



TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP24



THERMALLY ENHANCED SOIL VAPOUR
EXTRACTION TO REMEDIATE THE
UNSATURATED ZONE AT THE WESTERN
STORAGE AREA, HARWELL

CONTAMINATED LAND: **APPLICATIONS IN REAL ENVIRONMENTS**

CL: AIRE

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This is a CL:AIRE Technology Demonstration Report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of thermally enhanced soil vapour extraction to remediate volatile organic compounds. It is not a definitive guide to the application of this technology. CL:AIRE strongly recommends that individuals/organisations interested in using the technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

A mix of chlorinated hydrocarbons and non-halogenated aromatic compounds are being remediated using conductive heating thermally enhanced soil vapour extraction (TESVE) technology at the Harwell Science and Innovation Campus in Oxfordshire. This is the first application of TESVE technology in the UK using *in situ* thermal desorption (ISTD) technology.

Soil vapour extraction (SVE) is a well-established remedial technology that reduces concentrations of volatile contaminants from the unsaturated zone. SVE can be enhanced by the use of heat, in this case thermal conductive heating, to facilitate an increase in contaminant mass removal rate and total contaminant mass removed from a source area.

Chlorinated hydrocarbons, including tetrachloroethene (PCE), trichloroethene (TCE), trichloroethane (TCA) and chloroform were disposed in a series of 25 shallow unlined pits within Chalk bedrock on the site during the 1970s and 1980s.

Following the discovery of groundwater contamination in late 1989, a programme of work was implemented to delineate, contain and then remediate the groundwater contamination and its sources. A groundwater containment plant was installed on the site which became operational in early 1994. This came to the end of its design life in 2007 and was replaced by a more efficient plant.

The primary source material, which comprised laboratory waste and vessels which contained the solvents, was excavated and removed from the pits in 2004. Residual chlorinated hydrocarbons are present within the unsaturated and saturated zone beneath the pits.

In 2006 Provectus Group completed a series of remediation pilot trials evaluating various remediation technologies at the site. Both conventional SVE in long screened wells and focused SVE targeting discrete elevations in the Chalk were evaluated together with air/ozone sparging and thermal conductive heating enhancement options. The trials concluded that TESVE would be highly effective at reducing contaminant mass in the unsaturated zone and consequently the ongoing impact on groundwater quality.

In terms of the overall site remediation, phased works are currently in progress, sequentially working on each disposal pit area across the site. The primary aim is to reduce the mass of volatile organic compounds in the source area unsaturated zone to the extent that it is economically feasible, resulting in a diminishing flux of mass to groundwater over time. Progressive broad-scale SVE is being undertaken from a network of extraction wells targeted at depths from 3 m bgl to 20 m bgl in areas within and around former pit locations. The SVE process is then thermally enhanced by replacing selected SVE wells with *in situ* heaters which extend beneath the unsaturated zone under each disposal pit. Remediation work in this demonstration project focused on Pit Nos. 1, 2 and 3 and this vicinity of the Western Storage Area (WSA) of the site. The works were undertaken in a yearly cycle matching both water table fluctuations and available funding.

The following lines of evidence were apparent indicating that significant and effective contaminant source removal had been achieved through the utilisation of TESVE beneath Pit No.3:

- Contaminant mass removal rates increased from 2 kg/day under conventional SVE extraction to in excess of 17 kg/day during initial thermal enhancement works. Verification extraction monitoring seven months post-treatment recorded a rate of 0.1 kg/day confirming the occurrence of additional attenuation following treatment and that a high degree of clean up had been achieved.
- Free product identified in monitoring wells in the vicinity of Pit No.3 prior to thermal treatment attenuated during the course of the TESVE works and no evidence of its reoccurrence was apparent following completion of treatment.
- Increases in temperatures enhanced mobilisation and dissolution of hydrocarbons, making them available for extraction and/or biodegradation at elevated temperatures.
- Post-treatment analysis of groundwater samples has revealed significantly lower concentrations of dissolved phase hydrocarbons in the vicinity of the treatment area compared to untreated areas of the WSA.

- Analysis of condensate recovered in the latter stages of treatment revealed total contaminant concentrations to be one to two orders of magnitude lower than those recorded during the initial stages of the remediation works, indicating a significant reduction in pore water contaminant concentrations.
- Off-gas flow rate monitoring and analysis has revealed that approximately 1 tonne of contaminants have been removed during the course of the works undertaken at, and in the vicinity of, Pit No.3. It is estimated that in the region of 70% of the contaminant mass removed was extracted from the single TESVE well in the centre of Pit No.3.

High levels of power were shown to only be required for relatively short periods of time in order to raise the temperature of the treatment zone to the target level. Consequently due to the relatively rapid rate of remediation, TESVE is proven to be an economic and sustainable technology in many circumstances when the whole life cycle costs of the project are considered.

The project has demonstrated that the quantity of contaminant successfully removed from the unsaturated zone beneath the former pit areas increases significantly with the utilisation of thermal conductive heating enhancement of the SVE process. There is also evidence of groundwater quality improvement occurring in the saturated zone including the thermal desorption and removal of non-aqueous phase liquids identified within the most significantly contaminated pit areas.

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In 2006 Provectus Group completed a series of remediation pilot trials evaluating various remediation technologies at the site. Both conventional SVE in long screened wells and focused SVE targeting discrete elevations in the Chalk were evaluated together with air/ozone sparging and thermal conductive heating enhancement options. The trials concluded that TESVE would be highly effective at reducing contaminant mass in the unsaturated zone and consequently the ongoing impact on groundwater quality.

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ABBREVIATIONS

AEAT	AEA Technology
AIGE	AIG Engineering Group (now Provectus Group)
AOD	Above Ordnance Datum
ATEX	Atmosphere Explosibles (French)
Bgl	Below ground level
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CoC	Contaminants of Concern
COTC	Certificate of Technical Competence
CVOC	Chlorinated Volatile Organic Compound
DNA	Deoxyribonucleic Acid
DNAPL	Dense Non Aqueous Phase Liquid
EA	Environment Agency
ECC	Engineering and Construction Contract
ERH	Electrical Resistance Heating
GAC	Granular Activated Carbon
GC	Gas Chromatography
GC-MS	Gas Chromatography - Mass Spectrometry
HDPE	High Density Polyethylene
HSE	Health and Safety Executive
HSIC	Harwell Science and Innovation Campus
HZ	Heated Zone
ID	Internal Diameter
IMS	Integrated Management System
ISTD	<i>In Situ</i> Thermal Desorption
Kr	Vertical Permeability
Kz	Horizontal Permeability
LEL	Lower Explosive Limit
LNAPL	Light Non Aqueous Phase Liquid
MPE	Multiphase Extraction System
MTL	Mobile Treatment Licence (Environmental Permit)
NAPL	Non Aqueous Phase Liquid
NDA	Nuclear Decommissioning Authority
OD	Outside Diameter
PAHs	Polycyclic Aromatic Hydrocarbons
PCDD/F	Polychlorinated Dibenzodioxins and Furans
PCBs	Polychlorinated Biphenyls
PCE	Tetrachloroethene
PID	Photoionisation Detector
PLC	Programmable Logic Controller
PTFE	Polytetrafluoroethylene
QA/QC	Quality Assurance / Quality Control
qPCR	Quantitative Polymerase Chain Reaction
RFH	Radio Frequency Heating
ROI	Radius of Influence
RSRL	Research Sites Restoration Limited (formerly UKAEA)
SCR	Silicon Controlled Rectifier
SEE	Steam Enhanced Extraction
SVE	Soil Vapour Extraction
SVOCs	Semivolatile Organic Compounds
TCA	1,1,1-trichloroethane
TCE	Trichloroethene
TCH	Thermal Conductive Heating
TESVE	Thermally Enhanced Soil Vapour Extraction
TPH	Total Petroleum Hydrocarbons
TTZ	Target Treatment Zone
VOCs	Volatile Organic Compounds
WSA	Western Storage Area

1. INTRODUCTION

1.1 BACKGROUND

The management of organic chemical contamination in the Chalk forms a major part of the environmental restoration programme being carried out by the United Kingdom Atomic Energy Authority (UKAEA), now known as Research Sites Restoration Limited (RSRL) for the Nuclear Decommissioning Authority (NDA) at the Harwell Science and Innovation Campus (HSIC) in Oxfordshire. In 2005, AIG Engineering Limited (AIGE), now Provectus Group, undertook pilot scale evaluation of unsaturated zone remediation techniques at the Western Storage Area (WSA) and through utilisation of the most appropriate techniques, further undertook remediation of the most significantly impacted parts of the source term.

The principal objective of the project is source mass reduction, forming part of an overall strategy for managing the groundwater contamination from the WSA which has included removal of the waste from the pits and operation of a groundwater containment scheme since 1994.

The overall site remediation is being undertaken in phases which are currently still ongoing in 2010, with progressive broad-scale soil vapour extraction (SVE) being undertaken using a network of extraction wells targeted at depths from 3 m bgl to 20 m bgl in areas within and around former pit locations. The SVE process is then thermally enhanced by replacing selected SVE wells with *in situ* thermal conduction heaters which extend beneath each disposal pit within the unsaturated zone.

1.2 PROJECT AIMS AND OBJECTIVES

This remediation project demonstrates the application of thermally enhanced soil vapour extraction (TESVE) to remediate the residual contamination within the unsaturated zone and zone of water table fluctuation at the WSA, Harwell. This is the first application of TESVE in the UK using *in situ* thermal desorption (ISTD) technology.

The primary aim of the project is to reduce the mass of volatile organic compounds (VOCs) in the source area unsaturated zone to the extent that it is economically feasible, resulting in a diminishing flux of mass to groundwater over time.

Specific objectives of the project are to:

- Reduce the contaminant mass flux from the unsaturated zone into the groundwater which will help minimise the duration that active remediation measures will be required at the WSA;
- Reduce the overall level of contaminant mass residing in the source zone;
- Target more than 2 tonnes of contaminants to be removed/destroyed/degraded within the entire WSA area (Pit No.3 is only one fraction of the WSA zone and the target is referring to the full-scale remediation of various pits within WSA);
- Remove contaminants from the unsaturated zone that would not be removed by conventional SVE, including the heavier fraction of petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs);
- Abate emissions from the remediation such that there are “zero” emissions from the remediation location of the works and minimise secondary waste arising from the process; and
- Demonstrate to stakeholders that the best available techniques are being applied to address the chemical groundwater contamination at Harwell.

1.3 PROJECT REPORT SCOPE AND ORGANISATION

The purpose of the project report is to describe the design and implementation of TESVE for treatment of VOC / hydrocarbon contamination beneath former disposal Pit No.3 in the western part of the site and provide an objective assessment of the performance of the technology.

The report is divided into the following sections:

- Introduction – Giving a background to the site and remediation project together with the specific scope and purpose of the Technical Demonstration Project Report;
- Background to TESVE – Providing brief descriptions of the soil vapour extraction and thermal enhancement processes and some of the commonly utilised enhancement technologies;
- Site Description – Including summaries of the site history, environmental setting and nature of contaminants of concern;
- Technology Demonstration Support Issues – Giving details of the management of the project in terms of permitting requirements, operational and environmental controls and monitoring procedures;
- Pilot Trials and Remediation Design – Including a description of the pilot treatability study primarily focused on TESVE with a detailed description of the methodology adopted, together with discussion and interpretation of the findings of the trials;
- Set-Up and Operation of Full-Scale Thermally Enhanced SVE – Describing the application of TESVE to treat contamination beneath former disposal Pit No.3 with details of the plant and equipment utilised;
- Performance Monitoring and Evaluation – Including details of the monitoring and verification data obtained in relation to the works at Pit No.3 together with an assessment of contaminant mass removed;
- Economic and Environmental Considerations – Giving a discussion on costs and benefits;
- Conclusions; and
- Lessons Learnt.

2. BACKGROUND TO TESVE

2.1 SOIL VAPOUR EXTRACTION

Soil vapour extraction (SVE) is a well-established remedial technology that reduces concentrations of volatile contaminants from the unsaturated zone. SVE can be applied *in situ* or *ex situ*, depending on site specific constraints. The prefixes *in situ* or *ex situ* apply to whether the technique is applied to soils that are in an undisturbed state (*in situ*), or whether the soils have been excavated first and deposited (*ex situ*). The mechanism for contaminant removal is via extraction of soil vapour by creating a negative pressure in vertical or horizontal vapour wells in which the gaseous phase of volatile hydrocarbons is extracted.

Volatile constituents in soil gas are drawn toward the extraction wells inducing further volatilisation of contaminants adsorbed to soil. Extracted vapour (off-gas) is then treated as necessary before being released to the atmosphere. The increased air flow through the subsurface also tends to dry the soil, increasing permeability and may stimulate biodegradation of some contaminants, especially those that are less volatile (Förstner, 1997).

The SVE process is driven by the partitioning of volatile materials from:

- Adsorbed phases (attached to the surface of soil particles);
- Absorbed vapour phase – within soil gas in soil pores;
- Dissolved phase in soil pore water; and
- Non-aqueous phase liquid (NAPL) phase – residually held by capillary and surface tension forces.

The partitioning is controlled by both contaminant and soil properties. These properties include contaminant vapour pressure, Henry's law constant, solubility, soil permeability and organic carbon content.

There are a number of important factors that govern the successful application of SVE at a site which include:

- The target compounds of concern must be sufficiently volatile – with vapour pressure higher than 1 mm Hg and Henry's law constant higher than 0.001;
- The targeted soil must show high permeability potential, preferably with low heterogeneity and fracturing;
- A considerable vapour flow rate must be established through the affected unsaturated soils; and
- The air flow paths established by individual treatment wells must affect an adequate area to facilitate economically viable treatment of the contaminated area with a limited number of treatment wells.

2.2 THERMAL ENHANCEMENT CONTAMINANT TRANSPORT AND REMOVAL MECHANISMS

The performance of a SVE system is dependent on both the properties of the contaminants and the contaminated soil or rock mass. It is controlled by various transport and removal mechanisms (USEPA, 1997) including:

- Chemical partitioning to the vapour phase;
- Sorption of contaminant on soil/rock surfaces;
- Gas advection;
- Contaminant vapour diffusion; and
- Biodegradation.

The reaction kinetics of all of these mechanisms can be increased by the utilisation of thermal enhancement to facilitate an increase in contaminant mass removal rate and total contaminant mass removed from a source area.

Figure 2.1 summarises the physical property changes occurring during heating of water, trichloroethene (TCE), and tetrachloroethene (PCE). While chlorinated solvent density, viscosity, surface tension, and solubility vary slightly, vapour pressure and Henry's law constants increase dramatically with temperature.

- **Solubilities** of the two organic compounds depicted below increase exponentially with temperature, only at temperatures above the conventional boiling point of water.
- **Vapour pressure**, which is the pressure exerted by the gas phase in equilibrium with its liquid or solid phase, increases with temperature and boiling occurs when the vapour pressure exceeds atmospheric pressure. The gas phase concentration of a hydrocarbon compound strongly depends on its vapour pressure, therefore a temperature increase will improve mass transport by increasing the concentration in the vapour phase, even if the temperature is below the boiling point.
- **Viscosity** decreases by about one percent with each temperature increase of 1°C. Gas viscosities tend to be one to two orders of magnitude less than liquid viscosities, but also decrease proportionally with temperature. Typically the viscosity of a gas will decrease about 30% with a temperature increase of 100°C.
- **Density** of hydrocarbons decreases about 10% with a temperature change of 100°C. The density of water decreases about 4% over the temperature range from 0 to 100°C. Although these changes are small, they can affect contaminant migration because of the more rapid change of hydrocarbon density relative to groundwater density.

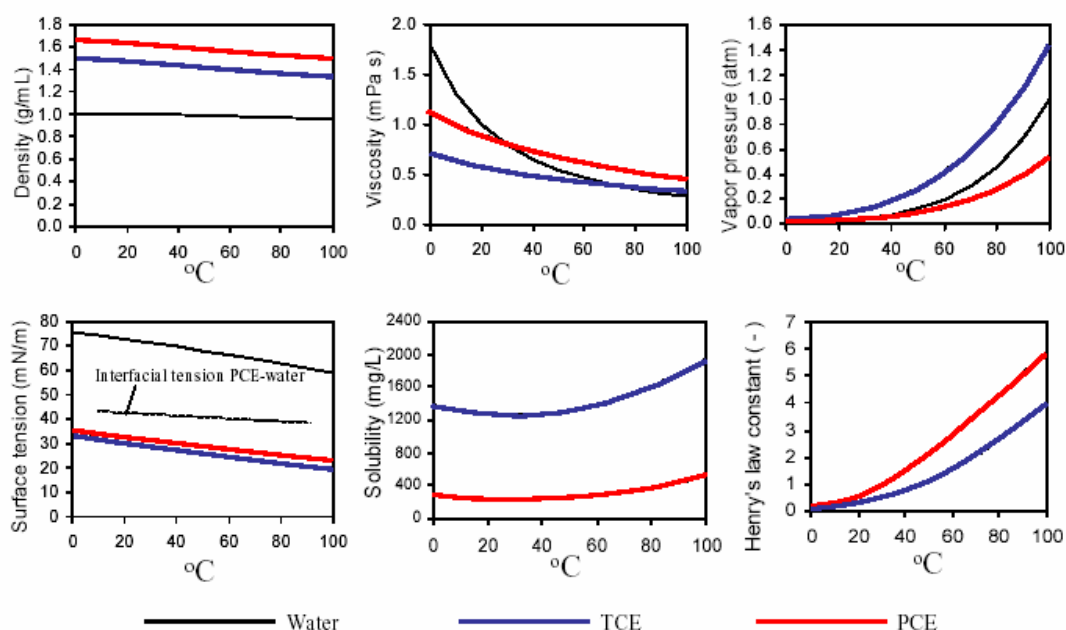


Figure 2.1: Properties of water, PCE and TCE as a function of temperature (Heron et al., 2008)

Target temperatures for treatment of chlorinated solvents and other VOCs are typically 100°C.

Drying of the soil/rock mass during thermal enhancement can increase the air permeability and therefore, particularly in relatively low permeability soils, increase the process of transport of contaminant vapours by gas advection as air is drawn through the soil by vacuum extraction.

Other mechanisms operate within pore water or underlying groundwater as a result of thermal processes and these include enhanced dissolution, hydrolysis (field example; Heron et al., 2005) and aqueous phase oxidation. However, vaporisation is dominant for most chlorinated solvents.

In circumstances where NAPL is present, the combined vapour pressure of the NAPL and pore water determine the boiling temperature and co-boiling of the two liquids occurs at temperatures less than the boiling point of water. Four fundamental laws of thermodynamics, which describe the composition of a gas mixture, help to explain this phenomenon:

- **Dalton's Law** states that the pressure exerted by a mixture of gases is the sum of the pressures that could be exerted by each individual gas occupying the same volume alone. The pressure that could be exerted by an individual gas is referred to as the partial pressure.
- **Raoult's Law** states that the equilibrium gas-phase partial pressure of a compound is equal to the product of the vapour pressure of the pure compound and the mole fraction of the compound in the NAPL phase.
- **Henry's Law** states that the equilibrium gas-phase partial pressure of a compound is equal to the mole fraction of the compound in the aqueous phase, multiplied by a constant, known as the Henry's law constant.
- **The Ideal Gas Law** states that the mole fraction of a compound in the gas phase is equal to the ratio of its partial pressure and the total pressure.

Based on these four principles, the concentrations of hydrocarbon contaminants in vapour extracted from a thermal treatment zone will increase with temperature. The boiling temperature of a liquid mixture is the temperature at which its total vapour pressure is equal to atmospheric pressure. Since the total vapour pressure is the sum of partial pressures of all of the components of the mixture, the boiling point of the mixture (eutectic point of the azeotropic mixture) can be achieved at a lower temperature than any of the boiling points of any of the separate components. The phenomenon is called co-distillation. The implication of TESVE is that many contaminants can be easily removed in vapour at steam temperature, even if their boiling temperatures are greater than 100°C. Table 2.1 below illustrates selected NAPL compounds and steam co-distillation points.

Table 2.1: Boiling points and co-distillation points of selected NAPL compounds (Perry and Green, 2007)

NAPL mixture	Component Boiling Points (°C)	Co-Distillation Point (°C) or Eutectic Point
Benzene Water	80.1 100	69.4
Ethylbenzene Water	136.2 100	92.0
Carbon tetrachloride Water	76.8 100	66.8
Chloroform Water	61.2 100	56.3
1,2 dichloromethane Water	83.5 100	72
Toluene Water	110.6 100	85.0
1,1,2 trichloroethane Water	113.7 100	86.0
Trichloroethene Water	87.1 100	73.1
Tetrachloroethene Water	121 100	88.5

In situations where concentration gradients are present between pores under vacuum and within an air stream but contaminants are also present away from the flowing air, contaminants will move by diffusion towards the air stream. Gas phase diffusion is generally much slower than advection in relatively low permeability strata and is often a significant performance limiting factor. In such situations increasing the temperature enhances the rate of vapour transport from low permeability zones to areas of higher permeability. Furthermore steam produced from boiling of pore water during thermal enhancement and the steam's pressure-driven flow to zones of high vapour flow will mobilise contaminant vapours from low permeability zones at a much higher rate.

Increases in temperature can also stimulate biological activity within the soil/rock matrix and therefore enhance biodegradation of contaminants.

When thermal enhancement is used in conjunction with SVE, a spike in the effluent concentration is typically observed, as volatile contaminants of concern are vaporised by boiling of NAPL and water within the target volume. It is important that the effluent treatment system is designed to handle both the elevated temperature (90°C -100°C) and the increased mass loading.

2.3 ENHANCED SOIL VAPOUR EXTRACTION TECHNOLOGIES

There are various methods to enhance the effectiveness of traditional SVE technology. Thermal and non-thermal methods can be differentiated.

2.3.1 NON-THERMALLY ENHANCED SVE TECHNOLOGIES

The most commonly applied non-thermal SVE technologies are:

- Air/ozone sparging; and
- Dual phase extraction.

The principles and applicability of these techniques are briefly reviewed in the following sections.

2.3.1.1 Air/Ozone Sparging

Air/ozone sparging involves injecting air or ozone enriched air into the saturated zone below or within the contaminated area through wells or sparging probes. The air rises through channels in the saturated zone and carries volatilised contaminants into unsaturated soil, where they are subsequently removed using SVE. Air/ozone sparging increases the dissolved oxygen levels in the groundwater, increasing the oxidation potential of the saturated zone and enhancing subsurface biodegradation of contaminants that are aerobically degradable. Soil heterogeneity greatly affects the distribution of air channels and the effectiveness of air sparging. Diffusion of contaminants into channels is slow. Air/ozone sparging is the most effective at removing volatile contaminants from the saturated zone at sites with homogenous, high-permeability soils and unconfined aquifers.

2.3.1.2 Dual Phase Extraction

Dual phase extraction (DPE) enhances contaminant removal by extracting both contaminated vapours and groundwater from the subsurface. DPE involves removal of contaminated water and soil gases from a common extraction well under high vacuum conditions. This is most applicable at sites with multiple phase contamination and low to moderate hydraulic conductivity soils.

2.3.2 THERMALLY ENHANCED SVE TECHNOLOGIES

There are various types of thermally enhanced SVE technologies, these include:

- Steam enhanced extraction;
- Electrical resistance heating;
- Radio frequency heating; and
- Thermal conductive heating.

The principles and applicability of these techniques are briefly reviewed in the following sections.

2.3.2.1 Steam Enhanced Extraction

Steam enhanced extraction (SEE) involves the generation of steam on the surface which is then injected into the treatment zone via a series of injection wells (Figure 2.2). This provides both heat and pressure to the treatment zone so that contaminants are driven ahead of the condensing water vapour towards the SVE wells. It is most applicable to moderate to high permeability soils and ideally requires a shallow confining layer to prevent steam breakthrough at the surface and a deep confining layer to prevent downward migration of contaminants (USEPA, 2004).

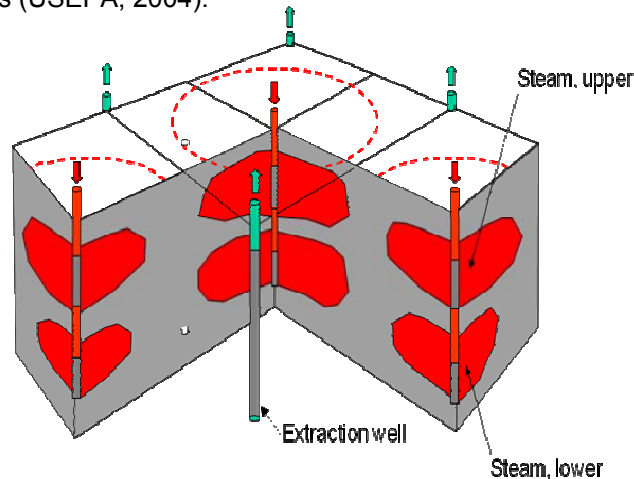


Figure 2.2: Schematic diagram showing a steam enhanced extraction process

2.3.2.2 Electrical Resistance Heating

Electrical resistance heating (ERH) involves passing an electric current through the soil between electrodes within the treatment zone (Figure 2.3); energy dissipated because of resistance is transformed into heat. Both three-phase and six-phase ERH techniques have been developed and have proven to be effective in relatively low permeability soils (Beyke and Fleming, 2005; CL:AIRE, 2008). Six-phase heating involves splitting standard line current from three phases to six phases. In heterogeneous strata the more electrically conductive zones will be affected first resulting in an uneven distribution of heat and as the soil dries out the conductivity and therefore heating efficiency decreases.

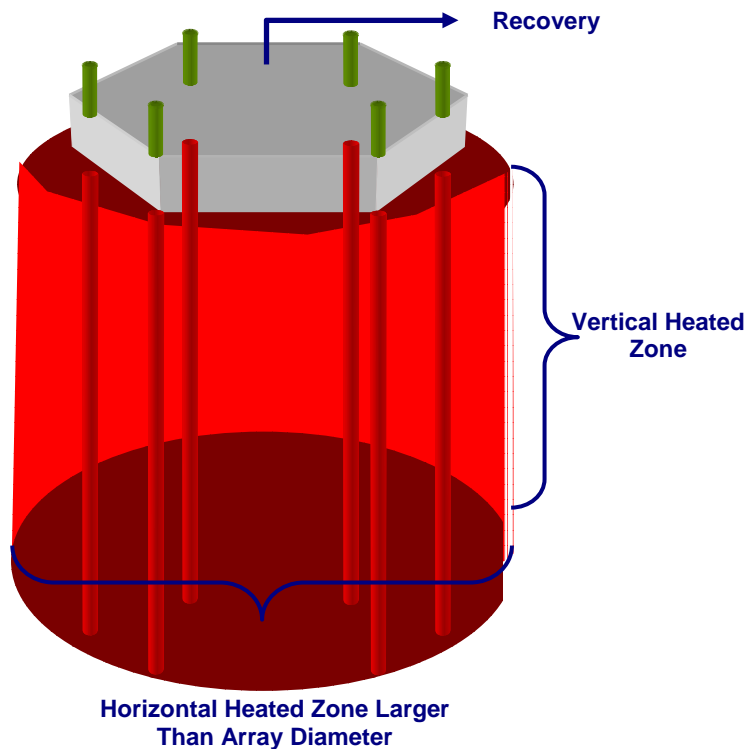


Figure 2.3: Schematic diagram showing an electrical resistance heating process

2.3.2.3 Radio Frequency Heating

Radio frequency heating (RFH) involves the utilisation of radio frequency waves emitted from electrodes or antennae within the treatment zone which increase molecular motion and heat the soil. This technique can also be effective in relatively low permeability soils but as with ERH, RFH decreases in efficiency as the soil matrix dries out (USEPA, 1997).

2.3.2.4 Thermal Conductive Heating

Thermal conductive heating (TCH) involves the application of heat to the treatment zone through conductive heat transfer generally utilising metal rods installed within cased wells, although thermal blankets can also be used as a heat source for shallow contamination (Stegemeier and Vinegar, 2001). The heater rods typically operate at a temperature of approximately 500°C. TCH is relatively simple to use and applicable to a wide range of organic contaminants and strata types. A common application of TCH technology utilises two types of thermal wells: (a) “heater-only” wells, which only inject heat into the soil surrounding them; and (b) “heater-vacuum” wells, which extract soil vapours as well as heat the soil (Figure 2.4). Heat flows through the soil from the heating elements primarily by thermal conduction. The conductive heating process is relatively uniform in its vertical and horizontal seep. This is because energy per linear metre input into the soil by thermal conduction heaters is uniform over each heater’s length, as well as from heater to heater and thermal conductivity values vary over a very narrow range over a wide range of soil and soft rock types, leading to a relatively predictable rate of heat-front propagation into the formation around each heater.

Treatment (destruction or removal) of the contaminants in the conductively heated soil can attain a destruction/displacement efficiency of 100%. This occurs because the coolest locations within the treatment zone can be heated. Convection of air and water vapour drawn into the zone further improves removal by evaporation, steam distillation and oxidation (Unified Facilities Criteria, 2006).

It is possible to achieve very high temperatures, between 300-500°C utilising TCH for treatment of high boiling-point contaminants such as polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins and furans (PCDD/F) and coal tar (Baker et al., 2006).

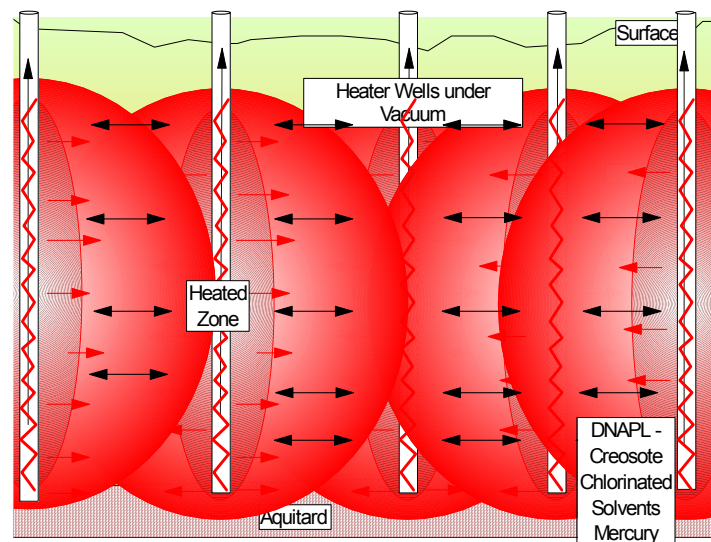


Figure 2.4: Schematic diagram showing a thermal conductive heating process

3. SITE DESCRIPTION

3.1 FORMER SITE OPERATIONS

The Western Storage Area (WSA) site occupies an area of approximately 1 ha at RSRL Harwell (boundary indicated in Figure 3.1). The site was originally licensed under the 1974 Control of Pollution Act. Twenty-five unlined pits excavated into the Chalk to a maximum depth of 4 m below ground level (bgl) at the WSA (Plate 3.1) were used for the disposal of various chemical wastes including chlorinated solvents and other organic chemicals. The chlorinated solvents were disposed over the period from 1970 to 1977 with later arisings being bulked up and sent for incineration off-site. The site is licensed by the Environment Agency in its aftercare phase until the licence can be surrendered.

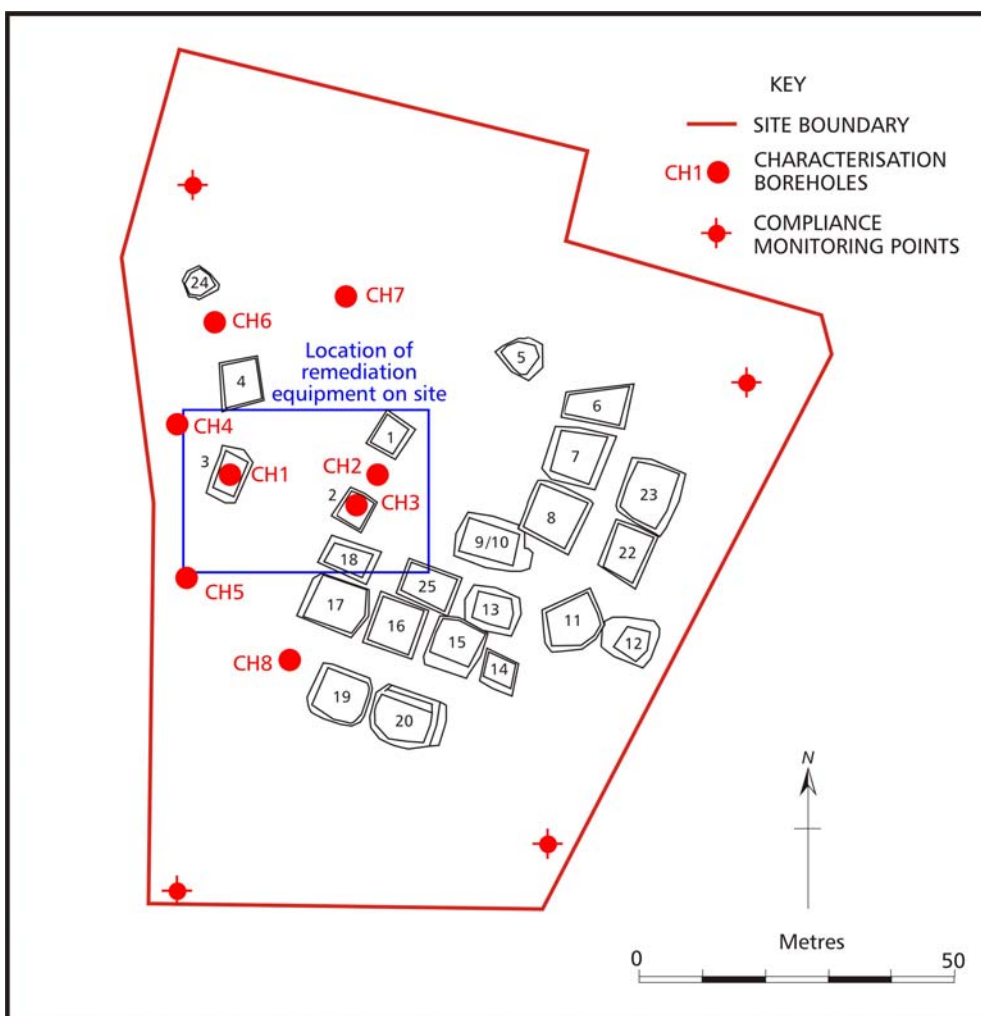


Figure 3.1: Site layout showing numbered pits and characterisation boreholes



Plate 3.1: Waste disposal works in operation c.1977

The methodology of contaminants' disposal and the exact amount of material disposed in the pits is not known. However it was discovered that the disposal of materials has caused chemical contamination of groundwater in the Chalk aquifer and is a continuing source of groundwater contamination below the WSA. Following the discovery of groundwater contamination in late 1989, a programme of work was implemented to delineate, contain and then remediate the groundwater contamination and its sources. A groundwater containment plant was installed on the site which became operational in early 1994. This came to the end of its design life in 2007 and was replaced by a more efficient plant (Figure 3.2).

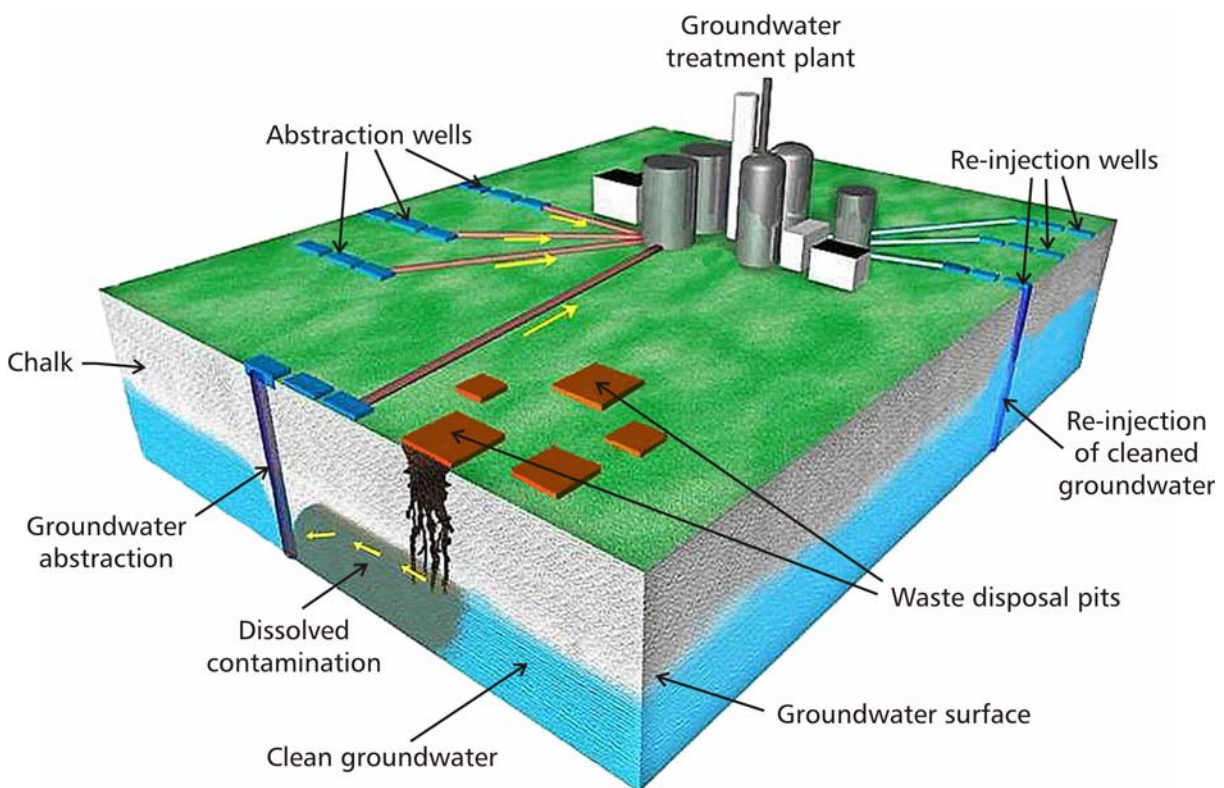


Figure 3.2: Schematic representation of the hydraulic containment of groundwater contamination at the WSA

Site investigations have confirmed a diverse range of chemicals, including mineral oils, chlorinated hydrocarbons (including chlorinated solvents and PCBs), pesticides and metals in the Chalk at the site. A major ground contamination investigation at the WSA reported by AEA Technology (AEAT) in September 1996 documented the presence of VOCs in chalk pore water samples collected from cored boreholes adjacent to the WSA disposal pits. Non-aqueous phase liquids (NAPL) containing significant levels of chlorinated solvents were also detected as oil films on fissures in the Chalk. Light NAPL has been identified periodically in groundwater monitoring wells in the vicinity of the disposal pits.

The primary source material, which comprised laboratory waste and vessels which contained the solvents, was excavated and removed from the pits in 2004 to a depth of approximately 150 mm below the original depth. The pits were backfilled with granular subsoil and a bentomat layer was installed approximately 1 m below ground surface; no clay was used to fill the pits and the pits were not capped.

3.2 STRATIGRAPHY AND HYDROGEOLOGY OF THE CHALK IN THE VICINITY OF THE SITE

The Chalk at the WSA site is a heterogeneous fractured rock with a dual porosity. It comprises strata of the Grey Chalk Subgroup (formerly essentially known as 'Lower Chalk') of the Cretaceous Chalk Group. The Grey Chalk is coloured by its clay content and reflects the relatively low sea-levels, and hence greater extent of land from which clays were sourced, at the beginning of chalk deposition. The Grey Chalk strata comprise interbedded layers of moderately weak, moderately strong and strong, locally weak and very strong light grey argillaceous chalk with a variable clay content.

The rock matrix itself has a relatively low effective permeability but high porosity (25%) and retains pore water (Plate 3.2). The Chalk also has a secondary porosity of 1% to 2% of the volume of the rock made up of fractures and rubble zones (highly fractured layers). Some of these fissures in the rock are highly permeable to fluid flow. Blocks of competent chalk matrix are bounded by fractures or rubble zones and have an average block size of 300 mm to 500 mm with some blocks as large as 1.1 m. A relatively soft weathered chalk is present to a depth of approximately 6 m to 8 m bgl and a laterally extensive horizontal layer of chalk marl at a depth of 30 m forms the base of the unconfined Chalk aquifer. The unconfined aquifer (known as the H1 unit) has an average estimated transmissivity of $600 \text{ m}^2\text{day}^{-1}$.

Groundwater elevation data collected by RSRL since 1991 indicate that groundwater levels in fissures vary seasonally with significant recharge occurring in the winter. The water level also varies year to year due to drought or exceptionally wet conditions, with a historical range of approximately 18 m from 5 m bgl to 23 m bgl (115 m AOD to 97 m AOD).

The groundwater flow direction in the unconfined Chalk aquifer at the WSA is to the north and north east during periods of high groundwater level and to the east and south east during times of low groundwater level. Groundwater flow in chalk fractures in the WSA is controlled by a series of abstraction wells arrayed around the perimeter of the WSA from the south east to the north.



Plate 3.2: Fractured Grey Chalk from characterisation borehole

3.3 NATURE AND EXTENT OF CHEMICALS OF CONCERN

Cored boreholes with associated pore water concentration profiles completed by AEAT in the mid-1990s and more recently by AIGE in 2005 have identified a range of conditions in the subsurface at the WSA from NAPL-coated fractures to the presence of high concentrations of dissolved VOCs in pore water from the interior of chalk blocks.

A total of eight rotary cored boreholes were sunk as part of the AIGE characterisation works undertaken as part of the initial design works carried out in Autumn 2005 (Plate 3.3). The locations of these boreholes are shown in Figure 3.1.



Plate 3.3: Rotary coring of characterisation boreholes

Significantly higher concentrations of VOCs were detected within chalk samples obtained from beneath the former pits (AIGE boreholes CH1 and CH3) compared to elsewhere on the site. Concentrations within these samples from below the pits ranged from 2 mg/kg to 73 mg/kg whereas in other areas concentrations detected ranged up to a maximum of 3 mg/kg.

Beneath the pits, the concentrations detected decreased with depth. This decrease was much more significant beneath Pit No.3 (CH1) compared to Pit No.2 (CH3). Total VOC concentrations of 73 mg/kg and 32 mg/kg were detected within samples from 6 m and 10 m beneath Pit No.3 respectively. These were significantly greater than concentrations detected from 14 m and 18 m depth as well as any of the levels detected beneath Pit No.2, which ranged from 2 mg/kg to 12 mg/kg.

Outside the footprint of the former pits total VOC concentrations were found to be variable with depth and apparently unrelated to lithology.

In summary, residual hydrocarbons are likely to be present within the unsaturated and saturated zone beneath the pits in various modes which include:

- Vapour within rock pores in the unsaturated zone;
- Adsorbed onto chalk particles;
- Dissolved into fluids (water or hydrocarbons) moving downwards through joints and fractures in the unsaturated zone;
- Diffused into relatively immobile chalk pore water in the unsaturated zone;
- Dissolved into hydrocarbons floating on the groundwater – NAPL;
- Diffused into relatively immobile chalk pore water within the saturated zone;
- Dissolved into mobile groundwater in joints and fractures in the saturated zone; and
- As dense immiscible solvent (e.g. DNAPL) moving downward through the Chalk aquifer.

Contaminants detected comprised a mix of chlorinated hydrocarbon and non-halogenated aromatic compounds consistent with those determined from previous assessments and the ongoing groundwater monitoring programme. The following contaminants were detected:

Chlorinated aliphatic hydrocarbons:

- Tetrachloroethene (PCE);
- Trichloroethene (TCE);
- 1,1-dichloroethene (DCE);
- cis-1,2-dichloroethene (DCE);
- 1,1,2,2-tetrachloroethane (PCA);
- 1,1,1-trichloroethane (TCA);
- 1,1-dichloroethane (DCA);
- 1,2-dichloroethane (DCA);
- Chloroethane;
- Carbon tetrachloride;
- Chloroform; and
- Dichloromethane.

Chlorinated aromatic hydrocarbons:

- 1,4-dichlorobenzene;
- 1,2-dichlorobenzene; and
- Chlorobenzene.

Non-halogenated aromatic hydrocarbons:

- Benzene;
- Toluene;
- Ethylbenzene;
- Xylene;
- 1,3,5-trimethylbenzene;
- 1,2,4-trimethylbenzene; and
- Naphthalene.

Proportions of individual contaminants varied from location to location both laterally and vertically. Generally chlorinated hydrocarbons were predominant, notably chloroform, dichloromethane, 1,1,1-trichloroethane and cis-1,2-dichloroethene. Of the aromatic compounds toluene and xylene were generally present in greater concentrations.

4. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

4.1 CONTRACT AGREEMENT AND PROJECT TEAM

The contract for “Unsaturated Zone Remediation, WSA Site Harwell” was tendered by RSRL on behalf of the NDA in April 2005 and let to AIG Engineering Group (now Provectus Group) in July 2005.

The management structure for the project is shown in Figure 4.1 below.

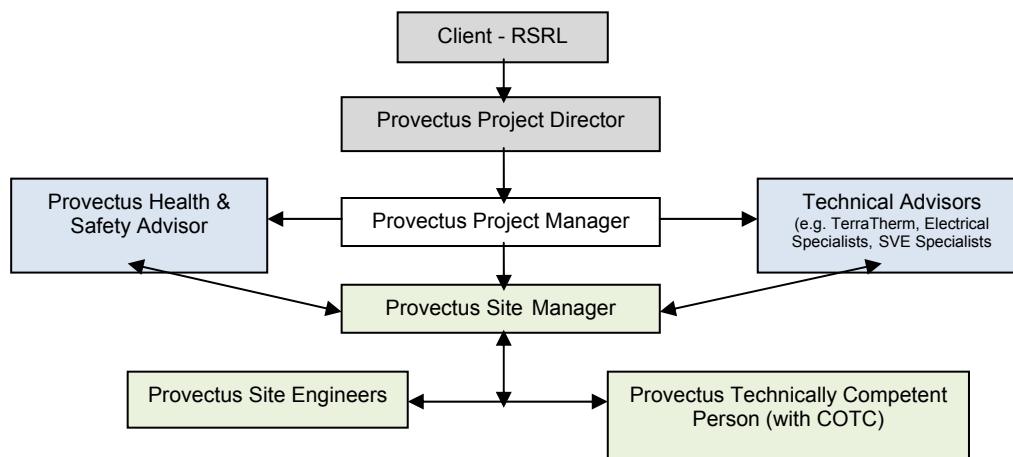


Figure 4.1: Project management structure

Provectus Group is an exclusive sublicense holder of the *In Situ* Thermal Desorption (ISTD) technology in Great Britain and has built its technical knowledge and expertise with the support of TerraTherm partners, which have over 10 years of experience in utilisation of ISTD technology.

4.2 PERMITTING REQUIREMENTS

The Health and Safety Executive (HSE) was given prior notification of the works to be undertaken as part of the project by RSRL through the issue of F10 forms in accordance with RSRL procedures.

RSRL Authorisation to Work Certificates and Permits to Dig were issued as appropriate for the various stages of the works.

An Environment Agency (EA) Mobile Treatment Licence (MTL) Deployment Form (WML2) was accepted by the EA for the works. The Deployment Form was used in conjunction with AIGE’s MTL Licence reference EAWML/71300. Periodic inspections of the site were made by EA officers during the course of the works.

The WSA itself is a licensed (closed) landfill, Licence Number EA WML 86127. The WSA is located on Harwell Science and Innovation Campus, within the area licensed under the Nuclear Installations Act (1965).

4.3 OPERATING SITE SECURITY

The WSA is located within the main security fence for the Harwell nuclear licensed site and also has a secondary internal security fence. The security at the site was maintained around the treatment area and compound.

4.4 OPERATIONAL CONTROLS

The extraction and treatment plant was regularly inspected by a trained operator, who undertook routine operational performance and maintenance checks. The operator also undertook routine soil gas, temperature and wellhead pressure monitoring from existing dedicated installations and other wells where feasible and appropriate.

Full documentation of the process and details of the quality control and quality assurance programmes implemented as part of the *in situ* treatment process were included in the project Working Plan, a copy of which was kept on site at all times during field works. The following quality assurance checks were undertaken at least on a weekly basis to ensure the effectiveness of treatment:

- Vacuum extraction pressure achieved at each wellhead, confirming negative (suction) pressure and enabling calculation of airflow achieved at each wellhead;
- Routine diagnostic checks on operational equipment, including water level in condensate tank; and
- Checking suction achieved at blower inlets suction manifolds and wellheads, to ensure satisfactory vacuum maintained at wellheads with no loss of pressure throughout system.

Monitoring of the following parameters within selected monitoring boreholes was undertaken during the treatment process, to ensure that optimal conditions were occurring for effective reduction of contaminants of concern:

- Temperature;
- Total volatile organic compounds; and
- Pressure.

A site logbook was maintained which included details of the following activities:

- Date of inspection;
- Hours of continued operation;
- Visitors to site;
- Weather, including temperature, rain and any visual flooding on site etc;
- Details of measured temperatures, pressure and airflow at SVE wellheads;
- Groundwater monitoring results;
- Soil gas/vapour monitoring results;
- Odour monitoring results;
- Inspection of SVE equipment and wellheads;
- Quantity of waste water generated/stored from water vapour trap;
- Inspection of containment measures; and
- Inspection of boundary fencing.

4.5 MAINTENANCE PROCEDURES

An inspection of the *in situ* treatment system was undertaken at least once every week of operation, to ensure optimal performance of the treatment system. This routine maintenance included the following:

- Checking all compression fittings, tightening connections for all wellheads, suction lines/manifolds where necessary;
- Addition of oil to motorised components where necessary;
- Replacement of off-gas abatement media where required;

- Draining of condensate from storage tank where required to suitable storage container for discharge or removal; and
- Checking all electrical connections and control systems.

4.6 QUALITY CONTROL PROVISIONS

Provectus Group operates an integrated health and safety, quality and environmental management system (IMS) conforming to the requirements of BS EN ISO 9001 quality management system, BS EN ISO 14001 environmental management system and OHSAS 18001 Occupational Health and Safety management specifications. The IMS is accredited by the British Standards Institution.

- All routine field monitoring was undertaken in accordance with written protocols set out in the working plans. Monitoring is undertaken by appropriately trained personnel only.
- All portable and fixed instruments utilised were calibrated according to manufacturer recommendations.
- All laboratory analysis was undertaken by a UKAS accredited laboratory, however duplicate samples were also collected and analysed to ensure accuracy and consistency of results.
- Sample blanks were analysed to verify there was no cross contamination during sampling.

4.7 ENVIRONMENTAL CONTROL MEASURES

4.7.1 OFF-GAS AND CONDENSATE

Organic vapours extracted from the underlying strata by SVE were conveyed to the treatment compound area via surface wellhead assemblies and a closed system of suction lines. The suction lines were constructed of plastic pipes (polyethylene or PVC) or heat resistant materials as required with the thermally enhanced SVE system connected by couplings to form an airtight seal. The lines were surface laid and led to the vacuum extraction unit located at the treatment compound area.

Prior to being drawn through the SVE unit, the air was drawn through a water vapour trap designed to remove condensate. Condensed foul water was pumped from the base of the trap (knock-out pot) to a storage tank, passed through an oil-water separator and granular activated carbon (GAC) filter vessels prior to being discharged to the RSRL WSA groundwater containment plant.

The process air was drawn by vacuum through the off-gas abatement unit comprising a series of GAC filter vessels, prior to discharge via the exhaust of the SVE unit.

4.7.2 PROCESS GENERATED WASTES

Process generated wastes (spent GAC media or condensate) were removed off-site in accordance with Duty of Care Provisions required under the Environmental Protection Act (1990), and in accordance with any relevant discharge consents. Copies of all waste consignment notices for off-site disposal were maintained and kept in the operational site file.

4.7.3 PROCESS MONITORING EQUIPMENT

The system was designed to be ATEX Category 3 compliant, as potentially explosive atmospheres (>20% Lower Explosive Limit (LEL)) may have developed in the SVE system. The unit was fitted with an in-line LEL detection system linked to an automatic system cut-off as a safety measure.

Regular off-gas monitoring from the odour abatement equipment was undertaken using a photoionisation detector (PID) calibrated to detect the volatile constituents of the contaminants of concern.

4.7.4 ODOUR EMISSIONS MONITORING PROCEDURES

Simple olfactory monitoring was undertaken regularly so that records of any odours could be noted in the site logbook. This form of monitoring took place at least once a week by a technically competent person to assess the presence of malodorous materials on site. If odours were assessed as being present the source of the odours could then be investigated. No significant odours were noted during the remediation works.

4.7.5 GROUNDWATER MONITORING

Regular groundwater monitoring was undertaken by RSRL from existing monitoring boreholes in the vicinity of the treatment area. These data were utilised to assess any impact of the remediation works on the groundwater regime.

5. PILOT TRIALS AND REMEDIATION DESIGN

5.1 SUMMARY OF FIELDWORKS FOR PILOT TRIALS AND REMEDIATION DESIGN

Fieldworks for remediation design were undertaken in two stages, an initial stage of drilling operations, characterisation investigation and well installation, followed by a series of trials utilising SVE plant and equipment.

The drilling works comprised the following:

- Sinking of eight rotary cored boreholes for supplementary site characterisation purposes;
- Logging, sub-sampling and laboratory analysis of rock cores;
- Adaptation of characterisation boreholes for utilisation as SVE wells by installation of permanent casing;
- Installation of pressure and temperature monitoring wells; and
- Installation of heater wells for SVE thermal enhancement.

The site trials comprised the following:

- Conventional SVE within a 12 m screened length of well;
- Thermal enhancement of SVE within a 12 m screened length of well;
- Focused SVE targeting three discrete 4 m elevations; and
- Air/ozone sparging enhancement within a discrete 4 m elevation above the groundwater table.

5.2 PILOT TREATABILITY STUDY

The pilot treatability study was designed to evaluate remediation of the unsaturated zone and zone of periodic water table fluctuation by SVE methods for the removal of volatile organic compounds (VOCs). Both conventional SVE in long screened wells and focused SVE targeting discrete elevations in the Chalk were evaluated.

Enhancements to the basic SVE methods were tested including thermally enhanced SVE and air/ozone sparging. The trials of the SVE enhancements followed initial operation of the SVE systems alone to provide data to assess the added value of the enhancements for VOC mass removal.

The nature of contaminants at the WSA, including a range of VOCs and semi-volatile organic compounds (SVOCs), the distribution of contaminants as NAPL on fissure surfaces and dissolved in pore water, and the large vertical range of periodic water table fluctuations at the site necessitated the consideration of SVE enhancements to maximise remedial performance.

Heating the Chalk increases the volatility of both VOCs and SVOCs within the matrix by a factor of 3-10. The volatility is directly interrelated with the vapour pressure and Henry's law constant, however it is contaminant dependent and may vary significantly in particular for high boiling point compounds. Thermal enhancement also potentially facilitates the mobilisation of organic contaminants trapped in chalk pore water into fissures by causing the expansion of pore water as it turns to steam. These mobilised contaminants can then be drawn from the formation by the SVE system (Bierschenk et al., 2008). In view of the low permeability and heterogeneous nature of the Chalk, the range and nature of contaminants present within the Chalk and the depth of contaminated strata, Thermal Conductive Heating (TCH) was considered to be the most appropriate thermal enhancement technology to be trialled at the site.

Consideration was also given to the potential for air/ozone sparging to enhance SVE by mobilising VOCs from below the water table during periods of high water by stripping VOCs from groundwater and the surfaces of submerged NAPL coated fissures into the unsaturated zone, where they can be extracted by the SVE system. The addition of ozone potentially results in supplementary *in situ* destruction of VOCs below the water table and reduced loading on the off-gas carbon treatment system.

5.3 DRILLING OPERATIONS

A total of 18 boreholes were sunk utilising rotary techniques as part of the initial design works at locations shown on Figure 3.1. A summary of the purpose, depth, diameter and installation details related to each of the boreholes is given in Table 5.1 below.

Table 5.1: Boreholes and installations utilised for pilot trials and remediation design

Borehole Number	Purpose	Depth (m)	Core Barrel Diameter (mm)	Installation Details
CH1/SVE1	Characterisation and SVE Well for thermal enhancement trial	18.0	143	100 mm ID stainless steel casing, solid from 0.0 m to 6.0 m, slotted from 6.0 m to 18.0 m with thermocouples at 6.0 m, 12.0 m and 17.5 m
CH2/SVE2	Characterisation and SVE Well for focused high vacuum extraction and air/ozone sparging enhancement trial	19.0	101	100 mm ID HDPE solid casing to 6.0 m
CH3	Characterisation and sparging well	24.8	101	100 mm ID HDPE solid casing to 6.0 m
CH4	Characterisation	21.6	101	100 mm ID HDPE solid casing to 6.0 m
CH5	Characterisation	21.9	101	100 mm ID HDPE solid casing to 6.0 m
CH6	Characterisation	22.0	101	100 mm ID HDPE solid casing to 6.0 m
CH7	Characterisation	22.0	101	100 mm ID HDPE solid casing to 6.0 m
CH8	Characterisation	22.0	101	100 mm ID HDPE solid casing to 6.0 m
PM1	Pressure and Temperature Monitoring	18.0	101	Thermocouple and pressure monitoring points at 6.0 m, 12.0 m and 17.5 m
PM2	Pressure and Temperature Monitoring	18.9	101	Thermocouple and pressure monitoring points at 6.0 m, 12.0 m and 17.5 m
PM3	Pressure and Temperature Monitoring	18.0	116 to 10.2 m then 101	Thermocouple and pressure monitoring points at 6.0 m, 12.0 m and 17.5 m
PM4	Pressure Monitoring	19.0	116	Pressure monitoring points at 6.0 m, 12.0 m and 17.5 m
PM5	Pressure Monitoring	18.3	101	Pressure monitoring points at 6.0 m, 12.0 m and 17.5 m
T1	Temperature Monitoring	19.0	116	Thermocouples at 6.0 m, 12.0 m and 17.5 m
T2	Temperature Monitoring	19.0	116	Thermocouples at 6.0 m, 12.0 m and 17.5 m
HW1	Heater Well	20.5	146	76.2 mm ID solid stainless steel casing sealed at base at 19.5 m and 19 mm ID galvanised steel pipework with thermocouples at 6.0 m, 12.0 m and 17.5 m
HW2	Heater Well	20.5	146	76.2 mm ID solid stainless steel casing sealed at base at 19.5 m.
HW3	Heater Well	20.5	146	76.2 mm ID solid stainless steel casing sealed at base at 19.5 m and 19 mm ID galvanised steel pipework with thermocouples at 6.0 m, 12.0 m and 17.5 m

Notes:

ID – Internal diameter

HDPE – High density polyethylene

5.4 WELL CONSTRUCTION

5.4.1 SVE AND SPARGE WELL

On completion of the characterisation boreholes a permanent casing was installed to facilitate subsequent use as SVE wells. Characterisation boreholes CH1 and CH2 were re-designated SVE1 and SVE2 for use in the Phase 1 pilot trials. Characterisation borehole CH3 was designated for use as the sparge well for the sparging trial.

The SVE1 well was sunk using water flush rotary coring through the centre of Pit No.3 to a total depth of 18 m bgl and was utilised for the conventional SVE and thermal enhancement trials. Pit backfill material was penetrated to 3 m depth over weathered Grey Chalk. Full details of the nature of the strata and rock fractures encountered are given on the SVE1 borehole record included as an example in Appendix 1. The well was constructed of 100 mm-diameter stainless steel casing to 6 m bgl and screened from 6 m bgl to 18 m bgl. Thermocouples were installed on the side of the casing at depths of 6.0 m, 12.0 m and 17.5 m for temperature monitoring during the thermal enhancement trial

SVE2 was sunk between Pit Nos. 1 and 2 and CH3 was located through the centre of the backfilled Pit No.2. Both wells were installed with solid 100 mm ID HPDE casing to approximately 6 m below ground level and were drilled to depths of 19.0 m bgl and 24.8 m bgl respectively.

5.4.2 MONITORING WELLS

A total of seven monitoring wells were constructed, two for pressure monitoring designated PM4 and PM5, two for temperature monitoring designated T1 and T2 and three for joint pressure and temperature monitoring designated PM1, PM2 and PM3. The installation details are summarised in Table 5.1.

The effective radii of the SVE systems were monitored with multi-level pressure monitoring points set at three elevations (5.5 m to 6.5 m, 11.5 m to 12.5 m and 17.0 m to 18.0 m bgl) on a radius extending horizontally from each SVE well at 4 m, 8 m and 12 m (Figure 5.1). The monitoring points comprised stainless steel sintered pots attached to 8 mm outside diameter (OD) polytetrafluoroethylene (PTFE) tubing set within a sand pack extending over the target interval with cement/bentonite grout between intervals and above the monitoring intervals to the surface.

The lateral and vertical temperature variation within the rock mass in the vicinity of the thermal enhancement trial was monitored by means of thermocouples set at three elevations (5.5 m to 6.5 m, 11.5 m to 12.5 m and 17.0 m to 18.0 m bgl) on a radius extending horizontally from SVE1 well at 0.69 m, 1.71 m, 4.17 m, 8 m and 12 m (Figure 5.1 and Plate 5.1). The thermocouples were set within a sand pack extending over the target interval with cement/bentonite grout between intervals and above the monitoring intervals to the surface.

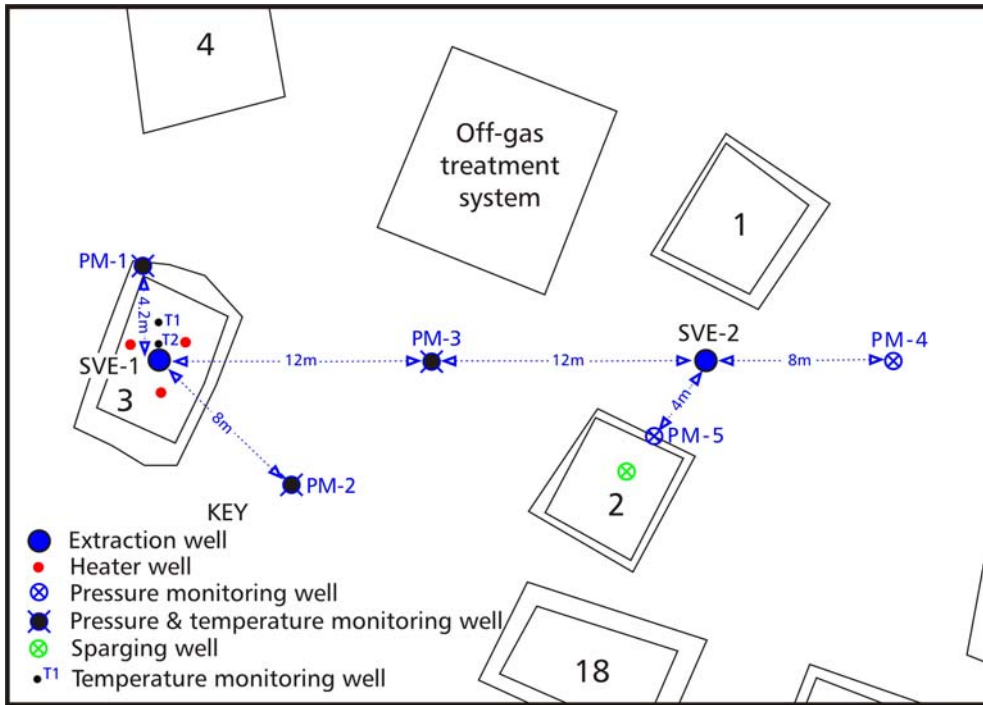


Figure 5.1: Pilot trial layout



Plate 5.1: Pilot trial heater wells, extraction well and temperature monitoring wells

Thermocouples were also installed on the SVE1 well casing and two of the three heater well casings as well as the SVE1 well head and surface pipe work exiting from the heat exchanger.

5.4.3 HEATER WELLS

Three heater unit boreholes were arranged at the corners of an equilateral triangle with 2.5 m sides centred around the SVE1 well installed through the centre of Pit No.3 (Figure 5.2 and Plate 5.1). The heater wells were drilled to a depth of 20.5 m and installed with 76.2 mm ID solid stainless steel casing sealed at base at

19.5 m and 19 mm ID galvanised steel pipework containing thermocouples fixed at depths of 6.0 m, 12.0 m and 17.5 m.

Heater elements consisting of a loop of approximately 12.5 mm diameter high temperature stainless steel alloy rod fitted with ceramic isolator beads along their length were lowered into each heater well by mobile crane to a depth of 19 m. The upper 5 m of the elements were composed of nickel 'cold' sections of low electrical resistance.

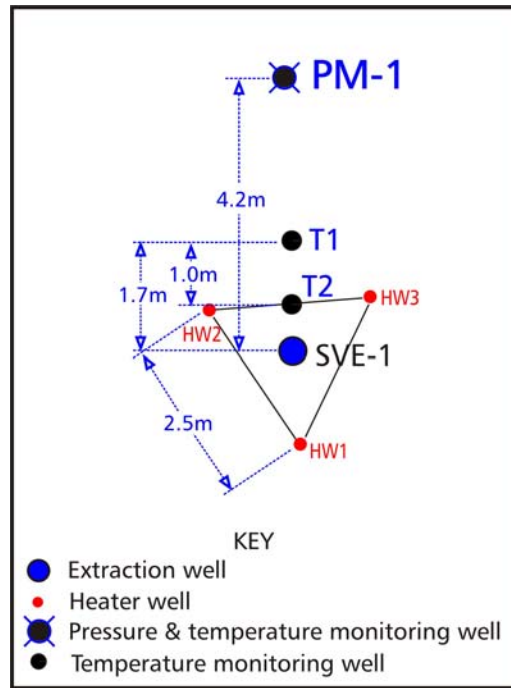


Figure 5.2: Pilot trial heater well layout

5.5 PILOT TRIAL PLANT AND EQUIPMENT

5.5.1 SVE AND SPARGING PLANT

The pilot trial SVE off-gas extraction (Plate 5.2) and treatment system included the following:

- A 500-600 m³/hr capacity ATEX Category 3 high vacuum blower unit including two rotary vane vacuum ATEX certified pumps housed in an acoustically lined ISO container;
- ATEX rated level controls and automatic regulator valves, a detonation flame arrestor, an infra-red Lower Explosive Limit (LEL) detection system with gas sampling system;
- A control panel with Programmable Logic Controller (PLC) and telemetry with SMS text message alerts for fault functions;
- Air/water knockout tank with fluid transfer pump including a level control system with high level shut-off;
- Five foul water storage tanks (approximately 1,000 litre capacity);
- A compressor for unit instruments and sparging;
- Three vapour phase granular activated carbon (GAC) units (two of approximately 1.5m³ capacity and one of approximately 3m³);
- 30 m vacuum pipework and Stortz connections from 2 SVE wellheads to pilot treatment unit;
- Headworks for connection of pipework to 2 SVE wells, fitted with sample ports; and
- Outlet blower had sampling valve fitted for determination of both airflow and inlet concentrations to GAC.

Additional equipment for sparging operations included an oxygen bottle, ozone generator and compressor.

Suction at each wellhead was manually controlled by a restrictor ball valve. The treatment plant was generally inspected daily by a trained operator, who undertook routine operational performance and maintenance checks. The operator also undertook routine soil gas, temperature and wellhead pressure monitoring from dedicated installations.



Plate 5.2: Pilot trial SVE plant

5.5.2 THERMAL PLANT

Equipment utilised specifically as part of the thermal enhancement trials included the following:

- Breakers, switchgear and relays;
- Silicon Controlled Rectifiers (SCRs) for controlling power to heater elements;
- Thermocouples for controls;
- Three thermal lances, heated section from 5 m to 19 m bgl;
- Heater cables; and
- A heat exchanger capable of condensing the extracted steam during thermally enhanced SVE operations.

5.6 CONVENTIONAL SVE TRIAL

5.6.1 CONVENTIONAL SVE TRIAL FIELDWORK

The conventional SVE trial was carried out utilising characterisation borehole CH1 which was subsequently designated well SVE1. The well was constructed through the centre of Pit No.3 in the western part of the site (see Section 5.4 and Figure 5.1).

The trial commenced with a step test and continued for an 11 day period without any equipment faults, or other delays or interruptions.

Monitoring during the high volume SVE trial was undertaken generally in accordance with the monitoring plan given in Table 5.2 below.

Table 5.2: Conventional SVE monitoring

Measuring Point	Method	Frequency	Quality Control	Use of Data
Subsurface pressure	Manually	3 per day for first three days, then daily or as required	Weekly data review	Radius of influence of the SVE
SVE VOC concentration	Manually/ laboratory analyses	3 per day for first three days, then daily or as required	Daily calibration Lab QA/QC Weekly data review	Mass flux and treatment performance
SVE flow	Manually	3 per day for first three days, then daily or as required	Daily calibration Lab QA/QC Weekly data review	Mass flux
Groundwater level	Manually	1 – 2 per week	Weekly data review	Water inflow

5.6.2 STEP TESTS

Step tests assist in system design by identifying the relationship between the applied vacuum and the resulting flow from extraction wells. The data can be utilised to select blowers and estimate vacuums needed to achieve a subsurface flow. A step test is performed by starting the SVE system at the minimum flow rate and increasing the flow in steps, taking vacuum (or pressure) measurements at the well field monitoring points during each step.

Each test comprised three steps of one hour duration, altering the amount of fresh air dilution as follows:

- Step 1 – Minimum flow rate
- Step 2 – 50% Dilution
- Step 3 – Dilution valve closed

The results of well field pressure monitoring undertaken during the two step tests, together with details of wellhead vacuum, air flow rate and off-gas concentrations are given in Table 5.3 below.

Table 5.3: Summary of step test results

WELL & STEP	Wellhead		Off Gas ppm	Well Field Pressure (-Pa) Distance From Well												
	Flow m ³ /hr	Vac -kPa		4 m			8 m			12 m			24 m			
				T	M	B	T	M	B	T	M	B	T	M	B	
SVE1	1	92	9.0	114	0	0	0	0	0	0	0	0	0	0	0	0
	2	109	14.1	173	0	0	0	0	0	0	0	0	0	0	0	0
	3	179	35.6	370	0	0	0	0	0	0	0	50	0	0	0	0
SVE2	1	80	1.6	33	50	50	100	0	0	0	0	50	50	0	0	0
	2	243	9.4	170	150	250	650	0	0	0	50	200	250	0	0	50
	3	302	13.7	190	200	400	950	0	0	50	100	300	400	0	0	100

Notes

- T = Top pressure monitoring point at 6 m below ground level
- M = Middle pressure monitoring point at 12 m below ground level
- B = Bottom pressure monitoring point at 17.5 m below ground level

Each step was applied for one hour, allowing sufficient time for conditions to equilibrate. In order to evaluate the well efficiencies at the various vacuum/flow conditions, the flow rate was divided by the wellhead vacuum to give specific capacity values. The results of the two step tests revealed considerable heterogeneity both laterally and vertically at the site. A significantly greater radius of influence (ROI) was apparent at SVE2 compared to SVE1. However, it should be noted that during the course of the subsequent thermal enhancement trial the ROI at SVE1 increased significantly.

5.6.3 CONVENTIONAL SVE TRIAL OBSERVATIONS

Contaminant mass removal rates decreased from 9 kg/day at the commencement of the trial to 4 kg/day after two days of operation. Thereafter a gradual decrease in mass removal rate was recorded, falling to a minimum of 1.8 kg/day at the end of the 11 day trial (see Figure 5.3). The wellhead vacuum and air flow rate remained relatively constant during the course of the trial at approximately -35 kPa and 200 m³/hr respectively.

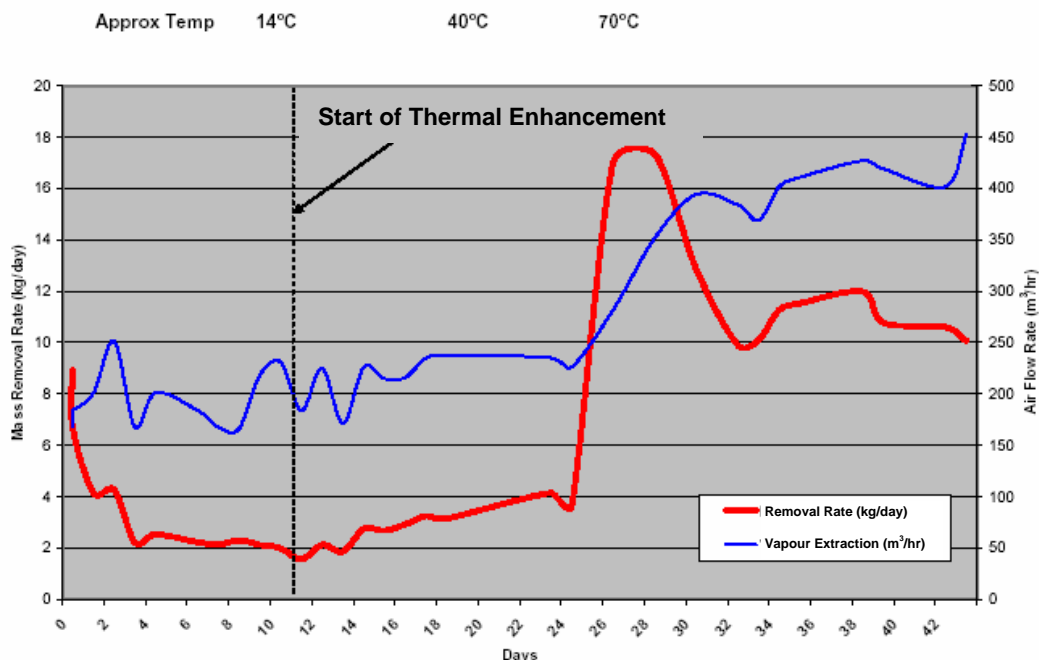


Figure 5.3: Contaminant mass removal and extraction rates during pilot trials

Relatively small negative pressures were recorded within the monitoring well field during the course of the trial. Pressures were generally of the same order as those recorded during the third step test, although a slight increase in negative pressure was detected locally towards the end of the trial, notably the middle well monitoring point, 4 m from the SVE well which increased to approximately -250 Pa.

Mass removal rates increased steadily following commencement of heating reaching a maximum of 17 kg/day after 14 days. This peak coincided with the rock mass temperature reaching the approximate co-distillation point of the predominant contaminant (TCE). Removal rates then decreased over the following 7 days until reaching a relatively consistent concentration at approximately 10 kg/day to 12 kg/day (Figure 5.3).

5.6.4 LABORATORY ANALYSIS OF OFF-GAS FROM CONVENTIONAL SVE TRIAL

Laboratory analysis of off-gas samples taken during the conventional SVE trial revealed the presence of significant concentrations of tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (TCA) and toluene.

5.7 THERMALLY ENHANCED SVE TRIAL

5.7.1 THERMALLY ENHANCED SVE TRIAL FIELDWORK

The thermally enhanced SVE trial was carried out as a continuation of the conventional SVE trial described above utilising well SVE1. Three heater unit boreholes were arranged in a triangle with two 2.5 m sides centred around the SVE1 well installed through the centre of Pit No.3 (see Section 5.4.3, Figures 5.1 and 5.2).

The thermally enhanced SVE monitoring programme included manual and automated measurements designed to control the system and gather data for system evaluation. Specific actions undertaken are outlined in Table 5.4.

Table 5.4: Thermally enhanced SVE monitoring

Measuring Point	Method	Frequency	Quality Control	Use of Data
Subsurface temperatures	Manually	3 per day for first three days, then daily or as required	Regular assessment, weekly data review	Temperature distribution in the subsurface
Heater temperatures	Automatic Manually	Continuous Daily	Weekly data review	Power input control
Subsurface pressure	Manually	3 per day for first three days, then daily or as required	Weekly data review	Radius of influence of the SVE
SVE concentration	Manually/laboratory analyses	3 per day for first three days, then daily or as required	Daily calibration Lab QA/QC Weekly data review	Mass flux
SVE flow	Manually/laboratory analyses	3 per day for first three days, then daily or as required	Daily calibration Lab QA/QC Weekly data review	Mass flux and energy balance
Groundwater level	Manually	1 – 2 per week	Weekly data review	Water inflow
Vapour stream temperature	Manually	1 – 2 per working day	Weekly data review	Energy balance
Condensate production rate	Manual reading	Daily or as required	Weekly data review	Mass flux and energy balance
Condensate concentration	Grab samples	Every 3 days or as required	Weekly data review	Mass flux
NAPL volume separated from condensate	Manual gauging	Daily or as required	Weekly data review	Mass flux
NAPL concentrations	Grab samples	Every 3 days or as required	Weekly data review	Mass flux

Temperatures of heater wells HW1 and HW3 were monitored separately. Three thermocouples were installed along each heater at depths of 6 m, 12 m, and 18 m below ground level.

Subsurface temperatures were monitored manually using type K thermocouples and hand-held readers.

5.7.2 THERMAL ENHANCEMENT PILOT TRIAL DIMENSIONS

The dimensions of the pilot test treatment zone in cross-sectional and plan views are shown in Figure 5.4. Red columns and circles represent heater borings, the green circle is the central SVE well and black dots are thermocouple monitoring locations.

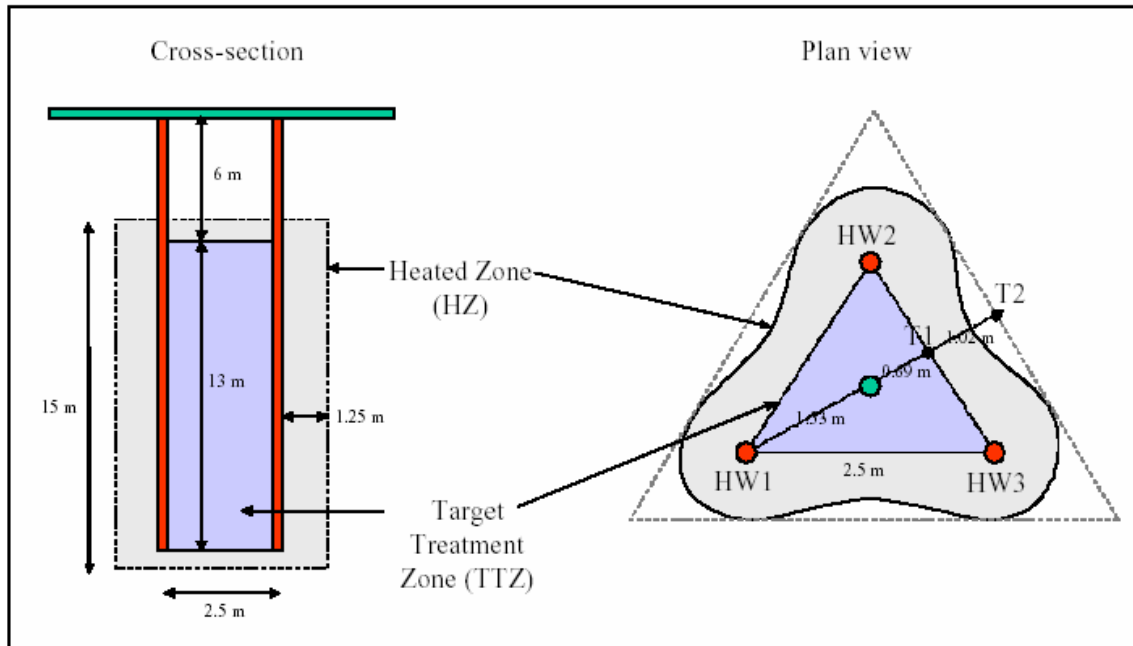


Figure 5.4: Thermal enhancement pilot trial dimensions

The Target Treatment Zone (TTZ) is defined by the triangle spanned by the heater borings, coloured light blue on the plan view drawing above. The zone that actually heats up significantly, the Heated Zone (HZ), is larger and irregularly shaped, this zone is coloured light grey. This zone is used for the mass and energy balance calculations presented in the following sections. The temperature monitoring locations, shown as black dots, were used to determine the dimensions used in the calculations.

Table 5.5 below summarises the volumes of the two zones. Note that an assumption about the size of the heated zone had to be made, based on field observations of temperatures at different distances to the central SVE well.

Table 5.5: Thermal enhancement pilot trial dimensions

	Target Treatment Zone	Heated Zone
Area	2.71 m ²	8.1 m ²
Upper depth	6 m	5 m
Lower depth	19 m	19 m
Volume	35.2 m ³	121.8 m ³

5.7.3 WATER MASS BALANCE METHODS

The water mass balance is calculated as follows:

$$M_{\text{extraction}} = M_{\text{out, liquid}} + M_{\text{out, vapour}}$$

where M denotes cumulative water masses.

The mass removal in the liquid form is a simple summation of flow rate measurements:

$$M_{\text{out, liquid}} = \sum (m_{\text{liquid}} \times \Delta t)$$

where the values for the flow rate m_{liquid} can be derived from a pump stroke counter or a water flow meter. Alternatively, M can be recorded periodically using a totalising flow meter, and the flow rate m calculated:

$$m = (M_2 - M_1)/(t_2 - t_1)$$

Where 1 and 2 represent the first and next data recording, respectively, and t is the time of the meter reading.

The water mass removal in the form of vapour (steam, water vapour) is calculated either by the liquid production rate in the condenser using a totalising flow meter, or from vapour flow rates determined by pitot tubes or equivalent:

$$M_{\text{out,vapour}} = \Sigma (m_{\text{steam}} \times \Delta t) = \Sigma (m_{\text{total vapour}} - m_{\text{non-cond}}) \times \Delta t$$

where m_{steam} is the vapour flow rate made up of steam, $m_{\text{total vapour}}$ is the total incoming vapour flow rate, and $m_{\text{non-cond}}$ is the vapour flow rate after the condenser (air mostly).

Figure 5.5 illustrates the streams that take part in the water mass balance. The red arrows represent the streams which can be quantified by field measurements.

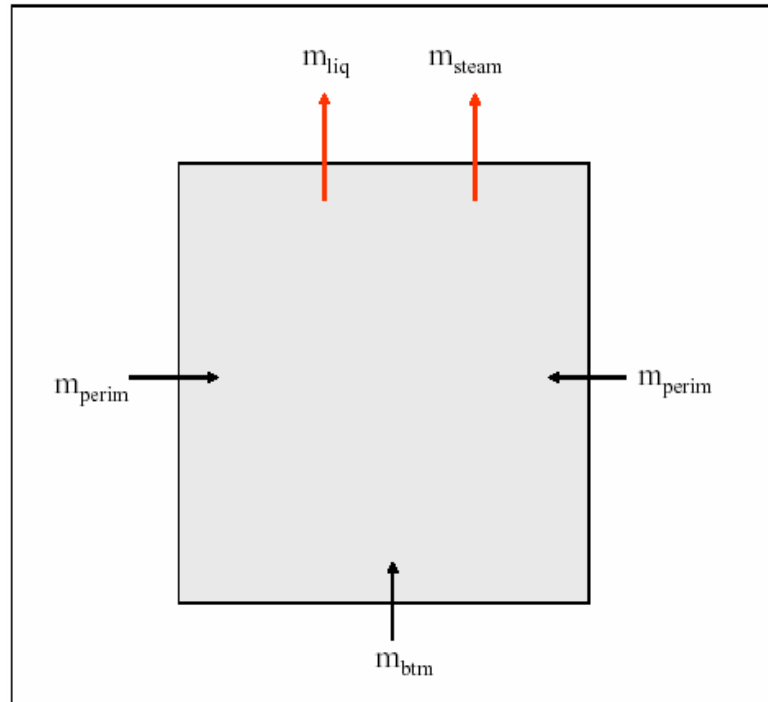


Figure 5.5: Mass balance principles for water. Note m_{perim} , m_{btm} denotes mass perimeter and mass bottom.

Total water extraction rates are estimated by the sum of the measured flows:

$$m_{\text{extraction}} = m_{\text{liquid}} + m_{\text{steam}}$$

There is no reliable way of estimating the volume or mass of water stored in the TTZ or HZ, or to measure the influx of water from the sides, bottom, or top by infiltration (the perimeter and bottom arrows shown on Figure 5.5). Thus, the only reliable measure is the quantity of water removed from the subsurface. This quantity can be compared to a relatively accurate estimate of the pre-treatment quantity of water within the TTZ and HZ, based on values of porosity and saturation for the different zones below the vapour cap and to total depth.

The total extracted volume can be compared to an estimate of the initial water content of the heated zone. Since 4540 litres were extracted, and the estimate of initial pore water in the HZ is 26,000 litres, approximately 20% of the pore water was removed as steam or as entrained water.

It was assumed that all the water accumulating in the liquid separator was extracted as steam. Therefore, no liquid water was included in this mass balance. In reality, some of the extracted water could have been entrained as liquid. This would upset the mass and energy balance calculations slightly.

5.7.4 ENERGY BALANCE ESTIMATION METHODS

Cumulative energy (E) is calculated as a summation of enthalpy fluxes (Q):

$$E = \sum (Q \times \Delta t)$$

An estimated energy balance is expressed as:

$$E_{in} = E_{out} + E_{storage} + E_{loss}$$

The energy fluxes are related for each time step as follows:

$$Q_{in} = Q_{out} + Q_{storage} + Q_{loss}$$

Where Q denotes enthalpy flux (in BTU/hr or Watts).

Figure 5.6 illustrates the streams that take part in the energy balance. The red arrows represent the streams which can be quantified by field measurements.

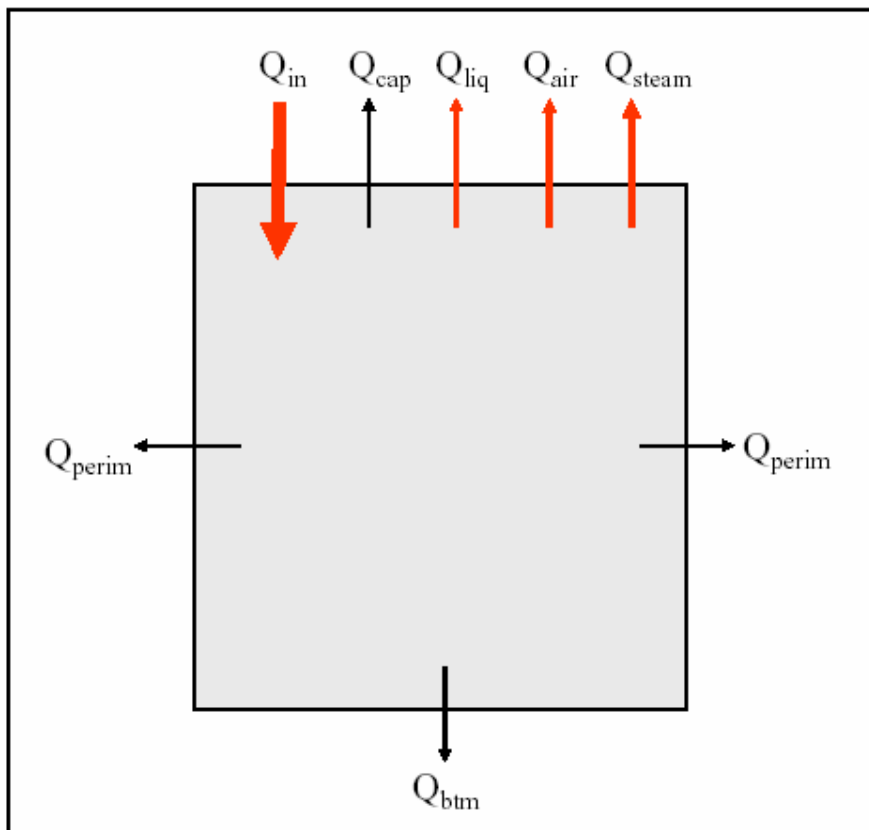


Figure 5.6: Energy balance schematic. Note Q_{cap} denotes Q captured (storage), see equation above.

For electric power, energy increments are estimated as follows:

$$Q_{in} = (Meter_2 - Meter_1) / (t_2 - t_1)$$

Where Meter denotes an electrical meter reading in kWh, and t denotes times of meter readings. Note that this meter reading must be after where the power is split between the process, lighting, office etc, and the ISTD well-field. Alternatively, the power usage of the surface facilities needs to be well known, so that this can be subtracted.

For the Harwell pilot test, a totalising meter was not used. Instead, the amperage to the heaters was recorded. From these values, the power input P was estimated as:

$$P = U \times I$$

Where U is voltage (assumed 230 V) and I is the amperage recorded in the log sheets, minus the estimated 3 Amps drawn by the heat exchanger.

The total energy removal from the heated volume is estimated as follows:

$$Q_{out} = Q_{liq} + Q_{non\ cond.\ gas} + Q_{steam\ out}$$

The energy flux in the extracted liquid is given by:

$$Q_{liq} = m_{liquid} \times c_{p, water} \times (T - T_0)$$

Where c_p is heat capacity, and T_0 is the ambient temperature.

For the extracted vapour stream, the energy flux in vapour and steam should be estimated based on treatment system data:

$$Q_{non\ cond.\ gas} = m_{air} \times c_{p, air} \times (T - T_0)$$

$$Q_{steam\ out} = m_{condensate} \times \Delta H_{steam-ambient}$$

Where m is mass flux, H is specific enthalpy (in BTU/lb), c_p is heat capacity (in BTU/lb/F), and T is temperature. The enthalpy of the steam can be estimated from steam tables, using a steam pressure of 14 psia, and an ambient temperature of 15°C:

$$\Delta H_{steam-ambient} = (1,150 - 20) \text{ BTU/lb} = 1,130 \text{ BTU/lb}$$

The actual heat loss cannot be calculated using accurate measures. However, an estimate can be made based on thermal profiles at the bottom and top of the treatment cell, and along the perimeter, using the following calculations:

$$Q_{heat\ loss} = A \times K_T \times dT/dz$$

where A is the surface area through which energy is conducted, K_T is the thermal conductivity of the subsurface material near the TTZ boundary, and dT/dz is the temperature gradient also expressed as $(T_1 - T_2)/(z_1 - z_2)$.

Heat loss calculations through the top, bottom and sides are accounted for by using a volume larger than the TTZ volume for the heat capacity calculations. The outer boundary HZ is set at one half well spacing farther out than the TTZ boundary (1.25 m in this case). This is a relatively approximate assumption (Figure 5.4).

Figure 5.7 shows energy flux (power) and cumulative energy balance for the pilot test.

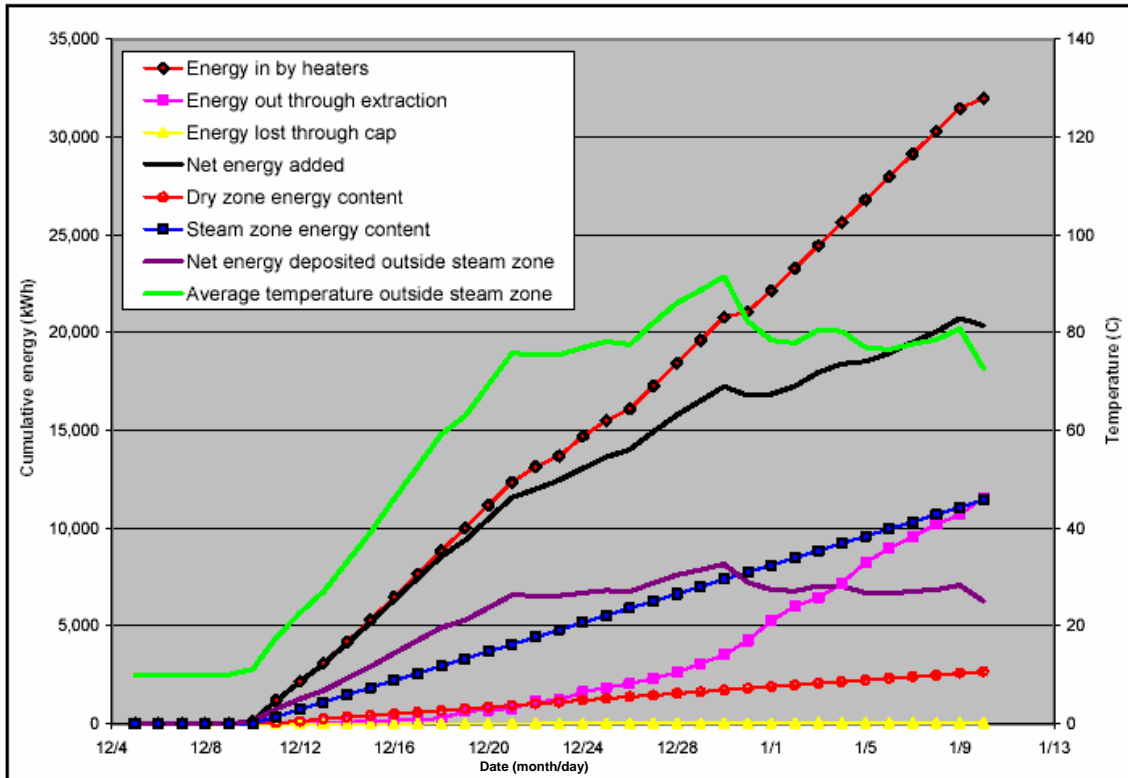


Figure 5.7: Energy flux results from energy balance calculations

The stored energy is related to the heated zone heat capacity, and the measured average temperature as follows:

$$E_{\text{storage}} = C_{p,\text{site}} \times (T_{\text{avg}} - T_0) + m_{\text{steam}} \times \Delta H_{\text{steam-ambient}}$$

Where $C_{p,\text{site}}$ is the overall heat capacity of the heated zone, estimated from the volume, saturation, and specific heat capacity of the soil and water:

$$C_{p,\text{site}} = V_{\text{soil}} \times C_{p,\text{soil}} + V_{\text{water}} \times C_{p,\text{water}}$$

The steam energy stored as a vapour at any given time is relatively small, and will be neglected in the calculations. For comparison with the measured temperatures, the energy balance can be used to estimate the average temperature ($T_{\text{energybal}}$) of the heated volume:

$$T_{\text{energybal}} = T_0 + E_{\text{storage}}/C_{p,\text{site}} = T_0 + (E_{\text{in}} - E_{\text{out}} - E_{\text{loss}})/C_{p,\text{site}}$$

which is the light green curve shown in Figure 5.7. Unless the assumptions are off or the site has unexplained heat losses, this estimated average temperature should be close to the true *in situ* average temperature. Major discrepancies indicate excessive heat losses, such as:

- Water flow through the site carrying energy away from the target zone.
- Escape of steam to surrounding areas through high-permeability corridors.
- Larger than expected surface heat losses.

It should be noted that the average temperature can only be estimated from thermocouples if the thermocouple network has a distribution that represents the whole volume and is properly sealed within the soil matrix. This is not the case for this pilot test, since only a few thermocouple locations were monitored. Therefore, a more refined calculation is necessary to close the energy balance.

The zones immediately around the heaters will be very hot and dry. That means that a more accurate account of the energy stored can be obtained by a summation such as:

$$E_{\text{storage}} = \sum (V_{\text{local}} \times C_p \times (T_{\text{avg,local}} - T_0))$$

Where V_{local} denotes a volume around the heater, c_p is the specific heat capacity of that volume, and $T_{\text{avg,local}}$ is the average temperature of that volume. Since the temperature distribution around the heaters may be approximated as a linear curve with the heater element temperature at a radial distance of 0 m, and steam temperature at the distance where the wet zone begins, the only other information required is the radius of the dry cylinder around the heater, the heater temperature, and the dry specific heat capacity of the soil.

The schematic temperature profile around a heater well is shown in Figure 5.8.

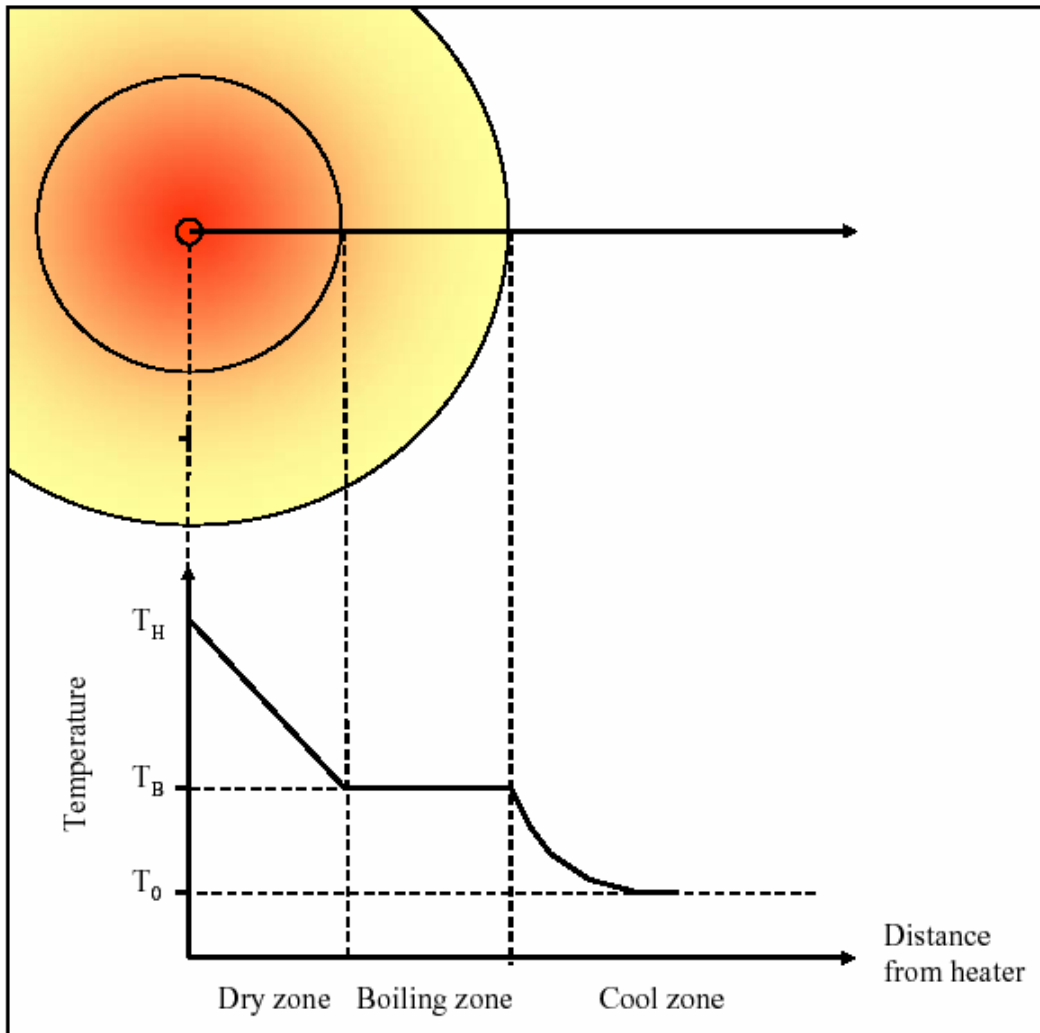


Figure 5.8: Schematic temperature distribution around each heater well

The energy used to heat the dry zone is the heat of vaporisation of the water initially present, plus the energy stored in the dry soil. The energy needed to boil the water is estimated based on the initial water content. The second contribution is derived from a solution for the differential equation

$$dE = 2\pi H c r dr ((T_B - T_0) + (T_H - T_0) (1-r/R)) \text{ integrated from } r = 0 \text{ to } r = R$$

The solution is:

$$E = \pi H c R^2 ((T_B - T_0) + 1/3 (T_H - T_B))$$

where H is the depth of the heated zone, c is specific heat of the dry soil, R is the radius of the dry zone, and T_H and T_B are the heater element temperature and the boiling point, respectively. It should be noted that this is less than what would result if the average temperature along the radius of the borehole is applied, since there is a much larger volume of soil radially farther away than close to the well.

The energy content in the boiling zone (or steam zone) is estimated based on the heat capacity of the native material and the temperature rise. Since the actual saturation in this zone varies from zero right next to the dry zone to 1 where the cooler zone begins, an average value for the heat capacities of dry and wet rock is used. In addition, an energy content necessary to boil 50% of the water in this zone is added, based on the assumption that the average saturation in the boiling zone is 0.5.

These calculation methods were used in preparation of the energy balance. The average temperature calculated is for the area outside the dry zone and the steam zone surrounding each heater. Based on this rather crude energy balance, the average temperature in the HZ volume is estimated as approximately 80°C near the end of the pilot test. Due to the heterogeneous distribution of temperature, and the sparsity of thermocouples in the ground, a direct comparison to measured temperatures is not possible. However, the energy balance shows that while the TTZ was heated adequately, the entire heated zone did not reach sufficient temperatures to achieve boiling in the whole volume. This will be discussed further below.

5.7.5 OBSERVED TEMPERATURES

During the first 2 weeks of heating, several of the heater can thermocouples stayed around 100°C, which is characteristic of the zones where steam is being formed, and where the material surrounding the heaters is drying. When the water is removed by boiling, the temperature of the surrounding rock starts to increase above 100°C. Towards the end of the pilot test, heater temperatures reached approximately 400°C - 500°C in the middle thermocouples in heater wells HW3 and HW1, and the deepest thermocouple in HW1. The shallow zones remained somewhat cooler, indicating that they heated less rapidly, which may be attributable to shallow airflow, or conductive heat losses at the top of the heaters. These temperature developments are typical of ISTD operations. However, during a full-scale project higher temperatures are typically reached by heating for a more prolonged period, and by having more overlap (superposition) of the heated zones than was possible in this small demonstration.

The upper thermocouple in the SVE well heated to around 97°C during the last week of operations. However, the bottom and middle intervals remained below 70°C. The SVE manifold remained at temperatures below 65°C throughout operations. For comparison, during typical full-scale thermal treatment, temperatures in the coolest locations are between 90°C and 100°C, and the extracted vapours reach temperatures between 95°C and 100°C. The relatively modest manifold temperature could be caused by the un-insulated metal manifold pipe exposed to the weather. The high temperature at the shallow thermocouple is in good agreement with the energy balance and the amount of condensate recovered, which indicates that a significant amount of steam was produced and extracted.

Thermocouple string T1 is located midway between two heaters, 1.25 m from each. During the course of heating, temperatures rose to around 70°C, followed by a decrease to 45°C. This behaviour may possibly be explained by increasing air flow and cooling in the middle region. Measured air flow rates at the manifold increased significantly midway through the heating period (Figure 5.3). Such increased air flow affected the subsurface temperatures and could have been caused by increased permeability of a zone, either by steam produced during heating displacing fines, or by the development of fractures due to the fluid flow. It is also possible that the flattening of the temperature curves in the SVE well was caused by the increased flow of cool air into the pilot test area. In a full-scale TESVE application, an outer ring of heaters typically extends

beyond the perimeter of the TTZ, such that the effect of cool air flow from outside the heated zone would have little if any effect on the temperatures of the interior of the TTZ.

5.7.6 LABORATORY ANALYSIS OF OFF-GAS

Laboratory analysis of off-gas samples taken during the TESVE trial detected concentrations of a wider range of contaminants compared to the conventional SVE trial, these included tetrachloroethene (PCE), trichloroethene (TCE), 1,1-dichloroethene (DCE), cis-1,2-dichloroethene (DCE), 1,1,1-trichloroethane (TCA), 1,1-dichloroethane (DCA), dichloromethane, dibromomethane, toluene and m/p xylene.

5.7.7 LABORATORY ANALYSIS OF CONDENSATE

Chloroform was the predominant VOC removed within the condensate with concentrations of up to 0.54mg/l. Total concentrations of VOCs detected within the condensate reduced slightly as the trial progressed, falling from 2.2 mg/l to 1.5 mg/l.

5.8 FOCUSED SVE TRIAL

The focused high volume SVE trials were undertaken utilising characterisation borehole CH2 which was subsequently designated well SVE2. The well was constructed within the open area between Pit No.1 and Pit No.2 in the western part of the site (see Section 5.4 and Figure 5.1).

The focused high volume trials were operated for a period of 9 days including 3 three-day intervals extracting from shallow, intermediate depth and deep SVE zones. The three zones were as follows:

- Shallow Zone: 6.2 m to 10.3 m bgl (4.1 m long zone);
- Intermediate Zone: 10.3 m to 14.4 m bgl (4.1 m long zone); and
- Deep Zone: 14.8 m to 19.0 m bgl (4.2 m long zone).

The shallow and intermediate focused zones were sealed by means of an inflatable double packer lowered into the well by means of a tripod and winch. The bottom packer was removed for formation of the deep focused zone with a single packer. The packers were 72 mm in diameter and were inflated by injection of water via a hand pump.

Limited benefits of focused high volume extraction were apparent from the trials. This was due to a number of factors including:

- The variable distribution of contaminant concentrations within the Chalk strata and Chalk fissures;
- No apparent significant increase in radius of influence achieved;
- No apparent significant increase in contaminant removal rate achieved; and
- Additional costs in construction of well installations.

Focused SVE application could have been successful if:

- Contamination would have been concentrated at particular depths, not disseminated within the entire strata; and
- The soil matrix did not present highly fractured and fissured properties, where potential contamination could have been trapped.

5.9 FOCUSED SVE TRIAL WITH AIR/OZONE SPARGING ENHANCEMENT

The focused high volume SVE trial with air/ozone sparging enhancement was carried out as a continuation of the focused deep high volume SVE trial utilising well SVE2.

An air/ozone sparging well (CH3) was constructed to a depth of 24.8 m bgl immediately beneath Pit No.2 - located 6 m south west of SVE2 well (see Section 5.4 and Figure 5.1).

Free product was encountered within well CH3 and the nearby RSRL monitoring well HWS58, some 11 m to the west. Attempts were made to remove the free product through the utilisation of skimming. This delayed the commencement of the sparging enhancement trial until after completion of the thermal enhancement trial. On completion of the skimming operations approximately 5 mm and 30 mm of free product were present within wells CH3 and HWS58 respectively.

The air/ozone mixture was delivered through nylon tubing to a porous sparge head suspended within the groundwater at the bottom of the sparge well.

A greater vacuum, flow rate and radius of influence (ROI) was apparent following re-commencement of the focused deep high vacuum trial in January 2006 compared to values recorded during the initial focused trials undertaken in November 2005. This reflects an opening up of subsurface pathways during the course of the trials.

Limited benefits of air/ozone sparging were apparent from the trials. This was due to a number of factors including:

- No apparent significant increase in contaminant removal rate achieved;
- No increase in off-gas volatile constituents' concentrations;
- Low groundwater levels, reducing the saturated zone volume treated; and
- Additional costs in operation of sparging installations.

5.10 ESTIMATION OF ROCK PERMEABILITIES AND RADIUS OF INFLUENCE

5.10.1 COMPUTER MODELLING

An evaluation of the pilot trial data was performed using a two dimensional analytical radial air flow porous media model (MDFIT – developed by Marley, Fengming and Droste of Envirogen Inc in 1994) in addition to empirical observations of the data.

The pressure distribution data along with other parameters such as well construction details and depth to groundwater were used as inputs into the 2-D radial porous media model to estimate the horizontal and vertical permeabilities in the trial area. During each model run, a calibration was performed to ascertain whether the model predicted vacuums (as a function of distance from the SVE well), provided reasonable approximation to the field measured vacuums. The estimated soil permeabilities are presented in Tables 5.6 and 5.7.

Table 5.6: Chalk permeability estimates Model Run 1

Well	Trial	Chalk Permeability (m ²)		Kz/Kr
		Horizontal (Kr)	Vertical (Kz)	
SVE1	High Volume	7.0E-13	1.0E-10	142
	High Volume with Thermal Enhancement	9.0E-12	1.0E-10	11
SVE2	Focused Shallow	4.5E-12	3.2E-10	71
	Focused Intermediate	7.1E-12	4.0E-10	56
	Focused Deep	8.9E-12	3.5E-10	39

Notes

Soil permeabilities determined using a 2-D porous media model

Kz/Kr = Vertical to horizontal permeability ratio

Chalk permeabilities were determined based on a groundwater table depth of 18 m

Permeability for thermally enhanced trial was determined at temperature of 15°C

Chalk Porosity assumed as 0.35

Table 5.7: Chalk permeability estimates Model Run 2

Well	Trial	Chalk Permeability (m ²)		Kz/Kr
		Horizontal (Kr)	Vertical (Kz)	
SVE1	High Volume	6.0E-13	1.1E-10	186
	High Volume with Thermal Enhancement	4.7E-12	1.7E-10	36
SVE2	Focused Shallow	4.7E-12	2.6E-10	55.5
	Focused Intermediate	6.5E-12	4.4E-10	67
	Focused Deep	7.3E-12	3.2E-10	44

Notes

Soil permeabilities determined using a 2-D porous media model

Kz/Kr = Vertical to horizontal permeability ratio

Chalk permeabilities were determined based on a groundwater table depth of 21.3 m

Permeability for thermally enhanced trial was determined at temperature of 45°C

Chalk Porosity assumed as 0.25

5.10.2 GENERAL OBSERVATIONS

The field vacuum distribution shows a very asymmetrical air flow pattern, representative of the fractured rock environment. The field vacuum data also indicates (based on the low vacuum or low vacuum gradient) that the air is likely flowing vertically to the well screen over a more limited radius than may be suggested by the porous media air flow model results.

The model calibration supports that the system is behaving as if there is no effective surface cover. This result supports that the air is readily available to flow vertically to the wells. However the poor sealing of the wells has been ruled out during the field testing works. This is more likely a result of rubble zones in the rock and/or surface features such as the backfilled pits.

The field data also show certain pressure monitoring points indicating a vacuum and yet others, closer to the SVE well show no or equal vacuum development, supporting preferential air flow or dead ends (no vacuum gradient) even along a single plane (PM3 to PM4).

The data collected from PM4, situated 8 m east of SVE2, suggest that this well is isolated from the system (i.e. there is very limited or no detectable vacuums observed at PM4 from any of the SVE trials).

5.10.3 NON-THERMALLY ENHANCED CONDITIONS

Under non-thermally enhanced conditions, the horizontal Chalk permeability (Kr) ranged from $6.0 \times 10^{-13} \text{ m}^2$ to $8.9 \times 10^{-12} \text{ m}^2$ (or 0.6 Darcys to 9 Darcys) and the vertical Chalk permeability (Kz) ranged from $1.0 \times 10^{-10} \text{ m}^2$ to $4.4 \times 10^{-10} \text{ m}^2$ (or 101 Darcys to 446 Darcys).

The high Kz/Kr ratio (approximately two orders of magnitude) determined from the analyses suggests a dominant Kz/Kr component of vertical flow occurring around the wells. This would be interpreted as a proportionally higher percentage of the air flow to the well is coming vertically down in close proximity to the well.

5.10.4 THERMALLY ENHANCED CONDITIONS

Under thermally enhanced conditions, the calculated horizontal Chalk permeability (Kr) ranged from $4.7 \times 10^{-12} \text{ m}^2$ to $9.0 \times 10^{-12} \text{ m}^2$ (or 5 Darcys to 9 Darcys) and the vertical Chalk permeability (Kz) ranged from $1.0 \times 10^{-10} \text{ m}^2$ to $1.7 \times 10^{-10} \text{ m}^2$ (or 101 Darcys to 172 Darcys).

The horizontal permeability in the vicinity of SVE1 increased by factors of 13 and 8 for Run 1 and Run 2 of the model respectively during the heating process. This is likely to be a result of the moisture removal during the trial. No significant increase in the vertical permeability was detected. However, the vertical to horizontal permeability ratio (Kz/Kr) is still greater than an order of magnitude, which continues to support a proportionally higher vertical flow of air to the well.

5.10.5 EFFECTIVE RADIUS OF INFLUENCE

A pore volume exchange rate rationale to illustrate the effectiveness of contaminant removal by SVE is conceptually similar to groundwater flushing of contaminants in soil. Clean air that is drawn through the soil acts as a vehicle for the transport of the contaminant from the soil into the vapour phase and thereby providing contaminant mass removal. In the absence of running a three dimensional theoretical model to estimate the mass removal rate, empirical observations by Xpert Design and Diagnostics LLC (XDD) have supported that 500 to 2000 pore volumes are required to significantly decrease the mass of the contaminant in the soils, assuming that mass transfer limitations are not dominant.

To develop a SVE system design, the air pore volume exchange rate as a function of the Radius of Influence (ROI) was estimated. For design purposes, and as described above, an air exchange rate of 1000 pore volumes per year is considered acceptable for effective SVE system operation.

The data analysis revealed that an effective ROI of approximately 2.5 m to 3 m is provided by the conventional SVE trial in SVE1. Under thermally enhanced conditions, the effective ROI increases (as a result of improved horizontal permeability) to approximately 6 m. The horizontal permeability has increased as a result of boiling off the pore water between the soil fractures which helped to exposed new air channels within the fractured rock.

The pore volume exchange analysis for the focused trials undertaken in SVE2 shows that the projected effective ROI falls between 3 m and 4.5 m with an increase in the effective ROI with depth.

5.11 EVALUATION OF RATE MASS TRANSFER LIMITED CONDITIONS

XDD LLC was commissioned by AIGE to perform analyses to determine how the measured vapour concentration from the thermally enhanced SVE trial could be interpreted with respect to rate limiting conditions.

As stated above, it was determined that there is sufficient evidence to support that the rate limiting conditions, resulting from the presence of preferential air flow pathways, exist at the site.

Additional analyses were performed on the field measured vapour concentrations during the thermally enhanced SVE trial to ascertain the presence of other rate limiting conditions.

Field measured vapour concentrations as a result of the thermal enhancement process were compared with projected theoretical vapour concentrations at field measured temperatures. The data analysis established that with an increase in temperature, the field measured vapour concentrations initially closely follow the theoretically generated concentrations. However, with increased temperature (which equates closely to test time), the actual measured concentrations deviate further (are slightly lower) from the theoretical values. The analysis also illustrated the following observations on the actions of thermal enhancement:

- The initial fluctuation in off-gas VOC concentrations in vapour phase were found to decline with time, due to the likelihood of rapid depletion of accessible contaminant; and
- The significant fluctuations in off-gas VOC vapour concentrations also would support the projected significant vertical (clean) air influx into the SVE well and the associated limited effective ROI.

5.12 PILOT TRIAL MASS REMOVAL ASSESSMENT

Off-gas sample analysis undertaken revealed it to contain a mix of contaminants and therefore a correction factor has to be applied to the PID monitoring reading.

The correction factor for a mixture (CF_{mix}) is calculated from the sum of the mole fractions of each component divided by their respective correction factors for the PID and lamp. Mole fractions for individual components were determined for gas samples obtained during conventional "cold" SVE and during thermally enhanced SVE. The CF_{mix} values determined were 0.57 and 0.51 respectively as detailed in Table 5.8.

Table 5.8: Determination of the correction factor for a mixture (CF_{mix})

VOC	CF 11.7eV Lamp	Mol wt (g/mole)	Mole Fraction (X)		X/CF	
			Non-thermal	Thermal	Non-thermal	Thermal
Tetrachloroethene	0.31	165.8	0.15	0.2	0.48	0.65
Trichloroethene	0.43	131.4	0.25	0.2	0.58	0.47
1,1-dichloroethene	0.8	96.9	0	0.025	0.0	0.03
cis-1-2-dichloroethene	0.8	96.9	0	0.025	0.0	0.03
1,1,1-trichloroethane	1.0	133.4	0.5	0.3	0.50	0.30
1,1-dichloroethane	0.6	99.0	0	0.025	0.0	0.04
Dichloromethane	0.89	84.9	0	0.025	0.0	0.03
Dibromomethane	0.6	187.9	0	0.025	0.0	0.04
Toluene	0.51	92.2	0.1	0.15	0.20	0.29
p/m Xylene	0.39	106.2	0	0.025	0.0	0.64
Sum X/CF					1.76	1.94
$1/CF_{mix}$					0.57	0.51

An appearance of the new chemicals during the thermally enhanced SVE is apparent when compared to the non-thermal unenhanced SVE. In particular the halogenated aromatic and aliphatic hydrocarbons, with the lower volatilisation potential and higher boiling point temperature have commenced to be recovered during the thermal treatment, as presented in Figure 5.9 below.

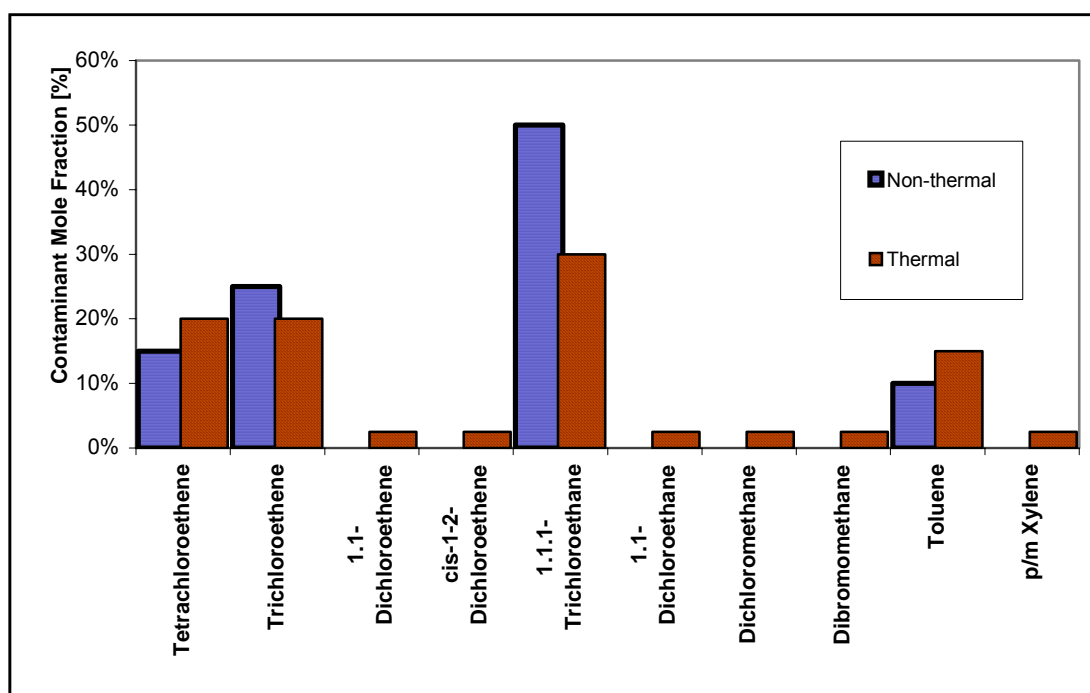


Figure 5.9: Contaminant mole fraction comparison for thermal and non-thermal phase

The following formula is used to convert from corrected parts per million (ppmv) values to contaminant concentration terms of mass per unit volume (mg/m³):

$$\text{Concentration (mg/m}^3\text{)} = \frac{(\text{Concentration \{ppmv\} X molecular wt \{g/mole\})}{\text{Molar gas volume \{L\}}}$$

For air at 25°C, the molar gas volume is 24.4 L/mole.

From determination of the air flow rate, calculated from the air flow velocity measurements and a knowledge of the pipe diameter at the monitoring point, the total mass of contaminants removed per day can therefore be established.

The approximate rate and total mass of VOCs removed has been calculated based on the following calculation:

$$\text{Average Mass Removal Rate (kg/day)} = \frac{(\text{Concentration \{mg/m}^3\} \text{ X Flow Rate \{m}^3\text{/hr\} X 24hr)}{10,000,000}$$

This has been equated for each individual period as detailed in Table 5.9 below.

Table 5.9: Estimation of rate and total mass of VOCs removed

Trial	Flow Rate (m ³ /hr)	Measured Concentration (ppm)	Correction Factor (CF _{mix})	Corrected Concentration (ppmv)	Trial Duration (Hours)	Average Removal Rate (kg/day)	Trial Total (kg)
High Volume Non Thermal	200	200	0.57	114	266	3.0	33
High Volume Thermal	300	350	0.51	180	744	6.9	214
Focused Shallow	180	90	0.57	51	70	1.2	3.5
Focused Intermediate	260	135	0.57	77	52	2.6	5.7
Focused Deep	250	150	0.57	85	73	2.8	8.5
Focused Deep with Sparging	420	75	0.57	43	217	2.4	21

The average mass of VOCs removed has been calculated for each consistent period during the unenhanced (high volume, focused deep and shallow) and enhanced air sparging and thermal treatment intervals. During each technological trial similar flow rates were maintained, however the duration was significantly longer for the thermally enhanced treatment, therefore the average mass removal rate was presented as the rate per day value. The high volume thermal treatment has demonstrated between two and six times higher mass performance removal rates in comparison to the unenhanced and air enhanced technologies. This indicates significantly better overall treatment effectiveness for the chlorinated solvent removal at the site.

5.13 INTERPRETED TEMPERATURE DISTRIBUTION AT END OF HEATING PERIOD

On the basis of the thermal monitoring data, the interpreted distribution of temperature in the vicinity of SVE1 well during the thermal enhancement trial at Pit No.3 is shown in Figure 5.10.

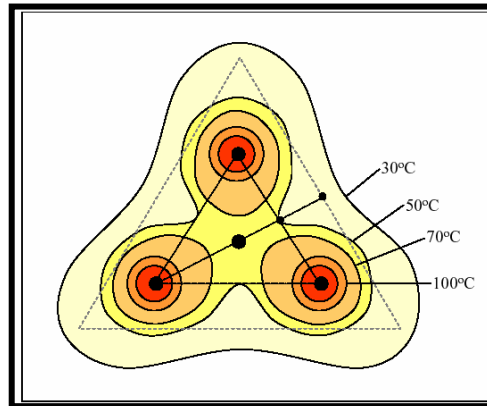


Figure 5.10: Temperature distribution at the end of heating interpreted based on observed thermocouple readings and the energy balance at Pit No.3

The dry zones around the heaters were estimated to have a radius of approximately 0.3 m. The steam zone radius was estimated at 0.6 m at the end of the pilot test. Around each heater, temperatures drop off with distance. The centre of the triangle, where the SVE is located, heated to approximately 50°C - 70°C, except for the upper interval which heated to 95°C.

While this heating was sufficient to achieve significant increases in vapour-phase removal of VOCs, it should be noted that the achieved temperatures are much lower than for a typical full-scale project which could potentially achieve temperatures of 90°C - 100°C throughout the target treatment volume. A typical full-scale TESVE temperature distribution for a VOC remediation project is shown in Figure 5.11.

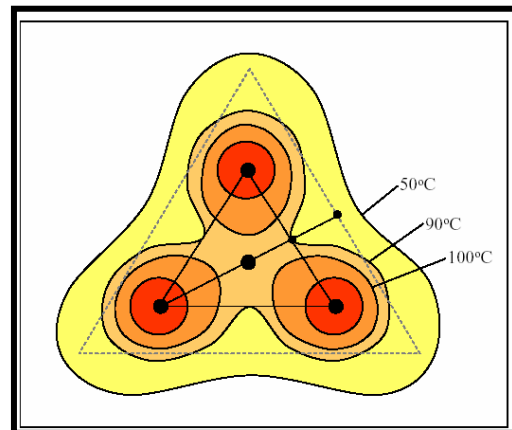


Figure 5.11: Temperature distribution at the end of a typical ISTD treatment project for the same boring configuration. Note that the central SVE well reaches temperatures between 90°C and 100°C.

Note that the inner triangle is above 90°C. The SVE well would reach temperatures between 90°C and 100°C, depending on the vacuum applied. Such high temperatures lead to boiling of all DNAPL and removal as a vapour. It also leads to boiling of a significant volume of pore water, leading to a steam drive towards the extraction well, carrying contaminants in the vapour phase.

5.14 OPTIONS FOR INCREASED MASS REMOVAL

The temperatures in both the SVE well and T1 and T2 increased during the test, but levelled out towards the end, indicating that the pilot volume would not heat much more without a change in the operational strategy. Such changes could have included:

- Addition of heaters;
- Increase of the power input to each heater; and
- Reduction in the vapour extraction rate (lower vacuum applied to extraction well, eliminating the adverse cooling effect).

The small scale and limited timeframe of the pilot test meant that the full potential of the heating could not be realised. However, the primary goal of demonstrating the capability of TESVE to substantially increase mass removal was met.

Figure 5.12 shows a schematic representation of the temporal variation in average TTZ temperature, extracted vapour VOC concentration, and cumulative mass removed for a typical full-scale TESVE project. The inserted lines indicate how far the pilot test progressed in relation to a typical full-scale project. The main points are:

- Temperatures achieved in the TTZ outside the steam zone were in the 50°C - 80°C range, which is much cooler than full-scale TESVE treatment temperature of 100°C. This means that steam was not generated throughout the pilot TTZ, which would result in less mass removal in the pilot than would be typical in a full-scale TESVE project.
- Vapour concentrations had begun to increase during the pilot trial, but since steam temperatures were not reached throughout the TTZ, it is possible that the maximum VOC removal rates which can be achieved were not reached.

The higher temperatures and mass removal rates observed during full-scale TESVE works are caused by a combination of factors:

- More overlap (superposition) of heated zones since each SVE well is surrounded by at least 6 heater wells, leading to more complete heating to steam temperatures;
- Longer duration of operation;
- Lower air extraction rates per SVE well;
- Interim sampling used to optimise operation and assess when to cease heating; and
- Full-scale systems are operated until diminishing returns in the vapour stream indicates that little mass is left in the ground (typically 2 to 4 months).

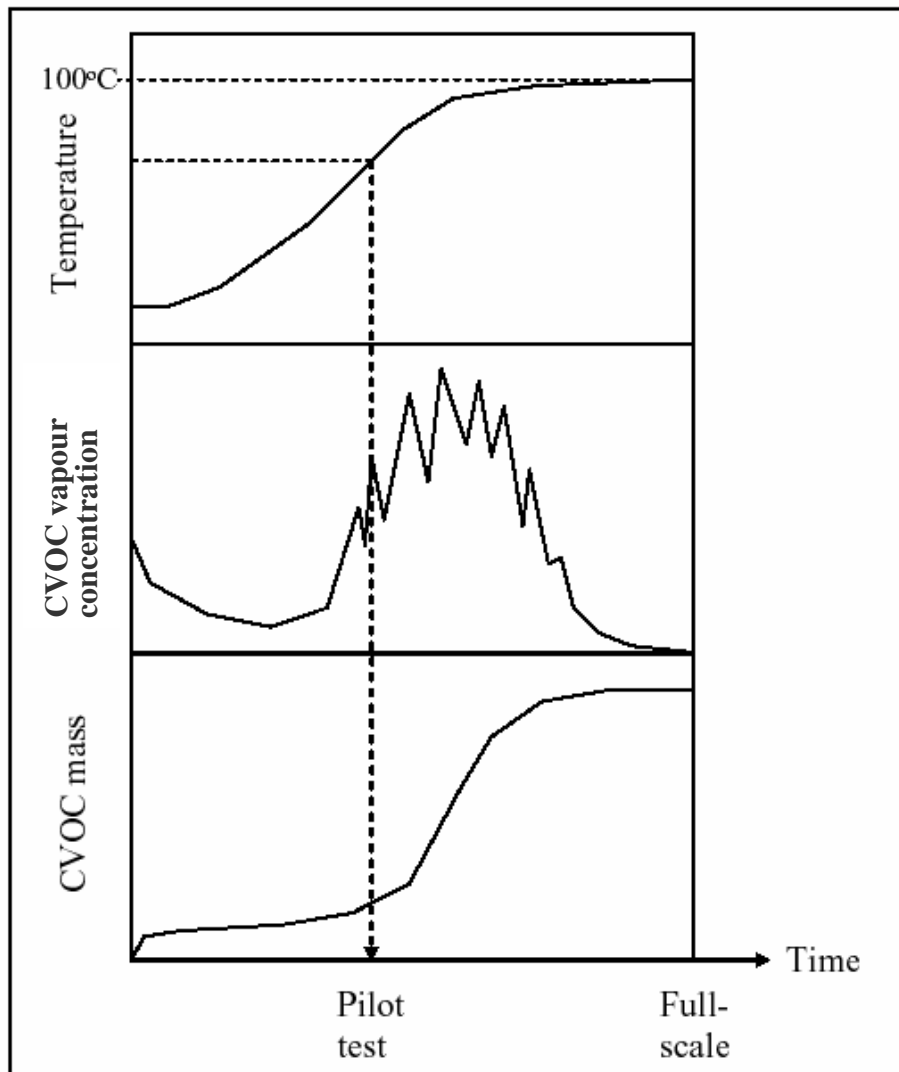


Figure 5.12: Schematic of variations in temperature, vapour concentration and total mass removal during a typical TESVE project

5.15 CONCLUSIONS AND RECOMMENDATIONS FROM THE PILOT TRIALS

Significant benefits of thermal enhancement to SVE were apparent from the trials. This could be due to a number of factors including:

- Increased contaminant mass removal rates resulting from contaminant mobilisation by:
 - Displacement as a NAPL;
 - Vaporisation and extraction in the vapour phase (predominantly for the more volatile constituents of the NAPL); and
 - Dissolution and desorption and removal with the extracted pore water.
- Increased horizontal permeability due to removal of moisture within the Chalk, with a resultant increase in radius of influence.

At this site it was anticipated that considerable benefits could be achieved in the utilisation of thermal enhancement of SVE operations in the immediate vicinity of the former disposal pits where high concentrations of contaminants were detected throughout the underlying unsaturated zone. However outside the pit areas operational costs were considered likely to limit the cost effectiveness of this technique.

On the basis of the findings of the pilot trials and previous studies undertaken on the site it was recommended that full-scale remediation of the unsaturated zone was undertaken within the Western Storage Area comprising the following:

- Soil vapour extraction across the central and western parts of the site in the vicinity of the former disposal pits; and
- Thermal enhancement of soil vapour extraction in areas of gross contamination notably beneath the footprint of the most severely contaminated disposal pits.

An extraction well spacing of 3 m to 6 m was recommended on the basis of the pilot trial data obtained. It was recommended that extraction wells were constructed so that they could subsequently be utilised as thermal enhancement heater wells where appropriate.

6. SET-UP AND OPERATION OF FULL-SCALE THERMALLY ENHANCED SVE

6.1 REMEDIATION STAGES

Remediation work focused on Pit Nos. 1, 2 and 3 and this vicinity of the site (as shown in Figure 3.1). The works were undertaken in a yearly cycle matching both water table fluctuations and available funding according to the stages summarised below.

From the 2006/2007 financial year funding:

- Conventional SVE from seven wells at and surrounding Pit No.3 (eight weeks);
- Heating and thermally enhanced SVE at Pit No.3 (first heating stage) and conventional SVE from wells in the intermediate area between Pit Nos.2 and 3 immediately to the east (fifteen weeks); and
- Continued thermally enhanced SVE at Pit No.3 following cessation of heating (first cool down stage) and conventional SVE from wells at and surrounding Pit No.2 further to the east of Pit No.3 (three weeks).

From the 2007/2008 funding:

- Continued thermally enhanced SVE at Pit No.3 following cessation of heating and conventional SVE from wells at and surrounding Pit No.2 as well as in the intermediate area between Pit Nos.1 and 2 further to the north of Pit No.2 (four weeks);
- Site shut down due to high groundwater levels during which time the rock mass beneath Pit No.3 remained in the range 34°C to 44°C (twelve weeks);
- Conventional SVE from seven wells at and surrounding Pit No.2 (one week);
- Continued thermally enhanced SVE at Pit No.3 and conventional SVE from seven wells at and surrounding Pit No.2 (two weeks);
- Additional air and ozone sparging enhanced SVE trials at Pit No.2 due to unseasonably high groundwater levels (four weeks);
- Heating and thermally enhanced SVE at Pit No.3 (second heating stage) and conventional SVE from wells at and surrounding Pit No.2 as well as in the intermediate area between Pit Nos.1 and 2 (four weeks);
- Continued thermally enhanced SVE at Pit No.3 following cessation of heating (second cool down stage) (two weeks);
- Continued thermally enhanced SVE at Pit No.3 and conventional SVE from wells in the intermediate areas between Pit Nos.2 and 3 and between Pit Nos.1 and 2 (one week);
- Continued thermally enhanced SVE at Pit No.3 following cessation of heating (two weeks); and
- Continued thermally enhanced SVE at Pit No.3 and conventional SVE from wells in the intermediate areas between Pit Nos.2 and 3 and between Pit Nos.1 and 2 (five weeks).

From the 2008/2009 funding:

- Additional monitoring, analysis and verification works at Pit No.3.

6.2 EXTRACTION AND HEATER WELL CONSTRUCTION

6.2.1 DRILLING OPERATIONS

A hexagonal extraction/heater well configuration was adopted, producing a series of four hexagons, some of which overlapped, as shown on Figures 6.1 and 6.2 and as summarised below:

- Wells 201 to 206 - installed at the perimeter of Pit No.3, centred around Phase 1 Well SVE1 (also known as Characterisation Well CH1);
- Wells 206 to 211 - installed in the area between Pit Nos.3 and 2, centred on RSRL monitoring well HWS58;
- Wells 212 to 217 - installed in the area at the perimeter of Pit No.2, centred around Phase 1 Well SP1 (also known as Characterisation Well CH3); and
- Wells 217 to 222 - installed in the area between Pit Nos.2 and 1, centred around Phase 1 Well SVE2 (also known as Characterisation Well CH2).

The wells were constructed in a hexagonal pattern to optimise heater and extraction efficiency.

Each location was initially sunk by open hole drilling with an air mist flush using an 203 mm (8") bit and temporary steel casing to a depth of 2 m below ground level.

Permanent 150 mm diameter casing was installed in each well and secured with grout. The casing was installed to facilitate SVE headworks construction and provide an effective seal between the atmosphere and the extraction zone during the vapour extraction process.

Each well was then advanced by open hole drilling with an air mist flush using a 136 mm (5³/₈") bit to a depth of 18 m below ground level.

Wells that were also considered to be utilised as heater wells were installed in a triangular pattern with a smaller spacing between them of approximately 1.5 m. This was in comparison to the standard extraction well, where the average distances ranged between 3 m - 4 m. A central well (SVE1) was located in the middle of the thermally targeted triangle, to serve as a main extraction well for the thermal treatment zone. The additional extraction wells were installed to serve as supplementary extraction points for further assessment of the contaminated pits.

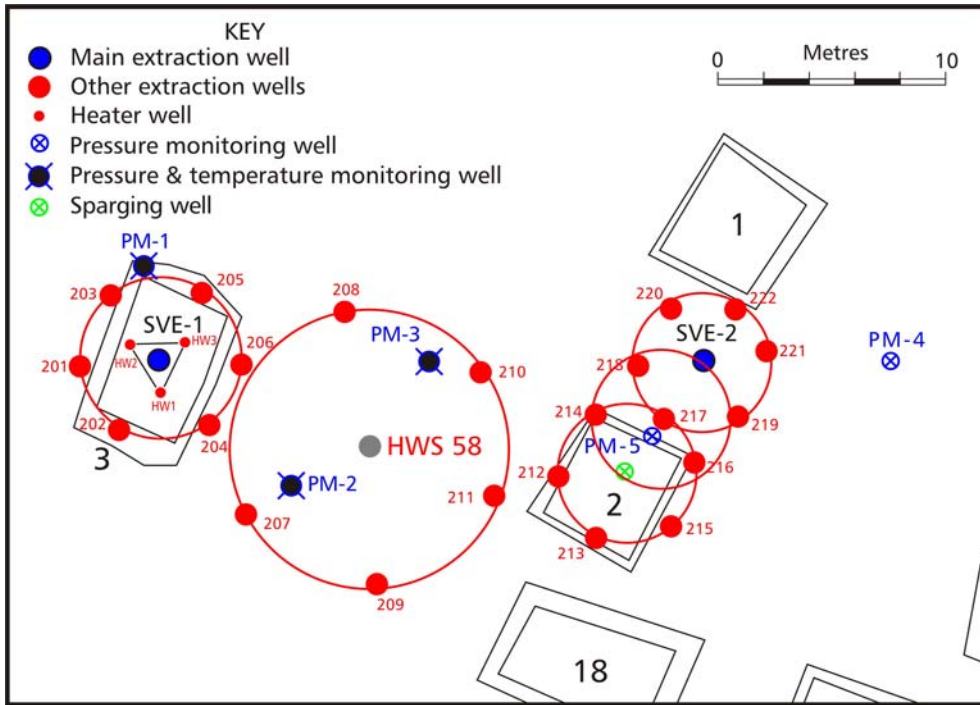


Figure 6.1: SVE well layout

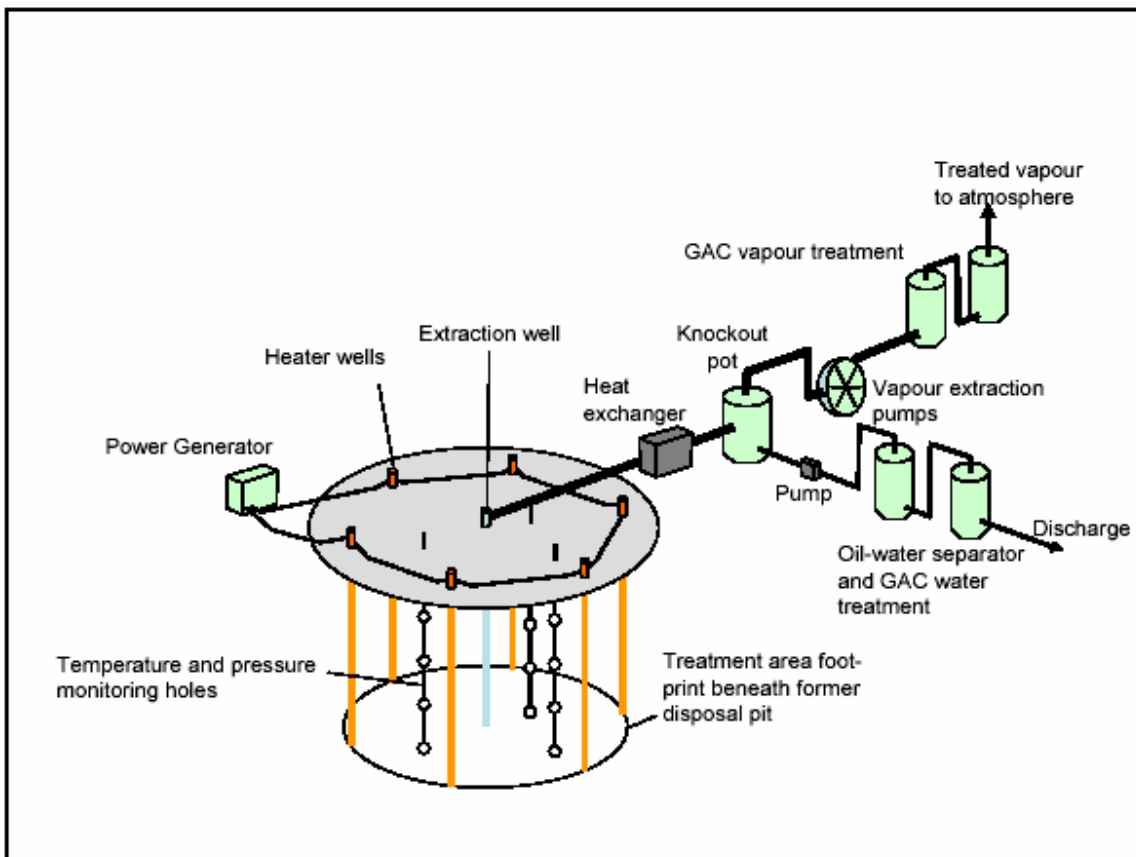


Figure 6.2: Schematic showing TESVE plant layout

6.2.2 HEATER WELL CONSTRUCTION AND MODIFICATION

Following completion of the un-enhanced stage of SVE works undertaken in autumn 2006, Wells 201 to 206 were converted from extraction wells to heater wells by the installation of 15.7 m long, 76.2 mm diameter stainless steel casing sealed at the base. The casing was lowered into place by a mobile crane and surrounded with a sand pack within the annulus and grouted in place at the surface.

Heater elements consisting of a 15.6 m long loop of approximately 10 mm diameter high temperature stainless steel alloy rod (10 m long) fitted with ceramic isolator beads along their length (Plate 6.1) were lowered into each of these heater wells by mobile crane to a depth of 15 m below ground level. The upper 5.6 m of the elements were composed of nickel 'cold' sections of low electrical resistance.

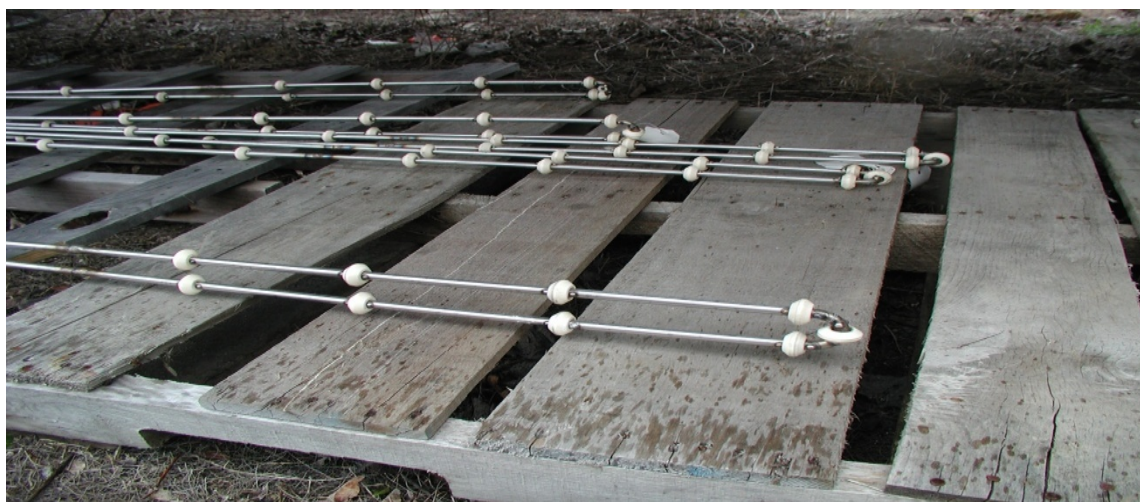


Plate 6.1: Heater rods

Heater wells installed as part of the 2005/2006 pilot trials (HW1 to HW3) were also utilised during the remediation works. Modifications to these wells were necessary due to presence of groundwater within the heater well casings following winter 2006/07. The modifications comprised the installation of 20 m long, 63.5 mm diameter stainless steel sleeves sealed at the base. Electrical continuity tests carried out on one of the rods indicated a short between heater rod and heater can. On inspection it was found that the base of this rod was warped. The warped basal material was removed and a new basal length of steel rod was welded in place and the repaired heater rod was craned into position. Further modifications were subsequently undertaken to prevent condensate escaping from the annulus between the original casing and the liner sleeve at the neck of wells HW1 to HW3. These modifications comprised the installation of pipework to divert condensate from the annulus to the SVE1 extraction well.

Due to the unseasonably high groundwater level during the summer of 2007 an attempt was made to raise the longer heaters HW1 to HW3 by one metre. This was successful for heaters HW1 and HW3 but the casing extension at HW2 could not be attached and was therefore left at the former level.

6.3 SVE PLANT OPERATION AND MAINTENANCE

Extraction wells were connected to the SVE plant via dedicated headworks, flexible hoses, control valves and manifold. The SVE plant was contained within a dedicated ISO container (Plate 6.2) with associated condensate collection system and off-gas granular activated carbon (GAC) treatment vessels.

The SVE off-gas extraction and treatment system included the following:

- An 1800 m³/hr capacity ATEX Category 3 high vacuum blower unit including six rotary vane vacuum ATEX certified pumps housed in an acoustically lined ISO container;
- ATEX rated level controls and automatic regulator valves, a Lower Explosive Limit (LEL) detection system with gas sampling system;

- A control panel including telemetry system with SMS text message alerts for fault functions;
- Air/water knockout tank with fluid transfer pump including a level control system with high level shut-off;
- Oil/water separator and liquid phase GAC unit;
- Vapour phase GAC units (Plate 6.3);
- Associated vacuum pipework and connections from SVE wellheads to treatment unit; and
- Headworks for connection of pipework to SVE wells, fitted with sample ports.

Suction at each wellhead was manually controlled by a restrictor ball valve.

Full documentation of the process and details of the quality control and quality assurance programmes implemented as part of the *in situ* treatment process were included in an operation and maintenance manual, kept on site at all times. The following quality assurance checks were undertaken generally on a daily basis to ensure the effectiveness of treatment:

- Vacuum extraction pressure and airflow rates achieved at each SVE wellhead, confirming negative (suction) pressure and enabling calculation of airflow achieved at each wellhead;
- Routine diagnostic checks on operational equipment, including water level in condensate tank; and
- Checking suction achieved at blower inlets, suction manifolds and wellheads, to ensure satisfactory vacuum maintained at wellheads with no loss of pressure throughout system.

An inspection of the *in situ* treatment system was undertaken at least once every week of operation, to ensure optimal performance of the treatment system. This routine maintenance included the following:

- Checking all compression fittings, tightening connections for all wellheads, suction lines/manifolds where necessary;
- Addition of oil to motorised components where necessary;
- Replacement of off-gas abatement media where required; and
- Checking all electrical connections and control systems.



Plate 6.2: SVE extraction system



Plate 6.3: GAC off-gas treatment system

6.4 THERMAL PLANT OPERATION AND MAINTENANCE

Details of the heaters utilised in the remediation works are summarised in Table 6.1.

Table 6.1: Pit No.3 heater details

Heater No.	Installation Date	Heater Details	Heater Can Details	Heated Zone (m bgl)
HW1	Nov 2005	18.4 m long loop of 10 mm diameter stainless steel alloy rod (14 m long) fitted with ceramic isolator beads along length with upper 4.4 m composed of nickel 'cold' sections of low electrical resistance	76.2 mm ID stainless steel casing sealed at base at 19.5 m with. 20 m long, 63.5 mm diameter internal stainless steel sleeves sealed at the base	3.4 to 17.4
HW2				4.4 to 18.4
HW3				3.4 to 17.4
201 202 203 204 205 206	Dec 2006	15.6 m long loop of 10 mm diameter stainless steel alloy rod (10 m long) fitted with ceramic isolator beads along length with upper 5.6 m composed of nickel 'cold' sections of low electrical resistance	15.7 m long, 76.2 mm diameter stainless steel casing sealed at base surrounded with a sand pack within the annulus and grouted in place at the surface	5.6 to 15.6

Equipment used to provide heat and thermal control included the following:

- 500 kVA - 3 Phase - Power Generator and fuel tanks;
- Circuit breakers, switchgear and relays;
- Silicon Controlled Rectifiers (SCRs) for controlling power to heater elements;
- Thermocouples for controls;
- Heater elements as detailed above;
- Heater cables; and
- A heat exchanger capable of condensing the extracted steam during thermally enhanced SVE operations (Plate 6.4).



Plate 6.4: Heat exchanger

The heating elements were connected into three heating circuits. Heater Circuit 1 comprised the heating elements installed in wells 201, 202 and 203, situated at the western edge of Pit No.3. Heater Circuit 2 consisted of the pilot trial heating elements HW1, HW2 and HW3, situated in the centre of Pit No.3. Heater Circuit 3 comprised the heating elements installed in wells 204, 205 and 206, situated at the eastern edge of Pit No.3.

Thermocouples installed within 19 mm ID galvanised steel pipework alongside the heater well casings were utilised to monitor heater well temperatures. The locations of the thermocouples were as follows:

- Heater Circuit 1 – Well 203 at 5 m, 10 m and 15 m below ground level;
- Heater Circuit 2 – Well HW1 at 6 m, 12 m and 17.5 m below ground level; and
- Heater Circuit 3 – Well 206 at 5 m, 10 m and 15 m below ground level.

Condensate collected during the process was treated in an oil water separator and GAC filter vessel prior to discharge to RSRL's groundwater containment plant located at the southern end of the WSA.

7. PERFORMANCE MONITORING AND EVALUATION

7.1 MONITORING AND INSTRUMENTATION

7.1.1 MONITORING SYSTEMS

The following monitoring systems were utilised to evaluate and control the treatment processes:

- Field measurement using portable gas or vapour monitoring equipment;
- Collection and analysis of soil gas samples extracted from below the land surface within treatment area;
- Routine measurement of temperatures at discrete depths below the ground surface within the thermal cell using thermocouples installed within SVE and heater wells;
- Vacuum pressure measured at operational wells;
- Routine sampling and analysis of condensate produced during thermal enhancement operations;
- Routine measurement of standing groundwater levels in wells in the vicinity of the remediation area; and
- Microbial sampling utilising Biotraps[®] containing porous beads which encourage microbial growth.

7.1.2 MONITORING AND SAMPLING PROCEDURES

Extracted soil gas samples were taken via a sampling tap situated in the connecting pipework between the SVE plant and the primary off-gas abatement unit and analysed in the field or collected and shipped off-site for laboratory analysis. This was typically as follows:

- Monitoring using Tedlar bag or carbon tube sampling and Gas Chromatography (GC) analysis to characterise the composition of soil gases at the site; and
- Monitoring using Photoionisation Detector (PID) for quantitative measurements of volatile organic compounds (Plate 7.1).

Samples of off-gas were initially collected using a Gresham sampling pump and tubes, then later using Tedlar bags. The use of Gresham tubes was discontinued when it was established that representative off-gas samples were not being obtained using this sampling technique. The representative sample was understood to be consistent with the PID measurement taken during the particular sampling period and showing similar chemical composition when compared to the samples taken within a short time frame, when no major changes in gas composition could have been expected. A comparison matrix for different sampling tools and analytical technologies is presented in Table 7.1, section 7.6.1.



Plate 7.1: Off-gas monitoring

Samples of condensate extracted during the thermal enhancement stage were collected in 1 litre amber glass bottles and 60 ml glass serum vials via a series of sampling taps situated at the knockout pot, oil water separator and at the RSRL groundwater treatment plant. The condensate samples were then dispatched for laboratory analysis.

Regular groundwater monitoring was undertaken by RSRL from existing monitoring boreholes HWS27 and HWS64 located in the vicinity of the treatment area. These data were utilised to assess any impact of the remediation works on the groundwater regime. Sampling from well SVE1 was also undertaken in August 2008, seven months following completion of treatment works at Pit No.3 for verification purposes.

Analysis of off-gas, condensate and groundwater samples was undertaken at an MCERTS, UKAS and ISO 17025 accredited laboratory to determine concentrations of a suite of hydrocarbon compounds.

The lateral and vertical temperature variation within the rock mass in the vicinity of Pit No.3 was monitored by means of thermocouples connected to a digital thermometer. Thermocouples installed within specific monitoring boreholes during the 2005/2006 pilot trial (designated T1, T2 and PM1) were utilised during the remediation works (Figure 6.2). The thermocouples were set at three elevations (5.5 m to 6.5 m, 11.5 m to 12.5 m and 17.0 m to 18.0 m bgl) on a radius extending horizontally from SVE1 well at 0.69 m (T1), 1.71 m (T2) and 4.17 m (PM1). The thermocouples were set within a sand pack extending over the target interval with cement/bentonite grout between intervals and above the monitoring intervals to the surface. The upper and lower thermocouples at location T1 were not operational. Thermocouples installed on the SVE1 well casing during the 2005/2006 pilot trial were non-operational during the remediation works.

Differential pressure in other wells not utilised for extraction was measured using a static pressure meter at well heads.

Microbial sampling was undertaken in August 2008, seven months following completion of the extraction works at Pit No.3 utilising samplers which contain porous beads engineered from a composite of aramid polymer and powdered activated carbon. These beads encourage microbial growth by providing high internal surface area with low-shear conditions and by concentrating limiting nutrients within the groundwater (Williams, 2008). Samplers were placed within the groundwater at well SVE1 beneath Pit No.3 and for comparative purposes at well 17B sunk at Pit 17B to the south-east in February 2008. The samplers were left in place for 30 days prior to being removed and despatched to a microbial laboratory for molecular DNA analysis. Quantitative polymerase chain reaction (qPCR) analysis of DNA extracted from the Biotraps[®] was undertaken. This technique utilises fluorescent dyes to facilitate estimation of the total bacteria and specific

numbers of *Dehalococcoides sp.* and *Dehalobacter sp.*, two species of bacteria capable of reductive dechlorination.

7.1.3 MONITORING EQUIPMENT

Field instrumentation utilised as part of plant, equipment, process and environmental monitoring undertaken during the course of the fieldwork included the following:

- A static pressure meter;
- Mini Rae photo-ionisation detectors (PID) for measurement of total VOCs, calibrated with isobutylene; a PID fitted with an 11.7 eV lamp was utilised for monitoring off-gas concentrations;
- An Airflow Instruments PVM100 Micromanometer for measurement of air flow velocity;
- A Geotechnical Instruments GA2000 five gas analyser and static pressure meter; and
- Omegaette HH306 datalogger thermometers for temperature measurements during the thermal enhancement trial.

7.2 GROUNDWATER LEVEL

Figure 7.1 compares 2007 and early 2008 RSRL groundwater level data at well HWS9, to the west of the WSA site, shown alongside annual data from the previous 16 years.

Groundwater level in the remediation area rose gradually during the course of the initial un-enhanced SVE stage from below 20 m depth to approximately 15 m bgl, reducing the thickness of the unsaturated zone available for remediation by approximately 5 m.

Groundwater continued to rise relatively rapidly during the system shut down period prior to commencement of the first thermally enhanced SVE stage, at which time it was standing at approximately 11 m bgl. The groundwater continued to rise to approximately 10 m bgl where it stabilised for the first half of the first heating stage through February 2007. It then rose again relatively rapidly during early March 2007 to approximately 8 m bgl. From mid-March, during the latter part of the first heating stage and through the first cool down stage the groundwater then gradually fell to a depth of below 12 m.

The limited extent of contaminated unsaturated zone available during the first thermally enhanced SVE stage as a result of the rise in groundwater level would have had a significant effect in reducing the effectiveness of the remediation works. Groundwater remained below 20 m depth throughout the 2005/2006 pilot trials. Consequently up to 75% less of impacted unsaturated zone was available for treatment during the height of the thermal enhancement works than had been utilised during the pilot trials in the previous year.

Heavy and prolonged rainfall in June and July 2007 resulted in a rapid rise in groundwater to approximately 10 m bgl (Figure 7.1). As a consequence of this, the second stage thermally enhanced SVE works at Pit No.3 programmed to commence in August 2007 were postponed.

From the commencement of the second un-enhanced SVE stage in the middle of August 2007 groundwater levels stabilised and gradually decreased from approximately 11.5 m to 14 m bgl.

During the second thermally enhanced SVE stage from the end of September until early November 2007 groundwater levels continued to gradually fall to approximately 16 m bgl. Groundwater levels dropped a little further to approximately 16.5 m bgl during the initial period of the second thermally enhanced cool down stage and then stabilised at this level from the end of November until mid December 2007 when they began to rise again reaching 15.5 m bgl during the Christmas shut down period. A more rapid rise in groundwater level was recorded in early January 2008 reaching approximately 14 m bgl by the end of the extraction period.

Further groundwater monitoring was undertaken in order to observe the annual groundwater level variations. The water table continued to rise through February 2008 with a slight drop recorded in the first half of March 2008 followed by a further rise, reaching 10.2 m bgl by the end of March 2008.

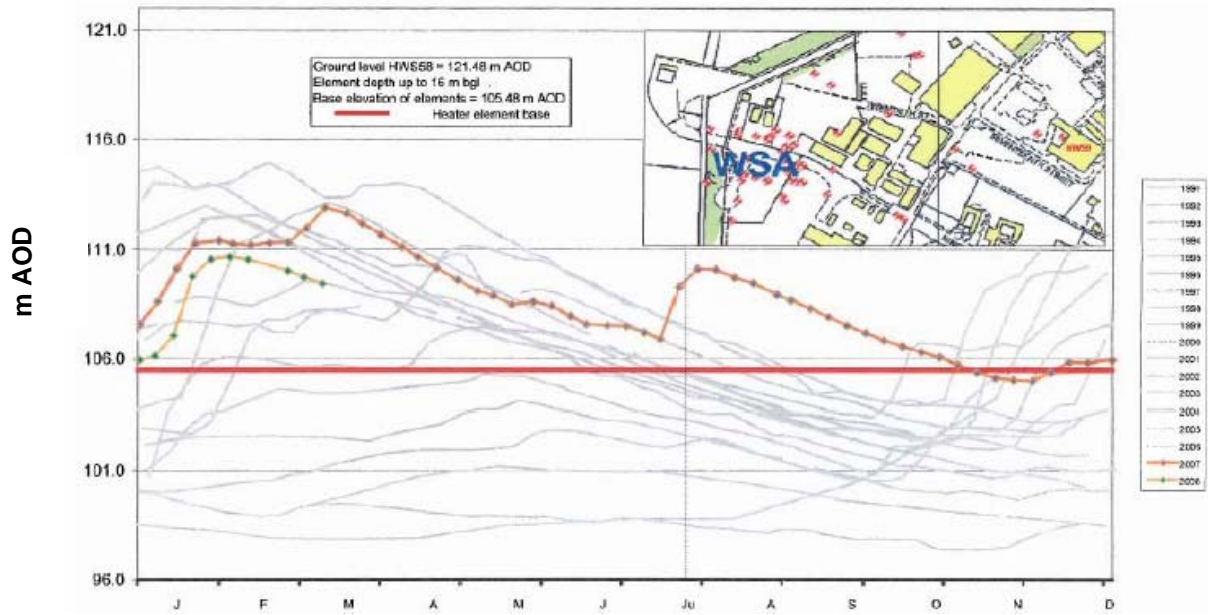


Figure 7.1 RSRL annual groundwater data for HWS9

7.3 ROCK MASS TEMPERATURES

Figure 7.2 shows temperatures recorded at the functioning temperature monitoring thermocouples installed in monitoring wells as part of the 2005/2006 pilot trial. The locations of the monitoring points are described in Section 7.1.2 and shown on Figure 5.1.

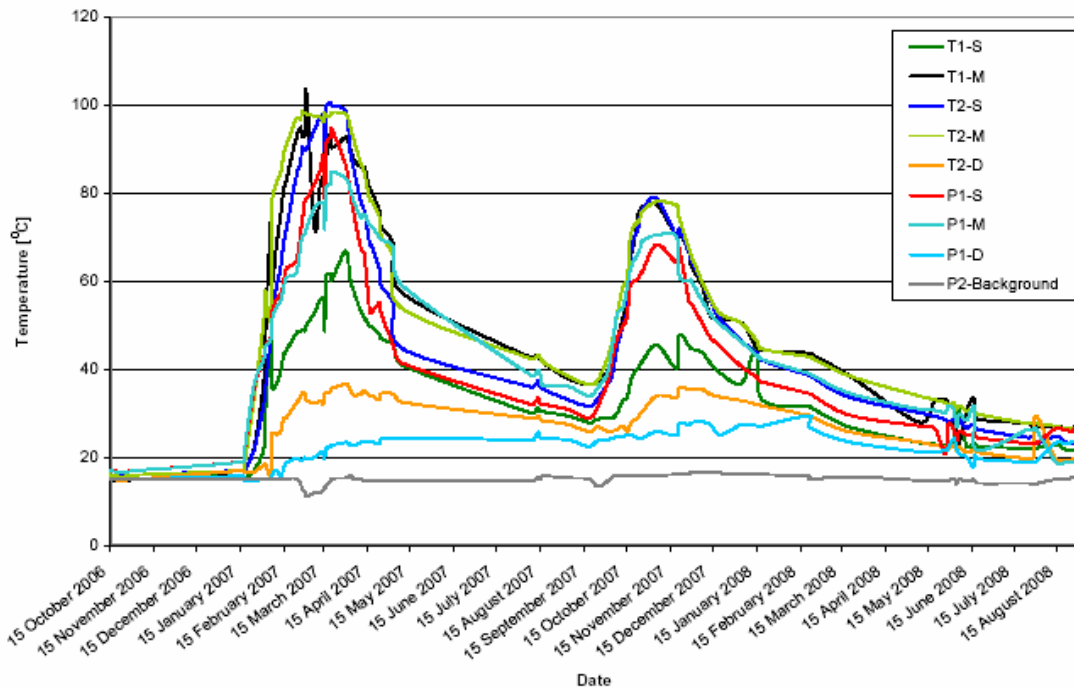


Figure 7.2: Rock mass temperatures

Rock mass temperatures recorded during the un-enhanced SVE stage generally remained in the range 13°C to 14°C.

During the first thermally enhanced SVE heating stage temperatures recorded in the shallow (5.5 m bgl - 6.5 m bgl) and middle (11.5 m bgl - 12.5 m bgl) thermocouples rose relatively rapidly during the first 3 weeks of heating. At these locations within Pit No.3 (T1 and T2) recorded temperatures reached approximately 90°C to 100°C after 7 to 8 weeks of heating and remained at these levels during the remainder of the first heating stage.

Rock mass temperatures beneath Pit No.3 remained in the range 34°C - 44°C from cessation of the first thermally enhanced cool down stage in May 2007 through the period of site shut down in June/July and the second un-enhanced SVE stage in August/September 2007. During this period the background temperature recorded by a thermocouple at location P2, located outside the effective radius of the heating zone, between Pit Nos. 2 and 3, was approximately 14.5°C. The significant difference between these two measuring points observed provides a clear indication of the high heat capacity of the rock mass. It is considered likely that during the early summer site shut down and second un-enhanced stage, at these elevated temperatures significant thermal and biological process would have been occurring within both the saturated and unsaturated zones resulting in a decrease in contaminant mass in this area of the site.

During the second thermally enhanced SVE heating stage, temperatures recorded in the shallow (5.5 m bgl - 6.5 m bgl) and middle (11.5 m bgl - 12.5 m bgl) thermocouples within Pit No.3 (T1 and T2) rose relatively rapidly during the first 2 weeks of heating, reaching approximately 70°C to 77°C after 5 weeks of heating.

Temperatures recorded at the shallow and middle thermocouples dropped gradually during the cool down stages to between 40°C and 60°C. The middle thermocouple at location PM1 immediately outside of Pit No.3 recorded the slowest rate of temperature drop, whereas the shallow thermocouple at this location recorded the most rapid rate.

During the thermally enhanced cool down SVE stages a gradual decline in the rock mass temperature was observed of approximately 1.5°C per day. The rate of decrease reduced to approximately 0.5°C per day once additional wells from the vicinity of Pit No.2 were introduced into the extraction field.

The two deeper thermocouples (17.0 m bgl - 18.0 m bgl) at locations T2 and PM1 remained within the saturated zone throughout the thermally enhanced stages of the works and recorded a gradual temperature rise to a maximum of 35°C and 27°C respectively, with a minimal or no drop in temperature during the cool down stage. These temperatures were significantly lower than those recorded during the 2005/2006 pilot trial at these depths when they were previously in the unsaturated zone. Notably the deep monitoring point T2 recorded temperatures in excess of 50°C during the Phase 1 trial.

7.4 CONDENSATE PRODUCTION

Two short periods of rapid condensate production were recorded during the first thermally enhanced stage. An initial period of rapid production happened as the rock mass reached 40°C to 50°C when approximately 25 m³ of condensate was produced over a two day period. The second period of rapid production occurred as the general rock mass temperature reached 80°C to 100°C when approximately 75 m³ of condensate was produced over 1 week.

At other times during the thermally enhanced stages condensate production occurred at a rate of approximately 0.5 m³ per day, decreasing to approximately 0.2 m³ per day during the second cool down stage. A total of 162 m³ of condensate were produced during the remediation works.

Laboratory analysis of the condensate revealed chloroform and 1,2-dichlorobenzene to be the predominant VOCs within the condensate.

The total concentrations of VOCs recorded within condensate samples reduced from 0.4 mg/l to 0.2 mg/l during the course of the second (2007/2008) period of remediation works. This final value was an order of magnitude less than the initial total VOC concentration in condensate recorded during the Phase 1 pilot trial (2.2 mg/l) and half the average total VOC concentration recorded during the 2006/2007 works.

The total concentration of VOCs recorded within condensate samples averaged approximately 0.5 mg/l and 0.3 mg/l in the first and second periods of remediation works respectively. This would equate to approximately 60 g of dissolved phase VOCs being extracted during the course of the works.

Condensate samples were also subject to analysis for a suite of SVOCs. The results revealed phenol, 4-methyl phenol and bis(2-ethyl hexyl phthalate) to be the predominant SVOCs to be removed in the condensate. The total concentrations of SVOCs recorded within condensate samples dropped during the course of the first thermally enhanced stage from over approximately 150 mg/l to approximately 50 mg/l. This would equate to approximately 10 kg of dissolved phase SVOCs being extracted during the course of the first period of the works.

SVOC concentrations in the condensate were approximately two orders of magnitude lower during the second period of works when total concentrations of SVOCs recorded dropped from over 3.2 mg/l at the start of the second TESVE stage to approximately 1.8 mg/l.

On the basis of an average SVOC condensate concentration of 2 mg/l, this would equate to approximately a further 60 g of dissolved phase SVOCs being extracted during the second TESVE stage of the works.

These analytical results indicate that a significant reduction in pore water VOC and SVOC concentrations had been achieved at Pit No.3 as a result of the remediation works.

7.5 GROUNDWATER QUALITY

Groundwater quality data from RSRL wells HWS27 and HWS64 located to the east and west of the treatment zone respectively revealed a clear relationship between the groundwater levels and contaminant concentrations. The groundwater level increase is reflected in the elevated concentration of dissolved hydrocarbons including petroleum hydrocarbons (TPH), VOCs, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), which are released from the unsaturated zone during seasonal periods of rising groundwater levels (usually in late autumn and winter).

Sampling at RSRL well HWS58 between Pit Nos. 2 and 3 has not previously been undertaken routinely due to the presence of LNAPL at this well. Approximately 30 mm of LNAPL was recorded at HWS58 following skimming operations to remove free product undertaken in December 2005 as part of the initial works associated with the pilot trials. Monitoring of groundwater level at HWS58 in the summer of 2007 revealed free product to no longer be present at this well and routine RSRL sampling commenced in October 2007.

Analytical data for groundwater samples taken from HWS58 located immediately adjacent to the heating zone have revealed a strong correlation with heating at Pit No.3 and increases in dissolved phase hydrocarbon concentrations during a period of relatively low and falling groundwater levels, whereas the concentration of dissolved hydrocarbons in samples taken from HWS57 and HWS64, located outside the thermal treatment zone, showed the reverse trend, matching the low groundwater levels. It is apparent that the high rock mass temperatures have enhanced mobilisation and dissolution of hydrocarbons, making them available for extraction and/or biodegradation at elevated temperatures. Concentrations were shown to fall again as extraction continued and the rock mass cooled during the cool down stage.

Additional groundwater analysis was carried out on samples from well SVE1 seven months following cessation of extraction works for verification purposes and to provide data to assist in assessment of microbial information (see Section 7.7). Figure 7.3 shows a comparative plot of concentrations of chlorinated ethenes for HWS27, outside the thermal treatment area, HWS58, adjacent to the thermal treatment area (formerly containing LNAPL prior to commencement of the works) and SVE1, within the thermal treatment area. Concentrations of chlorinated ethenes and other contaminants of concern from the site were generally found to be significantly lower adjacent to the thermal treatment area and one to two orders of magnitude lower within the thermal treatment area compared to other areas of the WSA site.

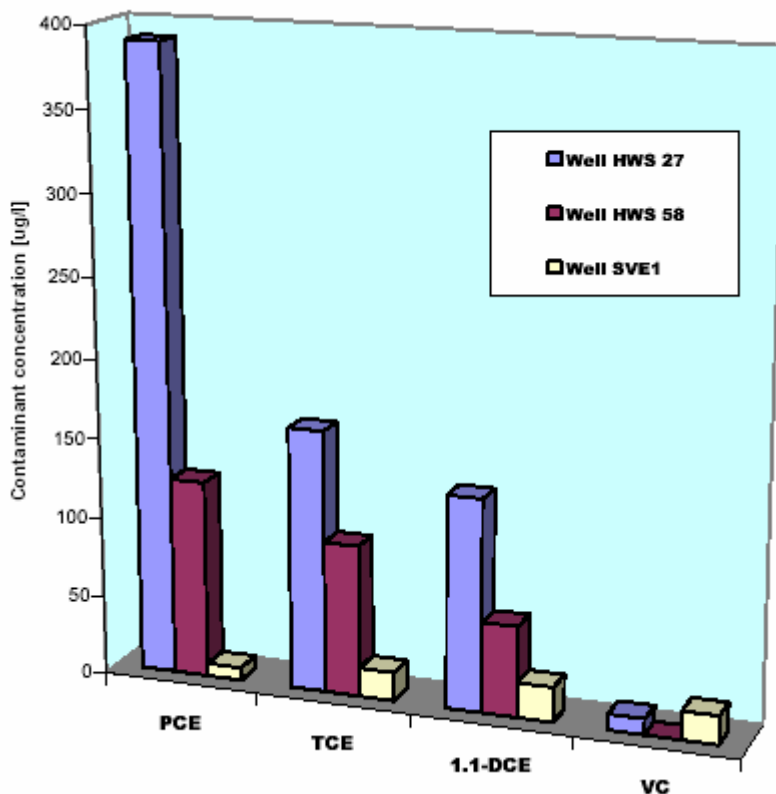


Figure 7.3: Concentrations of chlorinated ethenes in groundwater following completion of works

7.6 LABORATORY ANALYSIS OF OFF-GAS

7.6.1 ANALYSIS METHODOLOGIES

Off-gas samples were initially dispatched for laboratory analysis utilising the Gas Chromatography – Mass Spectrometry (GC-MS) method to determine concentrations of a suite of 61 VOCs. The level of detection for individual compounds provided using this technique was 10 ppm. During the 2005/2006 pilot trials and the initial 2006/2007 remediation works this technique was considered appropriate as VOC concentrations were relatively high (generally in excess of 100 ppm). However, as the works progressed recovered VOC concentrations dropped and significant discrepancies were noted between laboratory and field data.

The laboratory data were therefore subjected to a control checking procedure on the accuracy of results presented and chromatographic printouts of analysis results were requested.

The chromatograms clearly depicted a higher number of peaks corresponding to compounds previously not identified. The unidentified peaks together with corresponding retention times were listed and their Peak Areas and Peak Identifications were requested from the laboratory. Using this information, the raw laboratory data were reassessed to facilitate calculation of concentrations of detected VOCs that were previously not reported.

The concentration of VOC compounds was calculated according to the formula:

$$C_x \text{ [ppm]} = \text{Peak Area of Contaminant X} / \text{Peak Area of Standard (1,1,1 TCE)} * C_s \text{ [ppm]}$$

Where:

C_x – the area of peak in question [ppm]

C_s – standard concentration [125 ppm]

This assessment identified some inaccuracies in the previously reported data and notably, in one instance a significant deviation of 400 ppm was determined.

In order to gain more certainty in the accuracy of the laboratory test data three additional independent laboratories were utilised to analyse off-gas samples. In some cases duplicate samples were taken and sent to different accredited laboratories for comparative purposes.

The methodologies utilised at each laboratory were assessed in order to determine the most appropriate technique for the determination of VOC concentrations in off-gas samples. The findings of this assessment are summarised in Table 7.1.

Table 7.1: Summary of off-gas analysis methodologies and suitability assessment

Laboratory and Technique	Method of Analysis	Matrix	Limit of Detection	Proficiency Testing
Gas Chromatography-Mass Spectrometry (GC-MS)	<ul style="list-style-type: none"> <input type="checkbox"/> Solvent extraction <input type="checkbox"/> Standard 1,1,1 trichloroethane (TCE) <input type="checkbox"/> Contaminant identification based on qualitative comparison of Peak Retention Times t_R against the library search data <input type="checkbox"/> Calculation based on Tentatively Identified Compound (TIC) –1,1,1 trichloroethane 	Tedlar bags	10 ppm	<ul style="list-style-type: none"> <input type="checkbox"/> Very high limit of detection, some of compounds might not be identified <input type="checkbox"/> Compound identification based only on Peak Retention Times, which might cause certain inaccuracy <input type="checkbox"/> Possible interference with standard 1,1,1 TCA, which is a predominant contaminant identified within the DVE off-gas mixture. <input type="checkbox"/> 1,1,1 TCA derivatives (break down compounds) might not be detected
Automatic Thermal Desorption Gas Chromatography-Mass Spectrometry (ATD GC-MS)	<ul style="list-style-type: none"> <input type="checkbox"/> Carrier gas – helium <input type="checkbox"/> No solvent extraction <input type="checkbox"/> No standard <input type="checkbox"/> ATD –Tubes are uncapped and placed in a sequence of calibration standards and exposed in the ATD instrument. <input type="checkbox"/> The desorbed compounds are concentrated in a low thermal mass cold trap within the ATD prior to transfer through a heated line to GC. <input type="checkbox"/> The cold trap is heated rapidly to ensure that the sample is transferred to GC in a tight band. <input type="checkbox"/> The VOC species are separated in time by the GC, before introduction to the mass selective detector (MSD), where the responses obtained are compared with those from the standard tubes. <input type="checkbox"/> The MSD is used in scan mode to enable confirmation of the identity of the eluted compounds. <input type="checkbox"/> Dilution Factor (DF) 10-22 applied 	ATD-Tubes Tedlar bags	0.17 ppb	<ul style="list-style-type: none"> <input type="checkbox"/> Very low limit of detection <input type="checkbox"/> No interference with standard compound <input type="checkbox"/> All amount of contaminants is directly transferred into to thermal desorption column <input type="checkbox"/> Very accurate compounds identification based on Peak Retention Times and mass to charge ratio <input type="checkbox"/> ATD – tubes the most reliable sampling matrix in terms of capturing the organic compounds however due to the sampling method (1 single shot) might carry unrepresentative sample
Gas Chromatography-Flame Ionisation Detector (GC-FID)	<ul style="list-style-type: none"> <input type="checkbox"/> Direct sample injection <input type="checkbox"/> Standard – isobutylene <input type="checkbox"/> GC-FID technique measures the current that passes between the pair of oppositely polarised electrodes producing the chromatographic peaks. <input type="checkbox"/> The compounds are atomised in the flame to produced highly excited cationic intermediates and electrons that act as a charge carriers between the two electrodes. 	Tedlar bags	1 ppb	<ul style="list-style-type: none"> <input type="checkbox"/> Low limit of detection <input type="checkbox"/> Relatively inaccurate method of analysis for VOC species, highly depends on the redox state of the carbon, with fully oxidised carbon sometimes failing to ionise within the flame, where the responses might be lowered or may even be completely absent <input type="checkbox"/> Flame Ionisation Detectors impart no selectivity to the system and that it is solely the separational capability of the chromatograph that allows identification and quantification of individual contaminants
GC-MS Purge and Trap	<ul style="list-style-type: none"> <input type="checkbox"/> Carrier gas – helium <input type="checkbox"/> Sample injected into purge water reservoir <input type="checkbox"/> Mixture subjected to the thermal desorption <input type="checkbox"/> MSD and Peak Retention Time used for compound identification. 	Tedlar bags	0.2 ppb	<ul style="list-style-type: none"> <input type="checkbox"/> Very low limit of detection <input type="checkbox"/> Accurate compound identification based on Peak Retention Times and mass to charge ratio

It was therefore established that Automatic Thermal Desorption Gas Chromatography-Mass Spectrometry (ATD GC-MS) or Gas Chromatography-Mass Spectrometry Purge and Trap should be utilised for laboratory analysis of off-gas samples as these techniques provide a more accurate method of analysis with detection limits of an appropriate order at relatively low recovered gas concentrations. The ATD GC-MS was adopted throughout the second (2007/2008) period of works. The methodology provided analysis for a suite of 76 VOCs at levels of detection for individual compounds between 0.2 ppb and 1 ppb.

7.6.2 OFF-GAS CHEMISTRY

During the initial un-enhanced stage of the works 1,1,1-trichloroethane (TCA), tetrachloroethene (PCE), trichloroethene (TCE), chloroform and toluene were the main compounds recovered.

These compounds also predominated in the gas mix recovered during the majority of the first thermally enhanced heating stage and the initial cooling stage. The more sensitive chemical analysis undertaken on gas samples taken during the thermally enhanced stages revealed a greater range of compounds recovered than that recorded previously.

During the latter two to three weeks of the first cool down stage a distinct change in the composition of the off-gas was recorded. This was primarily in the form of a significant increase in the proportion of diethyl disulphide and tetrahydrofuran recorded within the gas mix. Although present in relatively low concentrations (between 3 ppm to 7 ppm) they formed in the region of 40% of the VOCs detected. Shortly before this change in off-gas composition occurred the extraction field was extended to include the wells surrounding Pit No.2. It is therefore likely that this change in chemistry is a result of commencing extraction from these wells, although there is also a possibility that it is a result of additional breakdown products being produced due to long term heating of complex chemicals.

The composition of the off-gas showed only minor variation throughout the second phase of the remediation works, with few significant changes occurring during the thermally enhanced and thermal cool down stages. The predominant compounds recovered in the gas mixture were chloroform, TCE, TCA and PCE.

During the initial period of the second thermally enhanced SVE stage the presence of 2-propanone (acetone) was recorded for the first time and increased quite substantially when rock mass temperatures reached 73°C, this was followed by sudden decline by the end of the heating stage and beginning of the thermal cool down stage. A very small concentration of ethanol was also recorded in the middle of the second thermal stage and was no longer present during the final cool down period. Shortly before the initial spike of acetone and ethanol was recorded the extraction field was limited to the thermally enhanced zone only (i.e. SVE1 well only). It is therefore likely that this change in off-gas mix composition and concentration is a result of the relatively high rock mass temperature within the extraction zone, which could influence the degree of volatilisation of these highly persistent, low volatility contaminants by increasing their vapour pressure, Henry's law constant and reducing the viscosity and surface tension.

7.7 LABORATORY MICROBIAL ANALYSIS

The results of the quantitative polymerase chain reaction (qPCR) analysis undertaken on DNA extracted from Biotraps[®] taken from well SVE1 and the control well 17B are summarised in Table 7.2.

Table 7.2: Microbial analysis results

Well	Total Bacteria (qEuBac) Copies/bead	<i>Dehalococcoides sp.</i>		<i>Dehalobacter sp.</i>	
		Copies/bead	% of total qEuBac	Copies/bead	% of total qEuBac
SVE1	9.04E+06	7.7E+02	0.009	1.3E+04	0.14%
17B	6.84E+06	<1E+02	Not detected	1.19E+04	0.17%

Moderate levels of total bacteria (qEuBac) were detected on both traps. As bacteria must be able to colonise the traps and grow *in situ* to be detected, these results would suggest that both locations harbour an active population of indigenous bacteria and that the conditions are suitable for growth.

Moderate to high levels of *Dehalobacter spp.* were detected at both locations. Low levels of *Dehalococcoides spp.* were detected at SVE1 although this species was not detected at all in the 17B control trap. These results confirm dehalogenating bacteria are present within the site.

It is not possible to conclude whether the thermal treatment has increased or decreased the populations of dehalogenating bacteria at SVE1 as data were not collected prior to the thermal treatment. However, if prior to thermal treatment, the groundwater beneath Pit No.3 had similar populations to those seen in 17B then it is possible that the thermal treatment may have resulted in conditions that are more conducive to the growth of *Dehalococcoides spp.* and hence reductive dechlorination for biological polishing. A programme of microbial analysis is planned at well 17B during and following TESVE works at the adjacent Pit No.18, which should provide further data on this matter.

7.8 MASS REMOVAL ASSESSMENT

7.8.1 PID CORRECTION FACTORS

Off-gas sample analysis undertaken revealed it to contain a mix of contaminants and therefore a correction factor has to be applied to the PID monitoring readings.

The correction factor for a mixture (CF_{mix}) is calculated from the sum of the mole fractions of each component divided by their respective correction factors for the PID and lamp. Mole fractions for individual components were determined for gas samples obtained during the various stages of the works.

The $1/CF_{mix}$ values determined were in the range 0.41 to 1.08, the higher values were generally recorded for the heating stages of the TESVE operations.

The following formula is used to convert from corrected parts per million (ppmv) values to contaminant concentrations terms of mass per unit volume (mg/m^3):

$$\text{Concentration (mg/m}^3\text{)} = \frac{\text{(Concentration \{ppmv\} X molecular wt \{g/mole\})}{\text{Molar gas volume \{L\}}}$$

For air at 25°C, the molar gas volume is 24.4 L/mole.

The weighted average molecular weights were calculated, using the mole fractions of the individual contaminants for each stage of the works. From determination of the air flow rate, calculated from the air flow velocity measurements and a knowledge of the pipe diameter at the monitoring point, the total mass of contaminants removed per day was therefore established.

The approximate rate and mass of VOCs removed was calculated for individual consistent periods of the remediation works to determine total contaminant mass removal.

7.8.2 MASS REMOVAL RATE

Figure 7.4 shows the variations in the mass removal rate during the course of the remediation works undertaken at Pit No.3 and the adjacent areas. Contaminants were extracted from both the thermally enhanced area at Pit No.3 and the unenhanced adjacent areas simultaneously during the majority of the works and therefore the recorded removal relates to both thermally enhanced and conventional SVE. However, at regular intervals throughout the works extraction was limited to well SVE1 only for short periods in order to estimate the mass removal contribution of the thermally enhanced works.

These assessments revealed that at the early stages of heating the single thermally enhanced well at Pit No.3 contributed the vast majority of the mass removed compared to the remaining eleven other unenhanced wells. This ratio dropped to about 50% immediately prior to the second heating stage and continued to fall thereafter. Mass removal from SVE1 at Pit No.3 increased from approximately 1 kg/day prior to heating up to in excess of 6 kg/day during the first stage of thermal enhancement. Rates then gradually dropped to between 2 kg/day and 3 kg/day and then fell further to approximately 1 kg/day as the rock mass slowly cooled following cessation of heating. Further extraction after a three month shut down, once groundwater levels had dropped in the summer of 2007, revealed an extraction rate of approximately

0.7 kg/day from SVE1. This indicates that biodegradation of the remaining contamination is likely to have occurred during the summer shut down while rock mass temperatures remained relatively high. Additional heating in the autumn of 2007 resulted in an increase in extraction rate to approximately 1.5 kg/day before falling to approximately 0.3 kg/day at the end of the extraction works.

Additional verification monitoring was undertaken in the summer of 2008 to evaluate any further attenuation that had occurred in the seven month period following cessation of extraction works. Extraction rates in the order of 0.1 kg/day were recorded over a two day period with rock mass temperatures remaining between 20°C to 30°C within the target treatment zone which would indicate that further biodegradation of residual contamination had occurred.

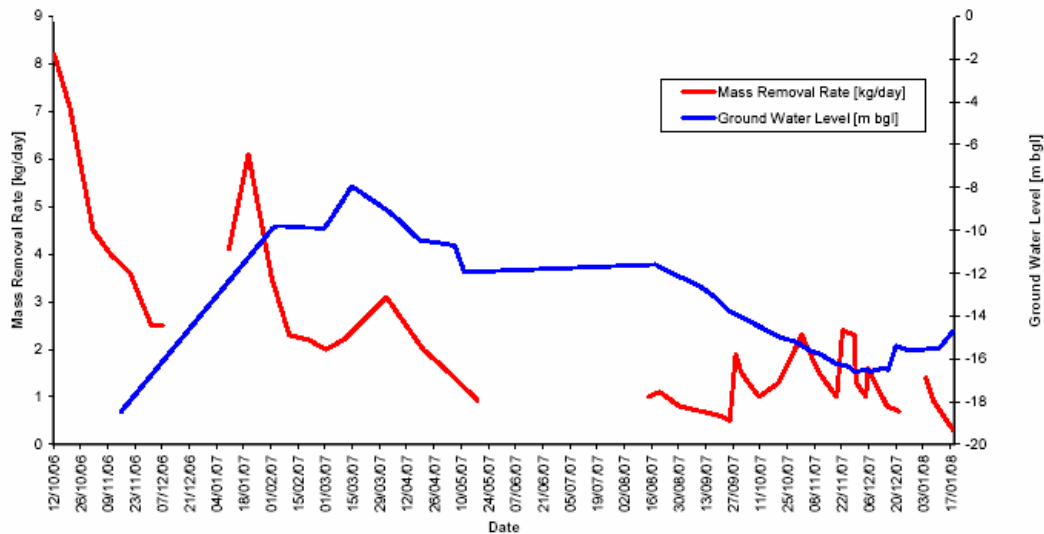


Figure 7.4: Contaminant mass removal rate for SVE1 at Pit No.3 and perimeter wells

7.8.3 TOTAL MASS OF CONTAMINANTS REMOVED

The estimated total mass of contaminants removed during the pilot trials and phases of remediation works equates to approximately 1 tonne. On the basis of the field measurements it is estimated that approximately 70% of this (700 kg) was derived from the thermally enhanced remediation of Pit No.3.

7.9 SUMMARY OF PERFORMANCE

The contaminant mass removal rate at Pit No.3 increased significantly with the introduction of TESVE following a period of conventional SVE, despite reducing from seven to one extraction well and a rapid rise in groundwater level and consequent decrease in extent of the extraction zone, immediately prior to commencement of heating.

Extraction rates remained relatively low during the second period of heating even though groundwater levels had dropped back near to and below the base of the target treatment zone. It is anticipated that this is due to a reduction in source material as a result of biodegradation that occurred during the shut down period while groundwater levels dropped. Rock mass temperatures remained in the range 34°C - 44°C during this period which would have helped to provide a favourable environment for biological activity.

Microbial sampling and analysis post-treatment has established the presence of an active population of indigenous bacteria, which included the dehalogenating bacteria *Dehalobacter sp.*, and, to a lesser extent, *Dehalococcoides sp.*

Further evidence of post-treatment attenuation was established when extraction was reapplied to Pit No.3 some nine months after cessation of heating and extraction respectively when the mass removal rate recorded was 0.1 kg/day. This value is significantly lower than the rate of 0.3 kg/day recorded at the end of the extraction works. The rock mass remained in the range 20°C - 30°C nine months following completion of heating confirming the high heat capacity of the rock mass and the favourable conditions for enhanced attenuation of residual contamination.

Free product identified in monitoring wells in the vicinity of Pit No.3 prior to thermal treatment is now no longer present. Furthermore, monitoring of groundwater quality in the vicinity of the thermal treatment zone revealed increases in dissolved phase hydrocarbons as the rock mass warmed. It is therefore apparent that increases in temperatures enhanced mobilisation and dissolution of hydrocarbons, making them available for extraction and/or biodegradation at elevated temperatures.

Post-treatment analysis of groundwater samples from below Pit No.3 have revealed significantly lower concentrations of dissolved phase hydrocarbons in this vicinity compared to untreated areas of the WSA.

Analysis of condensate recovered in the latter stages of treatment revealed total contaminant concentrations to be one to two orders of magnitude lower than those recorded during the initial stages of the remediation works (from over 150 mg/l to less than 2 mg/l). This indicates a very significant reduction in pore water VOC and SVOC concentrations reflecting the high degree of clean-up achieved beneath Pit No.3.

Approximately 1 tonne of contaminants have been removed from the 25 extraction wells during the course of the works undertaken at, and in the vicinity of, Pit No.3. It is estimated that in the region of 70% of the contaminant mass removed was extracted from the single TESVE well in the centre of Pit No.3.

8. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

8.1 ECONOMIC CONSIDERATIONS

Table 8.1 presents a realistic cost of implementation of TESVE technology for any potential site. As the table shows costs will vary depending on the nature of the contaminants of concern (CoC) and treatment volume. The volumetric cost is highly dependent on the type of contaminants present, which will directly influence the level of target treatment temperature to achieve the desired remediation effect. Consequently this will be reflected in the amount of energy consumed per volume of material undergoing thermal remediation.

Table 8.1: TESVE estimated project cost per unit volume and type of contamination present

Type of Contaminant	Site Scale (Treatment Volume)	Cost per Volume
Volatile Organic Compounds (VOCs) including chlorinated solvents and BTEX.	Small Sites (1000 m ³)	£100 / m ³
	Large Sites (100,000 m ³)	£80 / m ³
Polycyclic Aromatic Hydrocarbons (PAH), Polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins and furans (PCDD/F) and coal tar.	Small Sites (2500 m ³)	£280 / m ³
	Large Sites (100,000 m ³)	£100 / m ³

Scale and configuration of the treatment volume are two important factors which have an impact on the economic feasibility of TESVE technology. Unit treatment cost is substantially reduced with each metre depth of targeted zone. The majority of the cost will remain almost unchanged with increased volume but same treatment area.

Heavier and more persistent organic contaminants such as PCBs, PAHs, PCDD/F and coal tars, due to their physico-chemical properties such as high molecular weight, low vapour pressure and Henry's law constant, low solubility and high viscosity require more elevated treatment temperatures in the range of 200°C - 325°C to be vaporised and recovered from the soil matrix. Whereas lighter organic fractions like VOC and BTEX are successfully removed, when subjected to 80°C - 100°C thermal treatment, and therefore require much lower total energy input.

The most significant cost of a TESVE project is the capital cost associated with power supply and installation of TESVE units and array of equipment, which includes stainless steel heater rods, carbon steel casings, TESVE control panel, cabling, thermocouples, design and installation. Operation and maintenance costs, which are typically the most significant costs for non-thermal remediation technologies, together with the TESVE unit cost, become more cost-effective with larger treatment zones. Conversely, items like commissioning/decommissioning, off-gas and condensate treatment etc, remain practically invariant, unless there are site-specific conditions that will affect the effectiveness of by-products (off-gas and condensate) treatment and discharge.

Comparative cost structures and percentage contribution of each particular item to the total treatment cost are presented in Table 8.2.

Table 8.2: Cost distribution structure for TESVE project depending on the project's scale

Cost Breakdown Specification		
	Large Sites % Contribution to the Total Treatment Cost	Small Sites % Contribution to the Total Treatment Cost
Fixed Costs		
▪ Mobilisation and demobilisation	~7%	~5%
▪ SVE Unit (vacuum pumps and compressor) including installation	~10%	~8%
▪ TESVE Unit including heater rods, and temperature control units – including installation	~25%	~30%
▪ Operation and maintenance (including labour)	~10%	~15%
▪ Contingency	~20%	~20%
Variable Costs		
▪ Off-gas and condensate treatment with GAC	~3%	~2%
▪ Power Supply – generator hire plus fuel cost, depending on the target treatment temperature	~25%	~20%
Total Cost	100%	100%

Fuel consumption during the heating stage at the Pit No.3 increased to some 6000 litres/per week compared to approximately 1000 to 2000 litres/week during un-enhanced SVE stage. However, the heating periods are generally relatively short (between 6-12 weeks, depending on the CoC), and since TESVE projects are significantly shorter than conventional SVE projects, overall costs are therefore lower.

Cost associated with fuel/energy consumption can be substantially reduced from the total TESVE cost, if electricity is externally supplied from a sub-station.

8.2 ENVIRONMENT AND SUSTAINABILITY

At remedial options appraisal stage it is important that cost estimates include the total resource cost over time ("Life Cycle Costs") for each technically appropriate option. Furthermore, costs should be compared on a "like-for-like" basis of achieving a similar level of environmental performance, which is particularly important for evaluation of TESVE which has been proved capable of achieving high clean up standards in short time frames.

Baker et al., (2008) have compared Life Cycle Costs (LCC) for TESVE with a conventional multiphase extraction system (MPE) that had been in operation on a site in Southern California for nine years. Concentrations of 1,2-dichloroethane remained relatively high at the site following MPE treatment (up to 27,000 mg/kg). Fourteen months of subsequent TESVE using the existing extraction field and thermal conductive heating resulted in a reduction of average concentrations in the target treatment zone to 0.2 mg/kg. The study concluded that if TESVE had been utilised instead of conventional MPE there would have been a significantly higher degree of contaminant removal in a much shorter time frame with at least a 30% cost saving.

Experiments from laboratory studies along with field data from four sites have been used by VEGAS, the Research Facility for Subsurface Remediation at the University of Stuttgart, Germany, to conduct Life Cycle Assessments where TESVE and conventional SVE were compared for the purpose of estimating the secondary environmental impacts of such techniques. The results indicate that energy consumption and environmental impacts are favoured for TESVE as compared to conventional SVE. In addition to utilising 42% to 45% less energy, TESVE was projected to cost from 34% to 75% less than conventional SVE (Hiester and Schrenk, 2005).

It should be noted that the hardware and equipment utilised for TESVE and ISTD projects typically is recycled and reused many times over. Heaters are used for multiple projects, and can be cut and welded to new lengths. Process equipment is typically used for at least 5 applications, more often 10 or more before it reaches the end of its use. Very limited new materials are purchased for each new project.

8.3 COMPARISON OF COSTS FOR SVE AND TESVE

Table 8.3 below illustrates the considerable cost benefits that may be derived from adoption of TESVE over SVE at a site. Typically TESVE can be completed within less than 80%-90% of the duration normally adopted for conventional SVE works, with greater certainty of mass removal and significant cost advantage.

Table 8.3 Cost comparison matrix between TESVE and SVE technology implementation

Cost Breakdown Specification		
	SVE Technology	TESVE Technology
PROJECT DURATION	300 weeks	15 weeks
Fixed Costs		
▪ Mobilisation and demobilisation	~£20,000	~£20,000
▪ Installation	~£30,000	~£60,000
▪ SVE equipment	~£100,000	~£30,000
▪ TESVE equipment	£0	~£15,000
▪ Operation and maintenance	~£500,000	~£30,000
Variable Costs		
▪ Waste GAC (Off-gas treatment)	~£3000	~£3000
▪ Waste GAC (Condensate treatment)	~£500	~£1500
▪ Energy consumption	~£500,000	~£38,000
▪ Validation/testing	~£25,000	~£6000
Tonnes removed	2 tonnes	2.8 tonnes
Total Cost	£1,178,500	£203,500

8.4 HEALTH & SAFETY CONSIDERATIONS

In comparison to traditional remediation methods, for example dig and dump, the health and safety and environmental impacts of TESVE are far less. For example, contaminated soils are treated *in situ* therefore no soil is excavated and on-site workers and neighbours are not exposed to odours, noise, dust and vehicle movements associated with dig and dump projects.

The TESVE system itself can present operational health and safety risks. These include electrocution, mechanical equipment, combustion/explosion risk and exposure to organic vapours and hot conduit lines or steam. These risks can however be successfully abated through operating safe systems of work and using experienced personnel. As a result, not a single serious accident has been reported in the operational activities of TESVE or ISTD projects around the world, counting more than 30 projects globally over a period of 12 years.

A number of gases, vapours and liquids arising from the treatment process can cause harm to human health or the environment. These include:

- VOCs generated by heating and/or extracted by the vapour extraction process;
- Water condensate collected in the water vapour trap;

- LNAPL that may be collected from the vapour trap or oil water separator; and
- Spent media from off-gas abatement equipment and condensate treatment.

Each of the emissions can be monitored, contained, collected and treated, where necessary.

Wastes generated from the treatment process fall into four main types. These include:

- Off-gas vapours which are stripped of their contaminants in an array of cartridge type GAC vessels before discharge to atmosphere;
- Condensate waters which are passed through a pre-treatment plant consisting of cooling water, an oil water separator, a GAC vessel and holding tank prior to disposal;
- Absorbent materials contaminated with the chemicals of concern; and
- Free product contained in the cooling tank and oil water separator.

Provectus Group recycles a vast majority of the wastes generated during the treatment process. For example, the activated carbon is recycled once the vessels are fully spent. Condensate waters are discharged to RSRL's groundwater treatment plant after pre-treatment where they are re-introduced back into the environment.

The remaining process generated wastes are removed off-site in accordance with Duty of Care Provisions required under the Environmental Protection Act (1990).

All work relating to the technology is carried out in compliance with the Health and Safety at Work Act 1974 and other statutory requirements where applicable. The technology is also subject to a Mobile Plant Treatment Licence therefore all issues relating to waste are advised and monitored by person with a Certificate of Technical Competence (COTC).

9. CONCLUSIONS

Thermally enhanced soil vapour extraction (TESVE) utilising conductive heating technology is being successfully utilised to remediate hydrocarbon contaminants located beneath former waste disposal pits at the Western Storage Area (WSA) site.

For chlorinated solvents, the key contaminants of concern at this site, vaporisation is the dominant removal mechanism, as vapour pressure and Henry's law constants increase most markedly with temperature. Increasing temperature also decreases viscosity, increases solubility and decreases adsorption which all facilitate higher rates of extraction. Rapid rates of contaminant mass removal have been achieved by raising rock mass temperatures to between 70°C and 100°C, with additional polishing occurring by biological processes as temperatures drop very slowly following cessation of heating due to the high heat capacity of the rock.

The following lines of evidence are apparent indicating that significant and effective contaminant source removal had been achieved through the utilisation of TESVE beneath Pit No.3:

- Contaminant mass removal rates increased from 2 kg/day under conventional SVE extraction to in excess of 17 kg/day during initial thermal enhancement works. Contaminant removal rates gradually dropped during the course of thermal treatment reducing to approximately 0.3 kg/day. Verification extraction monitoring seven months post treatment recorded a rate of 0.1 kg/day confirming the occurrence of additional attenuation following treatment and that a high degree of clean up had been achieved.
- Free product identified in monitoring wells in the vicinity of Pit No.3 prior to thermal treatment attenuated during the course of the TESVE works and no evidence of reoccurrence of LNAPL was apparent following completion of treatment.
- Increases in temperatures enhanced mobilisation and dissolution of hydrocarbons, making them available for extraction and/or biodegradation at elevated temperatures.
- Post-treatment analysis of groundwater samples has revealed significantly lower concentrations of dissolved phase hydrocarbons in the vicinity of the treatment area compared to untreated areas of the WSA.
- Analysis of condensate recovered in the latter stages of treatment revealed total contaminant concentrations to be one to two orders of magnitude lower than those recorded during the initial stages of the remediation works (from over 150 mg/l to less than 2 mg/l). This indicates a very significant reduction in pore water VOC and SVOC concentrations.
- Off-gas flow rate monitoring and analysis has revealed that approximately 1 tonne of contaminants have been removed from the 25 extraction wells during the course of the works undertaken at and in the vicinity of Pit No.3. It is estimated that in the region of 70% of the contaminant mass removed was extracted from the single TESVE well in the centre of Pit No.3.

High levels of power are only required for relatively short periods of time in order to raise the temperature of the treatment zone to the target level. Consequently, due to the relatively rapid rate of remediation, TESVE is proven to be an economic and sustainable technology in many circumstances when the whole life cycle costs of the project are considered. Sites with one or more of the following situations or constraints would be worthy of appraisal for the utilisation of TESVE by thermal conductive heating:

- Stringent target levels must be achieved;
- Rapid remediation required;
- Relatively high concentrations of contaminants present;
- Excavation is expensive or impractical;
- The target unsaturated zone is deep;
- There is a mixture of contaminants;
- The site is complex;
- LNAPL present; and
- DNAPL present.

10. LESSONS LEARNT

A good understanding of the occurrence and degree of seasonal changes in groundwater level on a site will enable optimal design and effective operation of the heating stage of TESVE projects. Completion of heating prior to water recharge will facilitate maximum contamination removal from the unsaturated zone. Continued extraction after heating will also remove contamination mobilised from dissolved or free phase to vapour phase as the groundwater rises and warms as it enters the heated zone during winter.

Thermal operation should be ceased in the periods of high groundwater levels, to minimise the heat losses and maximise the power input into the unsaturated zone and recommenced after the groundwater level reaches the desired level, especially on sites with high groundwater fluxes.

Air/ozone sparging enhanced SVE trials should be conducted only in the periods of high groundwater levels and the trial treatment time should be relatively long in order to observe any physico-chemical changes that might have occurred in the saturated and unsaturated zone of the aquifer, especially in highly fractured rocks.

High extraction airflow rates can lead to rapid cooling of the soil/rock mass. Airflow through the extraction well network should be carefully controlled and balanced to minimise inefficiencies and heat losses from the system

Microbiological investigation is recommended to be undertaken before application of TESVE technology, especially for sites affected with halogenated hydrocarbons in order to establish the consortia of microorganisms present. The potential for biologically mediated contaminant reduction to assist thermal remediation during and after treatment may be considered to reduce total costs. If desired species of microorganisms, such as reductive dechlorinators, are present on site, they can provide a final polishing step or be a complementary process on the perimeter of the heated zone and inside hot spots during the cool down period.

The Automatic Thermal Desorption Gas Chromatography Mass Spectrometry (ATD GC-MS) or Gas Chromatography-Mass Spectrometry Purge and Trap techniques were found to provide the most accurate method of analysis for off-gas samples. This is due to the very low limit of detection, no interference with the standard and very accurate compound identification based on peak retention times and mass to charge ratio. These methods are considered most appropriate where low off-gas VOC sample concentrations are obtained for system performance evaluation and verification purposes.

Transparent and constant communication between all stakeholders is crucial when applying novel and cutting edge technology.

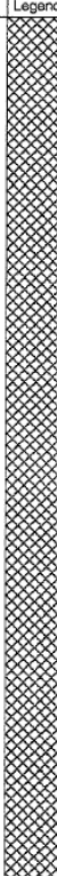
Where reliance is placed upon generated power, variations in fuel prices should be reflected in cost contingency.

REFERENCES

- Baker, R.S., Bierschenk, J.M., LaChance, J.C., Galligan, J.P., Tarmasiewicz, D., Heron, G., and Leach, W.R. 2008. Why In Situ Thermal Desorption can be the Most Cost-Effective Remediation Method for Many Sites. Proceedings of the Sixth International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2008).
- Baker, R.S., Brogan, D. and Lotti, M. 2006. Demonstration of Three Levels of In-situ Heating for Remediation of a Former MGP Site. Proceedings of the Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Columbus, OH May 2006).
- Beyke, G., and Fleming, D. 2005. In situ thermal remediation of DNAPL and LNAPL using electrical resistance heating. *Remediation*, 15(3), 5-22.
- Bierschenk, J.M., LaChance, J.C., Galligan, Heron, G., Tully D.M., Kozłowska A. and Langford S.R. 2008. Thermally Enhanced Soil Vapor Extraction Closing DNAPL Sites - Case Studies. Proceedings of the Sixth International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2008).
- CL:AIRE, 2008. In Situ Soil and Groundwater Decontamination Using Electric Resistive Heating Technology (Six-Phase Heating). CL:AIRE Technology Demonstration Project Bulletin TDP26 (April 2008)
- Environmental Protection Act 1990 (Chapter 43). 1990. UK Parliament Public General Act. http://www.opsi.gov.uk/acts/acts1990/Ukpga_19900043_en_1.
- Förstner, Ulrich. 1997. *Integrated Pollution Control*. Springer.
- Health and Safety at Work etc Act 1974 (Chapter 37). 1974. UK Parliament Public General Act. <http://www.opsi.gov.uk/acts/acts1974a>.
- Heron, G., Carroll, S., and Nielsen, S.G.D., 2005. Full-Scale Removal of DNAPL Constituents using steam enhanced extraction and electrical resistance heating. *Ground Water Monitoring and Remediation*, 25(4): 92-107.
- Heron, G., Baker, R.S., LaChance, J.C., Bierschenk, J.M., Ploug, N., Faurbye M., Langford S.R. and Tully, D.M. 2008. Thermal Conduction Heating for DNAPL Removal in Low-Permeability Soils and Bedrock. *ConSoil 2008*, Milan, Italy.
- Hiester, U. and Schenk, V. 2005. In-Situ thermal remediation: ecological and economic advantages of the TUBA and THERIS methods. *ConSoil 2005*, Bordeaux, France.
- Perry, R.H., Green, D.W. 2007. *Perry's Chemical Engineers' Handbook – 8th Edition*. McGraw-Hill.
- Stegemeier, G.L., Vinegar, H. 2001. Thermal Conduction Heating for In-Situ Thermal Desorption of Soils. *J Hazardous & Radioactive Waste Treatment Technologies Handbook*. Ch. 4.6-1, Oh, Chang H. (Ed.) Copyright 2001, CRC Press, Boca Raton.
- Unified Facilities Criteria. 2006: Design: In Situ Thermal Remediation. UFC 3-280-05. Department of Defense, USA.
- United States Environmental Protection Agency. 1997. Analysis of Selected Enhancements for Soil Vapour Extraction. Office of Solid Waste and Emergency Response (5102G). EPA-542-R-97-007.
- United States Environmental Protection Agency. 2004. *In Situ* Thermal Treatment of Chlorinated Solvents. Office of Solid Waste and Emergency Response. EPA/542-R-04-0100.
- Williams, H. G. 2008. Land Remediation Measurement – Molecular tools can provide lines of evidence for biological remediation. *AWE International Issue 10* p28-33 March 2008.

APPENDIX 1 - SVE1 WELL RECORD

Project Name UKAEA HARWELL	Project No. 100127	Hole Type RC
Location: WSA HARWELL		Scale 1:20
Client: UKAEA	Dates: 22/09/2005 to 24/10/2005	Logged By KC

Stratum Description	Legend	Depth (m)	Samples					Discontinuities				Well	
			Depth (m)	VOC's (mg/L)	TCR (%)	SCR (%)	RGD (%)	FI	Depth (m)	Type	Log		
BACKFILL TO PIT 3													
Weathered GREY CHALK		3.00											
Continued next sheet													

Remarks: 128 barrel from 0.0m to 1.4m with SW temporary casing. SWF barrel from 1.4m to 18.0m. Odour and PID reading of up to 51.2ppm noted on pulling core run from 3.5m to 4.5m. 100mm diameter stainless steel casing installed to 18.0m (slotted from 6.0m. Annulus: pea gravel 3.5m to 6.0m, bentonite seal 3.0m to 3.5m, cement/plaster sand grout 0.0m to 3.5m.



Project Name UKAEA HARWELL	Project No. 100127	Hole Type RC
Location: WSA HARWELL		Scale 1:20
Client: UKAEA	Dates: 22/09/2005 to 24/10/2005	Logged By KC

Stratum Description	Legend	Depth (m)	Samples				Discontinuities				Well	
			Depth (m)	GCs (mg/l)	TCR (%)	SCR (%)	RGD (%)	FI	Depth (m)	Type		Log
Weathered GREY CHALK												
Slightly clayey slightly silty sandy GRAVEL of weak to moderately weak argillaceous chalk		5.50										
Strong locally moderately strong light grey argillaceous CHALK		5.80										
		6.00	481.0									
				100	95	50	200					
Moderately weak light grey argillaceous CHALK		7.30										
....from 7.44 to 7.47m RUBBLE ZONE of weak gravel size chalk fragments		7.47										
Moderately strong locally moderately weak light grey argillaceous CHALK				100	76	39	75					
		7.99										

Remarks: 128 barrel from 0.0m to 1.4m with SW temporary casing. SWF barrel from 1.4m to 18.0m. Odour and PID reading of up to 51.2ppm noted on pulling core run from 3.5m to 4.5m. 100mm diameter stainless steel casing installed to 18.0m (slotted from 6.0m. Annulus: pea gravel 3.5m to 6.0m, bentonite seal 3.0m to 3.5m, cement/plaster sand grout 0.0m to 3.5m.



Project Name UKAEA HARWELL	Project No. 100127	Hole Type RC
Location: WSA HARWELL		Scale 1:20
Client: UKAEA	Dates: 22/09/2005 to 24/10/2005	Logged By KC

Stratum Description	Legend	Depth (m)	Samples				Discontinuities				Depth (m)	Type	Log	Well
			Depth (m)	OC's (mg/L)	TCR (%)	SCR (%)	RQD (%)	FI	Depth (m)	Type				
Moderately strong locally strong light grey argillaceous CHALK		8.50												
Moderately weak locally weak light grey argillaceous CHALK		9.12												
Moderately strong light grey argillaceous CHALKfrom 9.30 to 9.55m moderately weak from 9.55 to 9.58m RUBBLE ZONE of moderately weak gravel size chalk fragments		10.00												
Strong light grey argillaceous CHALK from 10.36 to 10.47m moderately weak locally weakfrom 10.47 to 10.57m moderately strongfrom 10.57 to 10.61m RUBBLE ZONE of moderately weak gravel size chalk fragments from 10.82 to 10.86m RUBBLE ZONE of moderately weak gravel size chalk fragmentsfrom 10.93 to 10.96m RUBBLE ZONE of moderately weak gravel size chalk fragments		10.30	239.0											
Moderately strong locally moderately weak light grey argillaceous CHALK		10.96												
Strong locally moderately strong light grey argillaceous CHALK		11.50												

Continued next sheet

Remarks: 128 barrel from 0.0m to 1.4m with SW temporary casing. SWF barrel from 1.4m to 18.0m. Odour and PID reading of up to 51.2ppm noted on pulling core run from 3.5m to 4.5m. 100mm diameter stainless steel casing installed to 18.0m (slotted from 6.0m. Annulus: pea gravel 3.5m to 6.0m, bentonite seal 3.0m to 3.5m, cement/plaster sand grout 0.0m to 3.5m.



Project Name UKAEA HARWELL	Project No. 100127	Hole Type RC
Location: WSA HARWELL		Scale 1:20
Client: UKAEA	Dates: 22/09/2005 to 24/10/2005	Logged By KC

Stratum Description	Legend	Depth (m)	Samples					Discontinuities					Well
			Depth (m)	TOC's (mg/L)	TCR (%)	SCR (%)	ROD (%)	FI	Depth (m)	Type	Log		
Very strong light grey argillaceous CHALK from 16.49 to 16.51m strong		17.00	16.12						16.12	JSP/S		-17	
			16.15							16.15			S/S
			16.21							16.21			S/S
			16.49		100	100	56		110	16.49			S/S
			16.51							16.51			S/S
Strong light grey argillaceous CHALK		17.50	16.58						16.58	S/S			
			16.76							16.76	J/S		
			17.14							17.14	JSP/S		
Very strong light grey argillaceous CHALK		18.00	17.18						17.18	J/S		-18	
			17.25							17.25			J/S
			17.27							17.27			J/S
			17.41		100	100	75			17.41			J/S
			17.52							17.52			S/S
.....at 17.95m ammonite fossil End of Borehole at 18.00 m		17.95	15.8					17.95	J/S				
		17.96	38.2					17.96	J/S				

Remarks: 128 barrel from 0.0m to 1.4m with SW temporary casing. SWF barrel from 1.4m to 18.0m. Odour and PID reading of up to 51.2ppm noted on pulling core run from 3.5m to 4.5m. 100mm diameter stainless steel casing installed to 18.0m (slotted from 6.0m. Annulus: pea gravel 3.5m to 6.0m, bentonite seal 3.0m to 3.5m, cement/plaster sand grout 0.0m to 3.5m.

