

# TDP Bulletin

CL:AIRE Technology Demonstration Project (TDP) Bulletins provide a summary of CL:AIRE approved Technology Demonstration Projects. TDPs have passed through the CL:AIRE application and review process, and represent demonstration for the specific conditions in which they are applied. This bulletin describes the principles behind Six-Phase Heating at a former manufacturing plant in Sheffield.

## *In Situ* Soil and Groundwater Decontamination Using Electric Resistive Heating Technology (Six-Phase Heating)



Figure 1: The site of Source Area 1, showing electrode arrays, extraction manifold and equipment locations

### 1. INTRODUCTION

This bulletin describes the UK's first use of Six-Phase Heating (SPH), an *in situ* electrical resistive heating technology, to mitigate the risk posed by historic contamination of the former tools manufacturing site in Sheffield by source removal. The demonstration has passed through CL:AIRE's peer review system and is a CL:AIRE Technology Demonstration Project (TDP 26). Figure 1 shows part of the site during the demonstration with the installed electrode arrays, the extraction manifold, and equipment compounds.

Previous investigations at the two hectare site showed high levels of contamination, including dissolved, adsorbed and free phase chlorinated hydrocarbons, in heterogeneous cohesive soils and mudstone. The principal contaminants of concern driving the risk were:

- Trichloroethene (TCE) and vinyl chloride (VC) in the soil – human health risk; and
- TCE within the groundwater – environmental risk.

The key objectives of the demonstration were to:

- Extract contaminants from soil and groundwater to achieve a minimum concentration reduction in TCE of 80% in both phases, and a 50% VC reduction in the groundwater. The 80% TCE reduction was set due to being the equivalent of less than 1% of the TCE's solubility limit;
- Achieve Site Specific Acceptance Criteria (SSAC) values for key targeted contaminants to the satisfaction of the regulators;

- Undertake the active remediation within a 30 week overall project timeline period as agreed with the client; and
- Provide the entire process of remediation design, installation, activation, verification, decommissioning in a 43 week period to allow for site sign-off for residential redevelopment.

The bulletin describes why electrical resistive heating (in this case SPH) in combination with dual phase extraction was selected as the most appropriate technology for this site due to its combination of contaminants, geology and direct proximity to residential properties.

This bulletin explains the background to the site, the technology evaluation and selection, the application of SPH and its performance against agreed project objectives.

### 2. BACKGROUND TO SITE

The two hectare site, located in Sheffield, close to the M1 motorway and in a densely populated area of residential properties, was formerly a tool manufacturing site where production had taken place for in excess of forty years. The site was acquired by Taylor Wimpey in early 2007 and proposed for residential redevelopment.

The site had been extensively sampled and two source areas of contamination were identified. Two significant investigations had been carried out on the site, in 1999 and 2004. The 1999 investigation included more than 75 window sampler locations, supplemented by 5 monitoring well installations. The 2004 investigation comprised 20 trial pits and a further 27 boreholes.

Site investigation information indicated an upper layer of Made Ground underlain by cohesive clays, silts and sands to between 3 and 4 m below ground level (bgl), over dense mudstone. Groundwater was generally recorded at between 3 and 4.1 m bgl.

Chemical analysis of soils revealed two distinct hotspots of chlorinated hydrocarbons in the vicinity of the former manufacturing and storage areas, subsequently referred to as Source Area 1 and Source Area 2. Contaminants of concern were identified as TCE and VC. Minor concentrations of other associated breakdown by-products were also recorded.

A Detailed Quantitative Risk Assessment undertaken for the site highlighted potential risks to human health for the proposed future land use, which had to be mitigated to satisfy planning conditions.

The total volume of soils to be treated was approximately 3,500 m<sup>3</sup> with the core area of each source area extending to 7 m bgl, within the mudstone. Approximately 630 m<sup>3</sup> of groundwater was impacted. The source areas had been delineated by previous site investigation works using trial pits, probe holes and boreholes.

### 3. TECHNOLOGY EVALUATION

Terra Vac evaluated several possible remediation techniques for the Sheffield site and compared them for technical, practical, and commercial suitability. A summary of the options is shown in Table 1. A significant factor in the process of evaluation was the close proximity of residential properties to the site.

#### 3.1 Cost/Benefit Analysis of Six-Phase Heating

As can be seen from the Table 1, SPH was not the cheapest solution offered. However, there were other factors to be considered in terms of the final decision:

**Table 1: Technology evaluation**

Technology	Timescale	£/Tonne	Advantages	Disadvantages
Excavation and disposal off site (dig and dump)	16 weeks	£125	<ul style="list-style-type: none"> <li>• Very rapid</li> <li>• High degree of confidence</li> </ul>	<ul style="list-style-type: none"> <li>• In excess of 700 vehicle movements through urban areas</li> <li>• Fugitive vapours to local residents</li> <li>• Groundwater and possible non-aqueous phase liquid (NAPL) at 3 m bgl</li> </ul>
<i>In situ</i> Bioremediation	40 weeks	£65	<ul style="list-style-type: none"> <li>• Lower cost</li> <li>• Minimal site disturbance</li> </ul>	<ul style="list-style-type: none"> <li>• Possible NAPL would slow treatment</li> <li>• Possible extended timeframe unacceptable to client</li> <li>• Cohesive soils prevent distribution of catalyst</li> </ul>
<i>Ex situ</i> Bioremediation	30 weeks	£50	<ul style="list-style-type: none"> <li>• Lower cost</li> <li>• Uses conventional equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Fugitive vapours during works</li> <li>• Reduced confidence in performance with cohesive soils</li> </ul>
<i>In situ</i> Chemical Oxidation	30-35 weeks	£85	<ul style="list-style-type: none"> <li>• Rapid reaction</li> </ul>	<ul style="list-style-type: none"> <li>• Possible dense non-aqueous phase liquid (DNAPL) and therefore likelihood of exothermic reactions</li> <li>• Reduced confidence due to cohesive soils and likely extended programme</li> <li>• Possibility of displacing contaminant and spreading plume</li> </ul>
Dual Phase Extraction	50 weeks	£63	<ul style="list-style-type: none"> <li>• Controlling extraction technique</li> <li>• Progress measurable</li> </ul>	<ul style="list-style-type: none"> <li>• Extended programme unacceptable to client</li> <li>• Cohesive soils restrict effectiveness</li> </ul>
Six-Phase Heating	20 weeks	£78	<ul style="list-style-type: none"> <li>• Most effective in cohesive soils</li> <li>• Rapid and extremely thorough</li> </ul>	<ul style="list-style-type: none"> <li>• Involves the use of specialist equipment requiring high voltage power</li> </ul>

- Very low level of local disruption; SPH is an *in situ* process and operates below the surface of the site. Installation is quick and causes minor disturbance to the site and surrounding area. Given that the site is located in an urban environment with residential properties adjacent, the local population will experience very little disruption. The installation and operation causes little in the way of noise, dust, or any other type of disturbance to the local population.

- Reduced remediation timescale; the use of SPH ensures that multi-phase contaminants are removed from soil and groundwater simultaneously, contributing to the accelerated remedial timeframe. The actual decontamination phase of the project was expected to take in the order of twelve to twenty weeks.

- Low risk of cost escalation; variable heating of electrical elements allows accurate targeting of contaminated layers, ensuring all contaminated areas are treated. The ability to accurately target only those contaminated areas means that the electrical current is used efficiently with effective budgetary control.

- Thoroughness of the process; the SPH process is extremely thorough, and a review of previous projects completed in the USA and mainland Europe showed that typically, residual contaminants are often below detection levels. This is particularly important in this project as stringent target levels are required to be achieved.

#### 3.2 Licensing Requirements

To obtain permission for this technique to be utilised, technical submissions had to be provided to the Environment Agency and the Environmental Health Officer. Terra Vac's Mobile Treatment Licence includes SPH as a remedial process.

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## 4. DEVELOPMENT OF SIX-PHASE HEATING

SPH was developed by Terra Vac Corp. and the Battelle Memorial Institute (BMI) in their Richland facility, Washington, under the auspices of the US Department of Energy (DOE). The objective of the research was to develop a technique to address persistent 'source' areas in former military establishments as part of the US Government's Superfund Program.

An *in situ* remedial technology was required which would be effective in a variety of soils with assorted contaminants in dissolved, adsorbed and free phases at varying depths. During the development of the process, many alternative technologies were trialled over many sites under close scrutiny from the regulators. Identical 'test areas' were created and seeded with varieties of contaminants and the rate of remediation tracked. SPH was proven to be an effective treatment technique.

## 5. DESCRIPTION OF SIX-PHASE HEATING

Electric current is passed through the impacted soils and groundwater by means of electrodes, spaced according to the conductive properties of the soil/groundwater (which will have been evaluated previously).

The current heats the soils resistively causing groundwater to boil, which is then extracted as steam together with volatilised contaminants. Electricity is distributed by the National Grid in three-phase format. This supply is further split into six phases by using sophisticated electrical hardware, as illustrated in Figure 2. The six-phase current distributes proportionately more electric power and provides good geometric coverage when applied in a hexagonal electrode array.

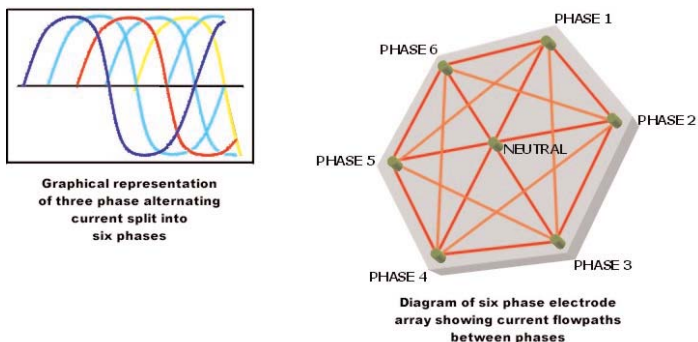


Figure 2: Electrical principles

Electricity will flow preferentially through low permeability, more cohesive soils, and their greater resistivity will cause these soils to heat more quickly. As no substrata can be assumed to be uniform in composition, each electrode has to be independently controlled and monitored to ensure the most efficient and balanced operation of the system. When sufficient power has been supplied, the heated soil will cause the interstitial water that is bound within the soils, as well as 'free' groundwater, to reach boiling point and volatilise. As the internal temperature rises, the contaminant molecules, including non-aqueous phase liquids (NAPLs), are liberated. In more cohesive soils like stiff clays, micro-fracturing is also caused which enhances the release of contaminants. The contaminants are then extracted with the steam 'carrier', which is recovered, and treated above ground.

Temperature can be regulated by the introduction of water via an independently controlled water supply. Water introduced to the area

surrounding the electrode increases the conductivity, resulting in increased current flow and subsequently temperature. The intention is that the contaminated areas should be heated in a uniform way to create the optimum conditions for volatilisation of interstitial water and 'free' pore water.

Pure water boils at 100°C and pure TCE at 87°C, however the boiling point is reduced when dense non-aqueous phase liquids (DNAPLs) are mixed with water, in comparison with pure compounds. Figure 3 shows graphically the reduced boiling point of dissolved phase TCE (73°C) compared to pure TCE and pure water.

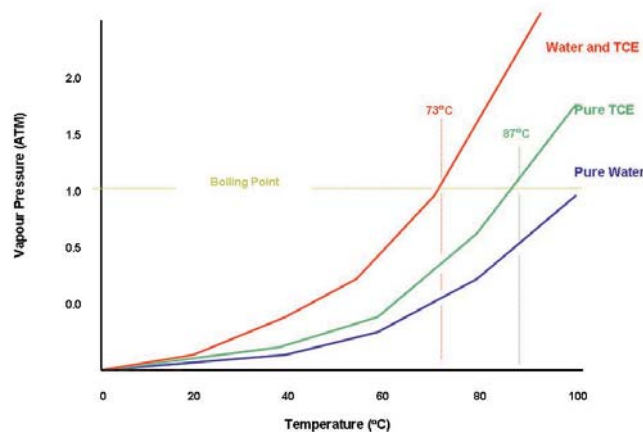


Figure 3: Plot of vapour pressure against temperature

## 6. ASSESSMENT CRITERIA, TRIALS & FULL SCALE WORKS

Terra Vac undertook the remediation of the Sheffield site as a turnkey project which included a first phase of demolition of all buildings on site (shown in Figure 4), removal of notifiable material and crushing of concrete slab and relic foundations.



Figure 4: Demolition in progress

### 6.1 Assessment Criteria

Table 2 shows the Site Specific Acceptance Criteria (SSAC) to be achieved as agreed with both the Environment Agency and the Local Authority, which were challenging in view of the overall 30 week remedial timescale required by the client.



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**Table 2. SSAC and maximum identified contaminant concentrations**

	Maximum Identified Concentration	Target Concentrations (SSAC)
<b>Soils (mg/kg)</b>		
TCE	202.38	4.6
VC	0.715	0.013
<b>Waters (µg/l)</b>		
TCE	538,200	4,626*

\*Lowest SSAC for Source Area 1

Dichloroethene (DCE) and other breakdown products, apart from VC, were not targeted due to being deemed less hazardous at low concentrations compared to the contaminant of concern, TCE and VC.

## 6.2 Pilot Trial

Terra Vac had proposed to undertake a soil heating pilot trial, involving mobilisation of all associated plant and equipment. Due to the client's restricted timeframe, it was not possible to undertake a full-scale trial. Instead, as part of the preliminary trial works, a Site Evaluation and Test Instrumentation (SETI) test was undertaken.

## 6.3 SETI Test

Prior to commencement of the project, a SETI exercise was undertaken, where critical subsoil electrical characteristics and safety sub-systems were evaluated in order to model the proposed remedial work.

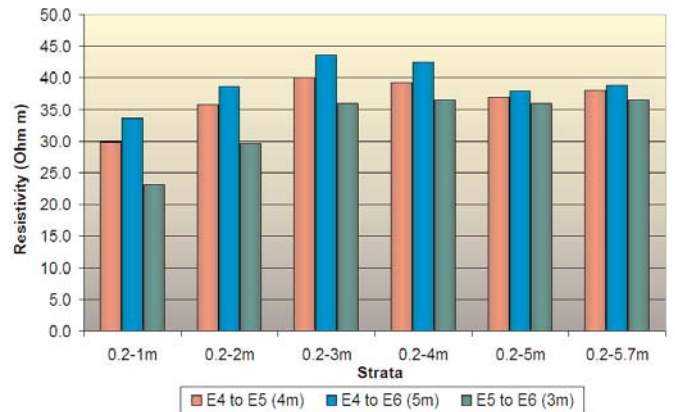
Several trial electrodes were installed at varying spacings in each source area to the proposed depth of treatment. This technique had previously been used successfully at a number of projects, although none of the sites had the same underlying geology as the Sheffield site. Soil resistivity was measured along with other critical electrical characteristics to enable a bespoke software model to be run which, when combined with starting and target concentrations, predicts electrical consumption, project timescales, extraction rates, etc.

The SETI exercise consisted of two phases; field testing, followed by laboratory testing. The information from the SETI test was then input into the SPH model. Field measurements from electrodes installed in the test areas measured soil resistivity at varying depths with different applied voltage and current. These measurements allowed calculation of electrode spacings and diameters at which efficient heating could be achieved.

Soil and groundwater samples collected from the treatment zones were subject to laboratory testing to confirm the effect of variable soil moisture content on electrical conductivity, soil bulk density, natural moisture content, particle size distribution, redox potential, total organic carbon, etc. A plot of soil resistivity variation with depth from Source Area 2 at the site is shown in Figure 5.

Results of the modelling indicated that the larger Source Area 1 required 48 electrodes and Source Area 2 required 19 electrodes. The depths of the base of each electrode in each source area varied from 3 m at the periphery of each source area to 7 m at the centre. In addition, several 'thermo wells' were installed within and outside each source area,

continuously monitoring soil and groundwater temperature at various depths throughout the treatment zone.

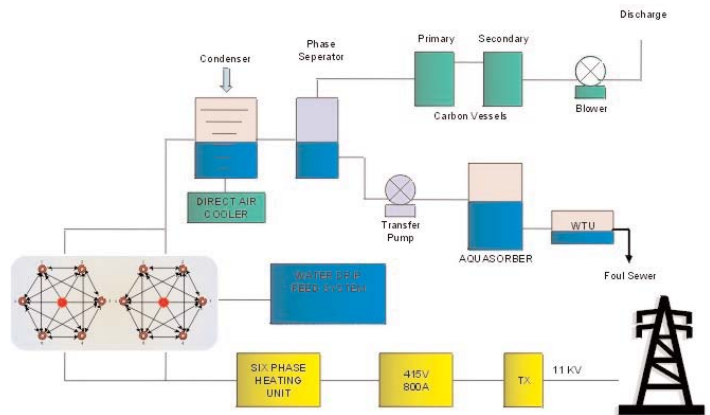


**Figure 5: Plot of soil resistivity variation with depth for Source Area 2**

## 6.4 Full-scale Works

Based on the findings of the SETI test and combined with the results of the supplementary laboratory analysis, the SPH system was deployed in April 2007. Given the programme constraints and commercial factors included within the contract, an in-house redesign of certain elements of the system hardware was undertaken to offer a greater degree of confidence of achieving the required results within the contract timeline.

Soil resistivity profiling with depth indicated current flow variations above and below groundwater and between the two differing soil types. These site-specific factors would tend to cause unbalanced current flows and result in uneven soil heating with depth. Measured site criteria, including soil conductivity, density and moisture content, were used to redesign the effective electrode diameter and derive the precise requirement for supplementary drip feed water to maintain electrical conductivity through drier, less conductive horizons. A schematic layout of the site showing the main elements of the remediation system is presented in Figure 6.



**Figure 6: Schematic layout of equipment**

An integrated dual phase vacuum extraction system was set up to recover liquids and vapours from the field and deliver them to the condenser and direct air cooler. Cooled contaminants could then be drawn through a phase separator vessel after which vapours are passed through primary and secondary granular activated carbon (GAC) vessels.

Separated waters were treated through an Aquasorber vessel filled with water phase GAC onto which dissolved phase contaminants were adsorbed followed by a multiphase treatment unit prior to discharge to sewer in accordance with the discharge consent.

Extracted vapour streams were initially monitored daily, but the required frequency reduced throughout the project, so as to enable mass balance calculations of both 'rate of extracted contaminant' and 'accumulated mass of contaminant extracted'. The measured parameters used to determine the rate and mass of contaminant removed included temperature, volumetric flow rate, and vapour concentrations. Confirmatory gas bag samples, analysed independently, were used to verify field measurements.

## 7. SYSTEM PERFORMANCE

Subsurface soil and groundwater temperature at varying depths was recorded and monitored continuously on-line from several thermo wells installed in Source Areas 1 and 2. This information, combined with current readings to the electrodes, was used to adjust system voltages to optimise the distribution of electric current to the subsoils to achieve even temperature control. A sample graph of soil temperature at varying depths from one thermo well for the duration of the project is shown in Figure 7.

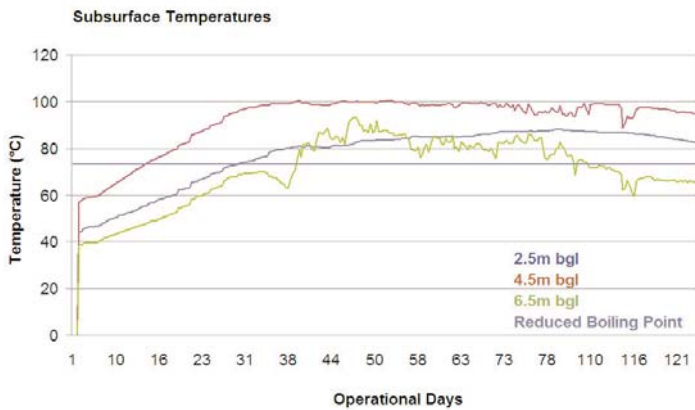


Figure 7: Recorded thermo-well plot of subsurface temperatures

As Figure 7 shows, subsoil temperatures increased rapidly over the first few weeks of the project due to the targeted control and distribution of electrical energy. The 73°C boiling temperature for TCE in water was achieved within three to five weeks. This temperature increase is reflected in the rate of recovery of contaminants in the vapour phase which can be seen to increase significantly over the same period, as shown by the vapour phase recovery rates in TCE equivalent in Figure 8.

Vapour phase recovery rates for each source area show an increasing trend which peaks at approximately day 43, after which there is an apparent downturn in the rate of extraction of TCE in the vapour phase. The curves shown in Figure 8 represent raw, untrended field data and reflect the frequent optimisation of the system with regard to subsoil temperature, current flow, applied voltages, vacuum influence, etc.

The secondary peaks at approximately day 93 and 120 are indicative of further optimisation of the system where the shutting of selected vapour extraction nodes meant that a greater vacuum effort was exerted over the residual contaminated volume. The ultimate decay in the rate of extraction is similarly reflected in the horizontal trend shown at the same

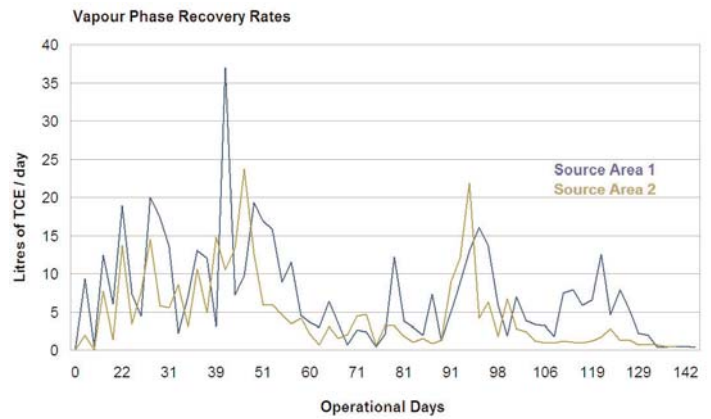


Figure 8: Plot of vapour phase recovery rates

stage in the graph of cumulative vapour phase recovery shown in Figure 9. This figure shows that the equivalent of 1662 litres of TCE was recovered from the subsoils over a twenty-week period. This quantity is approximately 70 times the quantity originally calculated.

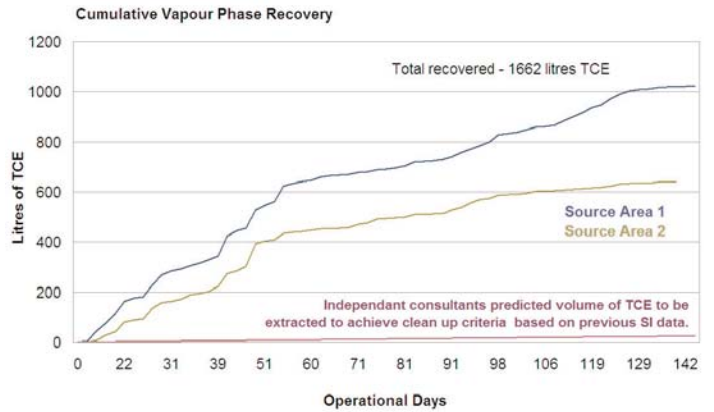


Figure 9: Plot of cumulative vapour phase recovery

Actual groundwater concentrations showed a dramatic net reduction in concentration of in excess of 99% over the project timeframe and are shown graphically for the two source areas in Figure 10.

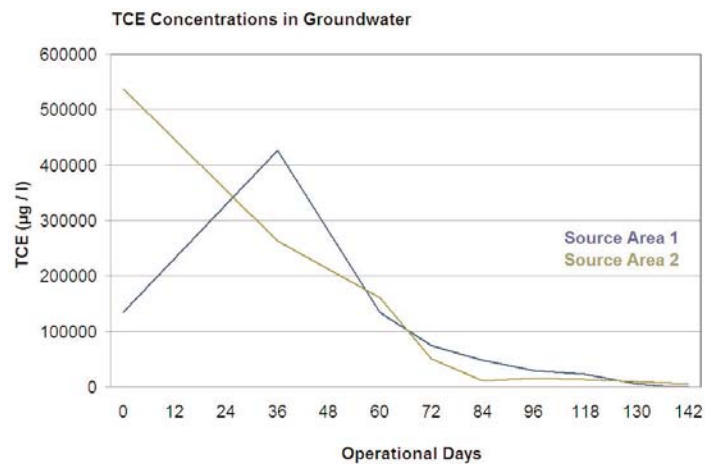


Figure 10: Plot of TCE concentrations in groundwater

The recorded apparent increase in groundwater TCE concentrations in Source Area 1 up until approximately day 40 is due to the suspected mobilisation of DNAPL at depth, as this time period coincides with subsoils reaching maximum temperature.

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**Table 3. TCE concentrations in soils and groundwater**

	Soil (mg/kg)		Groundwater (µg/l)	
	Source Area 1	Source Area 2	Source Area 1	Source Area 2
<b>Concentration (SI Report)</b>	202.38	57	9,252	49,545
<b>SSAC</b>	4.6	4.6	4,626	9,909
<b>Required Reduction</b>	97.73%	91.93%	50.00%	80.00%
<b>Baseline Concentration</b>	202.38	57	134,300	538,200
<b>Required Reduction</b>	97.73%	91.93%	96.56%	98.16%
<b>Verification Result*</b>	2.34	1.4	1,220	5,120
<b>Actual Reduction</b>	<b>98.84%</b>	<b>97.54%</b>	<b>99.09%</b>	<b>99.05%</b>

\*Thirty-two soil verification samples were used to derive these 95<sup>th</sup> percentile Upper Confidence Limits in accordance with CLR7.

Table 3 shows the actual achievement of the system compared to the SSAC based on the findings of the site investigation. Values for TCE have been presented in the above table due to the fact that they were at significantly higher concentrations than other chlorinated compounds and targeted as the primary contaminant of concern. Post remediation/validation sampling results showed final reductions in adsorbed and dissolved phase TCE concentrations in excess of 98% and 99% respectively.

As expected, after an initial period of operation of the SPH equipment, worst case VC concentrations in soil were seen to increase to 1.25 mg/kg attributed to the accelerated breakdown process. Subsequent to the full heating period, concentrations of VC were shown to have reduced to the Site Specific Acceptance Criteria. VC was recorded at maximum concentrations of 0.715 mg/kg with a derived SSAC of 0.013 mg/kg, subsequently validated.

## 8. VALIDATION

A rigorous validation regime was undertaken by independent consultants, which included the installation of a total of sixteen validation boreholes, with soil sample collection and analysis at 0.5 m vertical intervals throughout the depth of each borehole.

Soils in each borehole were tested on site using portable analysers at 0.5 m vertical intervals, with two selected samples from each borehole being sent to an independent laboratory for analysis. A total of thirty-two soil verification samples were recovered.

A total of eight groundwater verification samples were recovered from the site, five from the core area of Source Area 1 and three from the core area of Source Area 2. These samples were similarly sent to an independent laboratory for analysis.

All validation sample analytical results showed concentrations of TCE and VC below the derived site-specific acceptance criteria.

In order to achieve this, the SPH system had removed 70 times the quantity of contaminants originally estimated to be present in the subsoils based on initial site investigation data.

Separate soil samples were recovered from the treatment zone four weeks after completion to confirm soil moisture had returned to normal and no signs of 'heave' or desiccation were recorded.

## 9. SUMMARY AND CONCLUSION

After a programme of pre-notification to local residents and through the careful co-ordination of demolition and remediation, the works at the Sheffield site were shown to have achieved the requirements of regulators and client with negligible impact on the local environment/neighbourhood.

A key objective of the demonstration was to reduce contaminant concentrations by a minimum of 80% to achieve SSACs. This was based on previous SI data but, as can be seen from Table 2, more elevated concentrations measured prior to commencement of operations resulted in a significantly increased percentage reduction required.

Post remediation/validation sampling results showed final reductions in adsorbed and dissolved phase TCE concentrations in excess of 98% and 99% respectively. In order to achieve the above reductions more than 70 times the original anticipated mass of contaminants were removed, equating to >1187 kg TCE.

System redesign and continuous close monitoring and optimisation throughout the project allowed considerable programme savings to be made through maintained elevated contaminant extraction rates. Despite the removal of 70 times the envisaged mass of contaminant, the soil and groundwater remedial timeframe was reduced to 20 weeks allowing the client to occupy the site some 12 weeks ahead of the original programme.

By the end of 2007, main roads, sewers and the sales office were installed at the site and house building started in January 2008. All remedial equipment was demobilised in December 2007.

Final costs for the project fell within budget and were demonstrated to be more controllable and not subject to fluctuation due to such external factors as landfill charges and fuel price increases, which could have significantly affected alternative options such as excavation and disposal. Despite increased costs associated with treatment of the greater than envisaged mass of contaminants removed, these were offset by the shortened remedial timeframe, subsequently final project costs were in line with predicted costs.

As most of the chlorinated compounds were extracted in the vapour phase, almost constant monitoring of the extracted vapour stream was undertaken on-site together with confirmatory laboratory analysis of gas bag samples. Due to the conditions of the extracted vapour stream (high temperature and humidity with saturated concentrations of chlorinated compounds), some difficulties were experienced using conventional on-site monitoring equipment (Photo Ionization Detectors and Flame Ionization Detectors). Future projects would benefit from having an on-site gas chromatograph to more uniformly track extraction concentrations, preferably on a continuous basis.

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