAPL	Porzione intermedia: Benzene: 2,000 Naphthalene: 10,000 Benzo(a)pyrene: 100 TPH: 10,000 Fondo: No DNAPL	Porzione intermedia: Benzene: 0.35 Naphthalene: 5.7 Benzo(a)pyrene: 0.33 TPH: 43.15 Fondo: No DNAPL
Terminal One	Richmond, CA	nov/05	5.300	6	PCE	Argilla	100	Max: 34.2 Probabile presenza DNAPL	2,0	0,012
Confidential Chemical Mfg Site	Southern CA	dic/05	5.000	10,5	1,2-DCA	Argilla Limosa, sabbia	100	Max: 903 Probabile presenza DNAPL	Test pilota	0,23
Southern California Edison AOC-2	Alhambra, CA	gen/06	12.300	31,5	PAHs, PCP and PCDD/Fs	Limo sabbioso	335	Max.: Totale PAHs: 35,000 PCP: 58 PCDD/Fs: 0.194 (TEQ) Media: Totale PAHs: 2,306 PCP: 2.94 PCDD/Fs: 0.018 (TEQ)	PAHs [B(a)P-Eq]: 0.065 PCP: 2.5 PCDD/Fs: 0.001 (TEQ)	PAHs [B(a)P-Eq]: 0.059 PCP: 1.25 PCDD/Fs: 0.00011 (TEQ)
Confidential SE Site	-	mag/06	6.840	26,1	TCE	Riporti, saprolite, roccia fratturata	100	DNAPL	0.060	0,017
Rt. 44 Drum Site	Taunton, MA	mar/07	4.000	4,2	Clorobenzeni, Naphthalene, Toluene	Sabbia	Spessore insaturo: 150 Spessore saturo: 100	Max.: Totale TCB: 4000 Totale DCB: 450 Naphthalene: 2500 Toluene: 350 (DNAPL presente)	Non previsti limiti; Obiettivi: riduzione massa contaminanti per accelerare attenuazione concentrazioni nelle acque. Gli standard S2-GW3 sono: 1,2,4-TCB: 890 1,2-DCB: 290 Naphthalene: 990 Toluene: 990	Zona insatura: Totale TCB: 10.1 Totale DCB: 0.65 Naphthalene: 19 Toluene: 0.58 Zona satura: Totale TCB: 310 Totale DCB: 4 Naphthalene: 120 Toluene: 30
NASA Marshall Space Flight Center	Huntsville, AL	mag/07	750	11,1	TCE	Argilla, calcare	100	Max: 47.65 Probabile presenza DNAPL	1,0	0,060
Dyrup	Søborg, Denmark	June-07	130	6	Xylene	Argilla	100	1,100	Riduzione concentrazioni nell'area di sorgente	Obiettivi raggiunti
Pioneer Midler Ave.	Syracuse, NY	ott/07	12.312	7,5	PCE	Torba, marna, argilla	100	Max: 2,864 Probabile presenza DNAPL	5,6	3,8
Knullen	Odense, Denmark	Oct-08	2.500	10,8	PCE, DCE	Argilla, sabbia e giaia	100	340 Probabile presenza DNAPL	5	0.51
Memphis Depot, U.S. Defense Logistics Agency	Memphis, TN	nov/08	38.000	9	CVOC	Argilla limosa	100	Max: 73 Probabile presenza DNAPL	0,34	0,045

Summary of ISTD / IPTD Performance Data for SVOC Sites - TerraTherm, Inc., May. 2011

Sito	Luogo	Data completamento	Volume	Profondità	Principali contaminanti	Litologia suolo	Temperatura di processo	Concentrazioni prima (terreni)	Concentrazioni obiettivo (terreni)	Concentrazioni dopo (terreni)
			mc	m			°C	mg/kg	mg/kg	mg/kg
Skudelev	Skudelev, Denmark	Dec-08	1.700	7,5	PCE	Lenti di sabbia e torba, argilla	100	128 Presenza DNAPL	5	0,13
Japan Ministry of Environment IPTD Dioxin Demo	Yamaguchi, Shimonoseki Prefecture, Japan	feb/09	3	1,5	Diossine	Limo sabbioso	325	1,800 pg-TEQ/g	1,000 pg-TEQ/g	67.75 pg-TEQ/g
Confidential Mfg. Client	Danville, PA	mag/09	51.700	12	LNAPL and CVOC	Lenti sabbiose eterogenee	>95	Max 5,168 Probabile presenza DNAPL	Reduzione LNAPL a corrispondenti concentrazioni di CVOCnerl suolo per ridurre impatto sulle acque	Obiettivi raggiunti
Confidential Site Pilot	Confidential	Jun-09	400	9	Clorobenzeni	limo sabbioso, sabbia	100	Media: Totale CBs: 10,951	NA	Media: Totale CBs: 1,130
Reerslev	Reerslev, Denmark	Dec-09	11.000	12	PCE	Argilla, sabbia	100	78 Presenza DNAPL	1	0,047
Confidential Former Dry Cleaner Site	Endicott, NY	Apr-10	14.000	9	CVOC	Riporti, limo	150	125	0.56	0,04
Confidential Chemical Mfg Site	Santa Fe Springs, CA	set/10	10.374	19,5	CVOC	Limo e argilla	100	Max : 330 Probabile presenza DNAPL	Riduzione concentrazioni nel suolo e nelle acque	Obiettivi raggiunti
Vadsbyvej	Vadsbyvej, Denmark	Jan-11	1.500	13	PCE, TCE, DCE, VC	Argilla, sabbia	100	NA	Riduzione concentrazioni nel suolo	Obiettivi raggiunti
Groveland Wells Superfund Site	Groveland, MA	Feb-11	12.500	10	TCE	Sabbia e argilla	90	Max: 52	Riduzione concentrazioni nel suolo e nelle acque	Obiettivi raggiunti
Silresim Superfund Site	Lowell, MA	Feb-12	45.300	13,5	PCE	Argilla, limo, sabbia	100	Presenza NAPL	Riduzione concentrazioni nel suolo e nelle acque	Obiettivi raggiunti

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CURRENT ENVIRONMENTAL SOLUTIONS/GLOBAL ENGINEERING SOLUTIONS/NOCON

SIX-PHASE HEATING/ELECTRIC RESISTANCE HEATING

YEAR	CLIENT	LOCATION	CONTAMINANT	LITHOLOGY	ZONE TREATED	Area or Volume	% COMP.	NOTES
1993	DOE	Savannah River, GA	PCE	Sand. Clay	VADOSE	1.430	100	COMPLETE
1996	National Guard	Niagra Falls, NY	BTEX, TCE	Clay, Glacial Till	VADOSE, GW	3.000	100	COMPLETE
1997	US Air Force	Dover AFB, DE	Tracers	Sand, Clay, Gravel	GW	1.800	100	COMPLETE
1997	Army Corps of Eng.	Ft. Richardson, AK	TCE, PCE, TCA	Silt, Sand, Gravel	GW	5.800	100	COMPLETE
1998	Major Oil	Cincinnati, OH	Benzene	Clay, Silt	VADOSE, GW	1.800	100	COMPLETE
1998	Army Corps of Eng.	Ft. Wainwright, AK	BTEX, Diesel	Sand, Silt, Gravel	VADOSE, GW	1.000	100	COMPLETE
1999	Brown & Caldwell	Atlanta, GA	Kerosene	Sandy Clay, Sapprolite	VADOSE, GW	4.500	100	COMPLETE
1999	Mfg. Facility	Skokie, IL	TCE, TCA, DCE	Silt, Clay	VADOSE, GW	32.000	100	COMPLETE
1999	Army Corps of Eng.	Ft. Richardson, AK	TCE, PCE, TCA	Silt, Sand, Gravel	GW	3.700	100	COMPLETE
2000	Terra Vac	Seattle, WA	PCE, VC	Sand	GW	2.300	100	COMPLETE
2000	Avery Dennison	Waukeegan, IL	MeCl	Clay	VADOSE	16.000	100	COMPLETE
2000	DOE, EPA, NASA	Cape Canaveral, FL	TCE	Sand, Silt, Clay	VADOSE, GW	6.400	100	"BEST-IN-CLASS" for cost, effic, time
2000	Chem. Mfg.	Newark, CA	EDB	Silt, Clay	Lab Test	N/A	100	Lab Bench Study
2000	US Air Force	Plant 4, Ft. Worth, TX	TCE	Sand, Silt, Clay, Gravel	VADOSE, GW	4.000	100	Pilot Test Complete
2001	ICN Pharmaceuticals	Portland, OR	TCE	Sand, Silt, Clay	VADOSE, GW	19.000	100	COMPLETE-Achieved Drinking Water MCL'S
2001	Major Oil	Culver City, CA	MTBE	Sand	VADOSE, GW	5.000	100	COMPLETE
2001	Valeant Pharmaceuticals	Portland, OR	TCE	Sand, Silt, Clay	Lab Test	N/A	100	COMPLETE
2001	Chem. Mfg.	Newark, CA	EDB	Silt, Clay	Lab Test	N/A	100	COMPLETE
2001	USACE	Hunter Army AF	BTEX, PAH	Sand	VADOSE, GW	8.800	100	COMPLETE: 50,000 lbs removed in 8 weeks
2001	US NAVY	Alameda, CA	TCE	Sand	VADOSE, GW	600	100	COMPLETE
2002	Confidential	MA	TCE	Bedrock	GW	TBD	100	COMPLETE
2002	USACE	Silresim, Lowell,MA	VOCs	Sandy Loam	GW/Vadose	1.300	100	COMPLETE
2002	ICN Pharmaceuticals	Portland, OR	TCE	Sand, Silt, Clay	PHASE II	8000	100	COMPLETE:MET DRINKING WATER MCLs
2002	Zwijndrecht	Netherlands	TCE, PCE, DCE, VC,	Loam, Silt, Clay	GW/Vadose	2.800	100	COMPLETE:FIRST ERH CLOSURE IN EUROPE
2003	US Marine Corps	Camp Lejeune,NC	TCE, PCE, TCA, DCE	Sand, Silt, Clay	GW/Vadose	15.000	100	COMPLETE
2003	State of Oklahoma	Midwest City, OK	BTEX LNAPL	Sand, Silt, Clay	GW/Vadose	6.000	100	COMPLETE
2003	Private/Confidential	California	Mixed VOC's & BTEX	Sand, Silt, Clay	GW/Vadose	25.000	100	COMPLETE
2003	Private/Confidential	California	PCE, TCE, TCA	Sand, Silt, Clay	GW/Vadose	1.000	100	COMPLETE
2003	Petroleum Refinery	Washington State	Mixed	Sand, Silt, Clay	GW/Vadose	3 acres	100	COMPLETE
2003	Zoetermeer	Netherlands	DCE, VC, BTEX	Silty clay	GW, VADOSE	9.000	100	COMPLETE
2003	Temse	Belgium	PCE, CHLOROPHEHOLS	Silty clay	GW, VADOSE	500	100	COMPLETE
2004	IOWA DOT	Sioux City,Iowa	BTEX	Sand, Silt, Clay	Vadose/LNAPL	0.5 Acre	100	COMPLETE
2004	Mertert	Luxemburg	Benzene, Xylenes	Sand, Silt, Clay	Vadose/LNAPL	500	100	COMPLETE
2005	EPA Superfund	Fargo, ND	PCE, TCE, DCE, VC	Tight Plastic Clay	GW/Vadose/DNAPL	0.5 Acre	100	COMPLETE
2005	Dry Cleaner	Carson, CA	PCE	Sand, Clay,	GW, Vadose	.25 Acre	100	COMPLETE
2005	Utility	Confidential	DNAPL Various	Sand, Silt, Clay	GW,Vadose,DNAPL	5 acres	100	COMPLETE
2005	DOE Site T228	Savannah River T233	PCE, TCE	Sand, Silt, Clay	GW,Vadose,DNAPL	.5 acre	100	COMPLETE
2005	Bloomington MGP Site	Illinios	Coal Tar - viscosity reduction	Sand, Silt, Clay	GW,Vadose,DNAPL	1 hectre	100	COMPLETE
2006	Valero Petroleum	Palo Alto, CA	BTEX	Silty-Clay	GW,Vadose,DNAPL	.25 acre	100	COMPLETE
2006	DOE SITE T233	Savannah River T233	PCE, TCE	Sand, Silt, Clay	GW,Vadose,DNAPL	.5 acre	100	COMPLETE
2006	Fortune 500	California	PCE, TCE	Sand, Silt, Clay	GW,Vadose,DNAPL	TBD	100	COMPLETE
2006	Delft	Netherlands	PCE,TCE,BENZENE	Sand, Silt, Clay	GW,Vadose,DNAPL	2.000	100	COMPLETE
2006	DOE Savannah River	Savannah River, GA	PCE,TCE	Sand, Silt, Clay	GW,Vadose,DNAPL		100	COMPLETE - retained as design consultants
2007	USAF Kelly AFB B301	San Antonio, TX	PCE	Silty Clay	GW,Vadose,DNAPL	1.5 acre	100	COMPLETE
2007	Fortune 500	Springfield, Missouri	TCE	Silty Clay	GW,Vadose,DNAPL	0.5 acres	100	COMPLETE
2007	Ecclesfield	United Kingdom	PCE, TCE	Silty Clay	GW,Vadose,DNAPL	4 acres	100	OMPLETE (First Ever ERH in UK)
2007	Industrial	Missouri	TCE	Silty Clay	GW,Vadose,DNAPL	0,25	100	COMPLETE
2008	State of FL	Pensacola, FL	BTEX	Silty Clay	Vadose	0.5 acres	100	COMPLETE
2008	Frontier Fertilizar Superfund Site	Davis, CA	EDB,TCP,DCP, DBCP	Sand, Silt, Clay	GW,Vadose,DNAPL	2 acres	75	Stages 1 & 2 Complete, Stage 3 in progress
2008	USAF Kelly AFB S-1	San Antonio, TX	PCE	Silty Clay	GW,Vadose,DNAPL	1 acre	100	COMPLETE
2008	Brussels	Belgium	Chloroform, MIBK	Silty Clay	GW,Vadose,DNAPL	10.000	100	COMPLETE
2009	State of FL	Pensacola, FL	BTEX	Silty Clay	Vadose	.25 acres	100	COMPLETE
2009	Non Profit Org -	Massachusette	Fuel Oil #4 & 6	Clay, silty sand	GW, Vadose	0.5 acres	100	COMPLETE
2010	Albertslund	Denmark	PCE,TCE	Silty Clay	GW, Vadose	600	100	COMPLETE
2011	Brussels	Belgium	MIBK,ACETONE, CHLOROBENZENE	Silty Clay	GW, Vadose	5.000	75	
2011	Santa Monica	California	PCE,TCE,DCE	Silty Clay	GW, Vadose			contracted to review competitor failure- poor electrode design
2011	Bloomington MGP Site	Illinios	Coal Tar - steaming tests	Sand, Silt, Clay	GW,Vadose,DNAPL	1 hectre	100	COMPLETE
2011	US Air Force	Washington State	PCE,TCE,VC	Sand, Silt, Clay	GW,Vadose,DNAPL	2 acres	100	complete: Retained as design experts
2012	Confidential Client	France	Benzene	Sand	GW, Vadose		50	Low temp bio and high temp tests in progress
2012	Copenhagen	Denmark	PCE	Silt, Clay, Sand	GW, Vadose	1.500	contract	won bid - contract in progress
2012	State of Kansas - City of Wichita	Kansas	PCE	Silt, Clay, Sand	GW, Vadose		10	design in progress
2012	Bloomington MGP Site	Illinios	Deep Coal Tar	Sand, Silt, Clay	GW,Vadose,DNAPL	.25 acre	20	deep electrode design in progress
2012	Dry Cleaners	Windsor, NJ	PCE	Sand, Silt, Clay	GW,Vadose,DNAPL	.5 acre	0	Won Job- contract in progress

Projects in red are within the European Union