TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP16

EX SITU SOIL VAPOUR
EXTRACTION TO REMEDIATE
CHLORINATED HYDROCARBONS

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

CLAIRE

WHAT IS CL:AIRE?

CL:AIRE was established as a public/private partnership in March 1999, to facilitate the field demonstration of remediation research and technology, including innovative methods for site characterisation and monitoring, on contaminated sites throughout the UK. The results of project demonstrations are published as research or technology demonstration reports and disseminated throughout the contaminated land community.

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EX SITU SOIL VAPOUR EXTRACTION TO REMEDIATE CHLORINATED HYDROCARBONS

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This is a CL:AIRE Technology Demonstration Project 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 *ex situ* soil vapour extraction to remediate chlorinated hydrocarbons. It is not a definitive guide to *ex situ* soil vapour extraction. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

The project site, which is situated in North-West England, supported organic chemical manufacture from the 1940s to the 1990s when the last of the various plants were demolished to slab level. A number of chemicals used in production processes at the plants were released to ground during the lifetime of the plant including carbon tetrachloride (CTC) and chloroform (an impurity of the CTC).

A volume of approximately 2,500 m³ of soil (which included the highest concentrations of chlorinated organic compounds detected by previous investigations) was defined as requiring remediation with reference to Site Specific Target Levels (SSTLs). The area covered by this soil volume coincided with the location of the former CTC storage tanks.

The objectives of the project were as follows:

1.   An assessment of the performance of *ex situ* Soil Vapour Extraction (SVE) in above ground treatment beds;

2.   An assessment of the Health and Safety risks of excavation and treatment of chlorinated hydrocarbon contaminated soils along with a discussion of any associated air monitoring requirements;

3.   An assessment of the feasibility and uncertainties of a mass balance on volatilisation losses during excavation and treatment.

An *ex situ* SVE system was selected to remediate the site as it was assessed to be:

•   Cost-effective remediation when compared to other options;

•   Time-efficient remediation when compared to other options given the project aim which was to reduce concentrations of Volatile Organic Compounds (VOCs) in surface water drainage and remediate soils such that site specific cleanup criteria were met in a timeframe of 6 months or less;

•   The most efficient way to remediate contamination in awkward areas (e.g. within redundant process drains, clay pockets, former concrete structures, etc.).

The remediation methodology included excavation of contaminated soils, validation of soil quality in excavation sides and base, construction of the treatment bed, treatment bed filling, operation of the treatment bed, SVE plant operation and continuous assessment of treatment bed performance, periodic abstraction and treatment of water in the excavation, validation of soil treatment results and backfill of treated soils into the excavation void.

Health and Safety was treated as the number one priority at every stage of the project. Key elements included development of a pre-tender Health & Safety Plan, preparations of task specific method statements and risk assessments, management of risks arising from the release of VOCs to atmosphere and risk communication with neighbours to the site.

All treated material required validation testing prior to backfill. Concentrations in each treatment cell were below site specific cleanup criteria, with the exception of 1 treatment cell out of 40 cells, which did not meet the site specific cleanup criteria and was dispatched for off site pre-treatment and disposal. Validation sampling of the base and sides of the excavation void prior to backfill was carried out during the project - results indicated that the SSTLs were achieved.

Given that the project was competed in 6 months, the project achieved the stated contract objectives. In addition, there were no Health and Safety incidents or complaints from the public.

A VOC mass balance estimate is presented with the following parameters approximated:

•   Mass of contaminants present in remediation area at outset;

- Mass of contaminants emitted to atmosphere derived from extensive boundary and personal monitoring, weather data and air dispersion modelling. Personal and vapour monitoring points were situated at distances of 0-200 m from the excavation and treatment areas. Most emissions are likely to have occurred during excavation, treatment bed filling and treatment bed turning;

- Mass of contaminants present in activated carbon after treatment;

- Mass of contaminants collected by treatment system by measuring concentration passing through total discharge air flow;

- Mass present in treatment bed after treatment.

A VOC mass balance has been attempted using data collected through execution of the remediation project. Errors associated with the initial mass present and the mass emitted to atmosphere have not been quantified but are likely to be significant. However, the contaminant mass balance equates to within 10%. The authors are not aware of previous attempts to estimate the mass of VOCs emitted to atmosphere where excavation of VOC contaminated soils (including *ex situ* remediation and 'dig and dump') has taken place. The results presented by this mass balance indicate that 60-80% of VOCs present *in situ* prior to excavation may have been emitted to atmosphere. It is recommended that this finding is taken into account during the remediation options appraisal and design in relation to *ex situ* remediation of VOC contaminated materials.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

ADMS	Atmospheric Dispersion Modelling System (ADMS), Cambridge Environmental Research Consultants, 2002
AOD	Above Ordnance Datum
APF	Assigned protection factor
bgl	Below ground level
C_a	Concentration of contaminant in air
CFM	Chloroform
COC	Chain of custody
C_s	Concentration of contaminant in soil
CTC	Carbon tetrachloride
C_w	Concentration of contaminant in water
DOT	Department of Transport
EA	Environment Agency
EAL	Environmental Assessment Level
ESVE	*Ex Situ* Soil Vapour Extraction
GAC	Granular Activated Carbon
HDPE	High Density Polyethylene
K_d	Distribution coefficient
K_h	Henry's Law Constant
K_{oc}	Distribution coefficient for oil organic carbon
K_{ow}	Octanol/water partition coefficient
K_p	Partition Coefficient
MDL	Method Detection Limit
MEL	Maximum Exposure Limit
NAPL	Non Aqueous Phase Liquid
OES	Occupational Exposure Standard
PID	Photo-ionisation Detector
POCP	Photochemical Ozone Creation Potential
ppm	Parts per million
QA/QC	Quality Assurance / Quality Control
r_b	Bulk density
SSTLs	Site Specific Target Levels
STEL	Short Term Exposure Limit
SVE	Soil Vapour Extraction
SVOC	Semi Volatile Organic Compound
TWA	Time Weighted Average
US-EPA	United States Environmental Protection Agency
VOC(s)	Volatile Organic Compound(s)

1. INTRODUCTION

1.1 BACKGROUND

The technology demonstration described in this report took place within the bulk storage area of a former chlorinated rubber plant. Now demolished, this plant was situated within the central area of a former chemical works (also demolished, referred to in this report as 'the site'), which is situated in North-West England. The site, which was made up of a number of chemical plants, supported organic chemical manufacture from the 1940s to the 1990s when the last of the plants was demolished to slab level. Certain chemicals used in production processes at the plants were released to ground during the operating lifetime of the site. The former chlorinated rubber plant, referred to in this report as 'the plant', was one such plant where releases to ground occurred, in particular carbon tetrachloride (CTC) and chloroform (CFM) from the plant's above ground bulk chemical storage area.

A phased sequence of environmental site investigations has been carried out at the site. Ground conditions comprise made ground (variable depths but average occurrence 0 – 0.5 m of hardcore, pipe trenches, submerged concrete structures with associated viscous organic product containing chlorinated hydrocarbons) overlying a medium sand (average 0.5 – 2.0 m thickness), which in turn, overlies a stiff clay (>2.0 m). Soil samples generally collected from the upper 2 m of the soil profile and analysed for Volatile Organic Compounds (VOCs) have detected concentrations of these compounds (of which an average of 97% are CTC and CFM) of over 10,000 mg/kg.

ABB Engineering Services (ABB ES) were commissioned by the site owner to select and implement a remediation solution to (i) prevent CTC from contaminating a local stream and (ii) leave the area occupied by the chlorinated rubber plant suitable for commercial end-use. A volume of approximately 2,500 m³ of soil (which included the highest concentrations of CTC and CFM detected by previous investigations) was defined as requiring remediation with reference to site specific cleanup goals. The area covered by this soil volume coincided with the location of the former CTC bulk storage tanks.

1.2 PURPOSE AND OBJECTIVES

The objectives of the remediation project were:

- To remediate soils in the former bulk storage area to a standard that protects environmental receptors proximal to the site (i.e. the surface water drainage ditch to the east and the brook to the west);

- To remediate soils in the former bulk storage area to a standard that protects human health receptors in the event that the site is developed for industrial / commercial end-use;

- To carry out all work to the highest possible safety standards;

- To complete any remedial action within a 6 – 12 month time frame.

One of the key issues associated with implementation of the remediation project was the management of Health and Safety, in particular, release of VOCs to atmosphere and potential subsequent exposure of site workers or off site residents / the local community. As a consequence of this, a great deal of data was collected relating to potential exposure of site workers and off site residents to VOCs including use of real time photo-ionisation detectors (PIDs), personal monitoring units and passive boundary monitoring tubes. These data, in combination with soil and groundwater data, were used to prepare a VOC mass balance for the remediation as part of this demonstration project. Hence, the objectives of the demonstration project were:

- To assess the performance of *ex situ* soil vapour extraction (SVE) in above ground treatment beds;

- To assess the Health and Safety risks of excavation and treatment of *ex situ* chlorinated hydrocarbon contaminated soils along with a discussion of any associated air monitoring requirements;

- To assess the feasibility and uncertainties of a mass balance on volatilisation losses during excavation and treatment.

1.3 SCOPE OF WORK OF THE REPORT

This report presents the key aspects of the remediation project (including background to SVE, remedial technology selection, regulatory issues, system design and performance and economics) with a focus on the additional objectives that have been illustrated for the benefit of CL:AIRE and those interested in these aspects which are performance of *ex situ* SVE, Health and Safety issues associated with excavation of soils contaminated with VOCs and the feasibility of a VOC mass balance.

1.4 REPORT ORGANISATION

The report is divided into the following sections:

- Introduction;

- Background to the development of *ex situ* vapour extraction including theory and selection of preferred remedial method;

- Site description including history, drainage, geology, hydrogeology and contaminant distribution;

- Technology demonstration support issues including regulatory approval, compliance and licensing, Health and Safety and Quality Assurance/ Quality Control (QA/QC);

- Remediation design – including environmental and human health risk assessment, derivation of site specific target levels and delineation of remediation volume;

- Design and installation of *ex situ* SVE system including treatment bed, vapour extraction plant and water treatment arrangements;

- Implementation of the soil treatment using *ex situ* SVE including excavation of soils, loading the treatment bed, periodic turning of the treatment bed, operation of the treatment system and reinstatement of the successfully treated soils;

- Performance monitoring of treatment system including treatment beds and calculation of VOC mass recovery rates;

- Air dispersion modelling to estimate mass of VOCs released to atmosphere as a result of project operations;

- Performance evaluation including a VOC mass balance for the project;

- Economic considerations;

- Conclusions;

- Lessons learned.

2. BACKGROUND TO THE DEVELOPMENT OF *EX SITU* SOIL VAPOUR EXTRACTION

2.1 INTRODUCTION

This chapter provides a brief description of Soil Vapour Extraction (SVE) and *Ex situ* Soil Vapour Extraction (ESVE). It then outlines the selection process undertaken leading to the use of the method at the demonstration site. For more detailed information see LaGrega *et al*., 1994.

2.2 WHAT IS SOIL VAPOUR EXTRACTION?

At its simplest, soil vapour extraction is a means of removing volatile organic compounds (VOCs) from unsaturated soils. It is a physical mass recovery technique for this group of compounds.

In a typical granular mineral soil, VOC contaminants are likely to be present within pore spaces. Uncontaminated soil pores will contain pore water, residually held in the soil pore, with the rest of the pore space containing gas, also termed soil vapour. The gas within the pore space will be made up of water vapour, the gaseous components of air (but probably in different proportions to air), with other gases such as methane.

A typical VOC present in soil will exist in four 'phases' within soil pore spaces. These phases describe the physical form of the VOC in a soil:

- Adsorbed phase (molecules actually attached to soil particle surfaces);

- Liquid phase (residually held by capillary and surface tension forces within pore spaces);

- Dissolved phase (within pore water);

- Vapour phase (within soil gas in soil pores).

In an unsaturated soil contaminated with a VOC (or mixture of VOCs) at equilibrium (i.e. has not been disturbed by any external influence for some time), the VOC will exist in all four phases in proportions determined by the soil's and the VOC's physico-chemical characteristics. These phases will co-exist in this 'steady state'. Individual molecules may move from one phase to another, often termed 'partitioning', but the overall proportions of the phases will remain constant.

The SVE technique takes advantage of the physical properties of VOCs, specifically, the ability of the compounds to easily partition into the vapour phase from the other phases present.

If the soil gas is removed from a pore space in an unsaturated soil, using, for example, a vacuum pump drawing soil gas into an extraction well, there is a means of removing VOC mass from the soil. Given that VOC vapour (within soil gas) is in equilibrium with the other VOC phases listed above, when VOCs are removed from a pore space, the system will restore equilibrium through partitioning of VOCs into the vapour phase from the other phases present. If this process of volatilisation (partitioning to the vapour phase) and soil gas removal is continued, then it can lead to increasing VOC contaminant mass removal from unsaturated soils.

Once soil gas is extracted from soils through a vacuum pumping system it is then treated to control VOC emissions to atmosphere. The two most common vapour treatment methods are:

- Granular activated carbon adsorption; and,

- Catalytic oxidation.

The increased oxygen flow through the subsurface can also stimulate aerobic biodegradation of some VOC contaminants. However, the mechanism for the degradation of VOCs is not within the scope of this work, particularly as the target contaminant, carbon tetrachloride is not biodegradable in aerobic environments at rates significant to the remediation.

Figure 2.1 displays a typical *in situ* soil vapour extraction scheme.
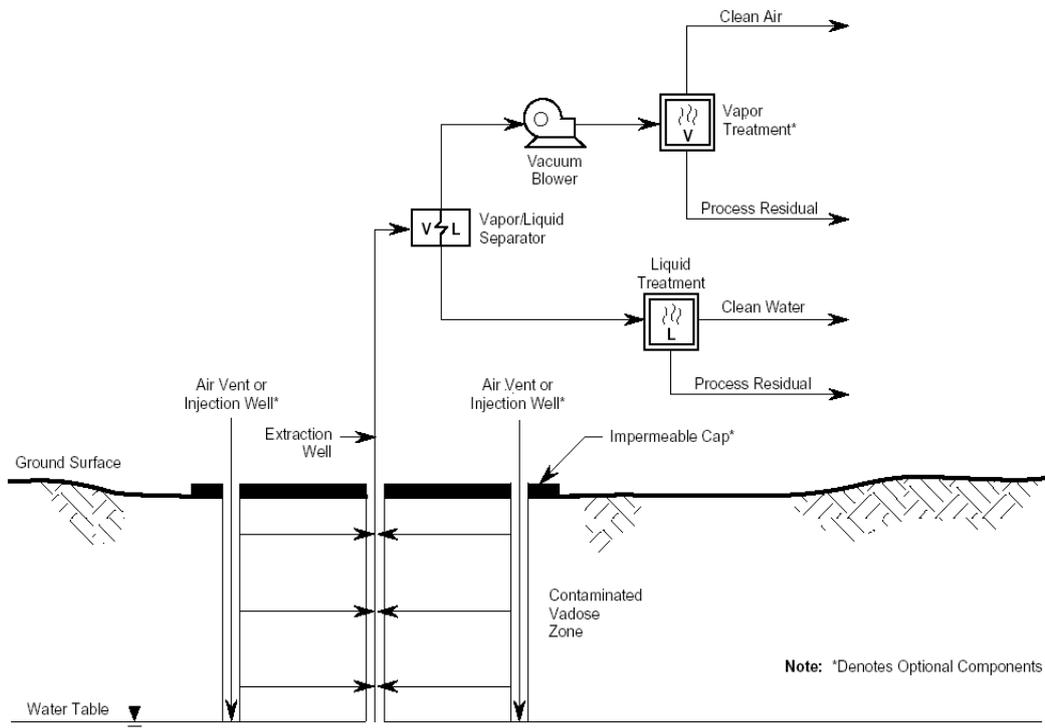
Figure 2.1: Generic *In Situ* Soil Vapour Extraction Scheme (from USACE, 2002).

The SVE technique may be considered to have two basic requirements to be applied successfully:

- The contaminant must be volatile; and,

- It must be possible to extract soil vapour from the soil pores in the contaminated soil.

Any assessment of the SVE technique in its application to the remediation of a particular site must first consider these two requirements. It is as part of the second consideration that application of SVE *in situ* or *ex situ* may be made depending on specific site constraints.

The terms *in situ* and *ex situ* simply 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 in some form of treatment area (*ex situ*).

2.3 OVERVIEW OF SOIL VAPOUR EXTRACTION THEORY

The performance of SVE is based on the physical properties of the contaminants and the soil medium in which they are found. The most important characteristics influencing SVE for a contaminant are vapour pressure and Henry's Law Constant while the most important characteristics influencing soil vapour extraction for a soil-type are soil sorption coefficient and air permeability.

2.3.1 VOC PROPERTIES

Vapour pressure, the tendency of a solid or liquid to evaporate, is defined as the force exerted by the vapour of a chemical when it is in equilibrium with its pure solid or liquid form. A high vapour pressure aids soil vapour extraction by ensuring the contaminants are available in soil gases for extraction from non aqueous phase liquid (NAPL).

Solubility controls the degree to which a VOC dissolves into groundwater and pore water present in the unsaturated soils. The Henry's Law Constant affects the ability of a substance to volatise from aqueous solution.

The octanol/water partition coefficient (K_{ow}) of a VOC is defined as the ratio of its concentration in octanol to its concentration in water of a two-phase octanol/water system. K_{ow} is an essential parameter in describing the fate of organic chemicals in environmental systems. It is related to the water solubility, soil/sediment adsorption coefficient and the bio-concentration factors for aquatic species. The meaning of K_{ow} in terms of remediation is the tendency of a chemical to partition itself between an organic phase and an aqueous phase. VOCs that have a low K_{ow} value (<10) may be considered relatively hydrophilic and tend to have a high water solubility and small oil/sediment adsorption coefficients. Conversely, a chemical with a large K_{ow} (>10^4) is considered hydrophobic and tends to accumulate at organic surfaces, such as on humic (high carbon content) soils (USACE 2002).

Figure 2.2 below displays the relationship of these parameters and other properties with the soil, water and contaminants in their different phases.
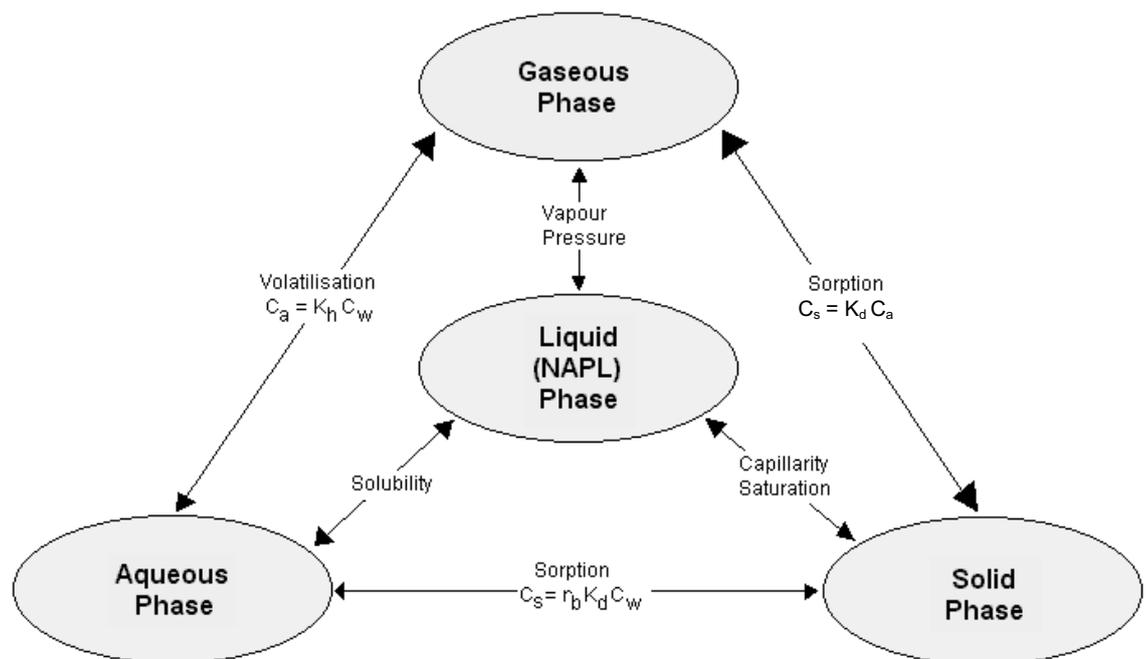
Figure 2.2: The Partitioning of VOCs (adapted from USACE 2002).

In this figure C_a, C_w and C_s, refer to the concentration of VOC component in air, water and soils respectively. K_h refers to the Henry's coefficient. K_d refers to the partition coefficient (gas-solid or water-solid as applicable) and r_b to the bulk density of the soil.

2.3.2 SOIL PROPERTIES

Soil sorption coefficient (K_d) controls the distribution of vapours after partition from the other phases, it determines whether the VOC contaminant remains in the vapour phase where it is free to move along pressure gradients, through interconnected soil pores, or it is sorbed to the surface of soil particles. Soil sorption coefficient is strongly related to the organic carbon content of the soil. As the proportion of organic carbon in the soil increases, so does the sorption coefficient. For this reason, higher organic carbon concentrations in soils result in lower proportions of VOC mass capable of being recovered by SVE over a reasonable time frame as much of the contaminant may be sorbed to the surface of soil particles.

Soils are highly variable in their physical and chemical characteristics. In most cases, variability is much greater vertically than horizontally. The soil variability, in turn, will result in variability in the distribution of water and contaminants and the ease with which they can be transported within, and removed from, the soil at a particular site. This soil heterogeneity may isolate areas of the subsurface from the effects of SVE.

Air or pneumatic permeability incorporates a number of soil properties to allow quantification of how easily a non-compressible gas can move throughout the soil. The soil properties influencing air permeability are:

- Stratigraphy;

- Air filled porosity;

- Particle size distribution;

- Residual saturation; and

- Presence of preferred flowpaths.

The complexities of the relationships between these properties means that air permeability can only be properly measured in the field. Preferably, the air permeability of a site should be measured in a number of locations to ensure that a representative value for the site is obtained, and even then, small-scale changes in soil properties can have large effects on the results.

Water content of soil in a SVE system can influence the success of the system greatly as water content influences many of the properties listed above. Water content, however, can also increase sorption coefficients to soil at very low values. A range of 94 to 98.5% relative humidity in soil gas appears to be optimal for SVE (FRTR 1995, USACE 2002).

USEPA (1996) defines the following (Table 2.1) as suitable remediation parameters for a SVE scheme.

Table 2.1: Parameters for Remediation Using SVE.

Contaminant Property:	Soil Property:
VOC Vapour Pressure > 0.5 mm Hg	Soil Permeability > 10^{-6} cm²
Dimensionless Henry's Constant >0.01	Soil Moisture < 50%
	Soil / Air Filled Porosity < 40%

2.3.3 PROPERTIES OF CARBON TETRACHLORIDE

The physical and chemical properties of carbon tetrachloride are outlined in Table 2.2. These properties dictate the rate and potential for physico-chemical interaction of the contaminant with the surrounding environment.

Table 2.2: Physical and Chemical Properties of Carbon Tetrachloride.

Property		Information / Value
Chemical Formula		CCl_4
Chemical Structure		Cl—C—Cl with Cl above and Cl below
Molecular Weight		153.82
Colour		Colourless
Physical State		Liquid
Melting Point		-23°C
Boiling point		76.5°C
Density		1.594 g/ml
Odour		Aromatic, Sweet, Ethereal
Odour thresholds:	In Water	0.52 mg/L
	In Air	40 parts per million (ppm)
Solubility	Water at 20°C	800 mg/l
	Organic Solvents	Miscible
Partition Coefficients	Log Kow	2.64
	Log Koc	2.04
Vapour Pressure	At 20°C	91.3 mm Hg
Henry's Law Constant	At 20°C	2.04×10^{-2} atm-m³/mol
	At 24.8°C	3.04×10^{-2} atm-m³/mol
	At 25°C	2.94×10^{-2} atm-m³/mol
	At 30°C	3.37×10^{-2} atm-m³/mol
Auto Ignition Temperature		Non-flammable
Flashpoint		Non-flammable
Flammability Limits		Non-flammable
Conversion Factors	ppm (v/v) to mg/m³ In air at 25°C	1 ppm = 6.39 mg / m³
	mg/m³ to ppm (v/v) In air at 25°C	1 mg / m³ = 0.16 ppm
Explosive Limits		Non explosive

The vapour pressure of carbon tetrachloride at 20°C is 91.3 mm Hg, far in excess of the minimum discussed (0.5 mmHg) as practical for SVE. The Henry's Constant at 2.94×10^{-2} is also above the minimum practical recommended value (0.01).

SVE is therefore a potential technique for the remediation of carbon tetrachloride.

2.4 CASE STUDIES OF CARBON TETRACHLORIDE REMEDIATION USING SVE

2.4.1 CASE STUDY 1: HASTINGS SUPERFUND SITE

In situ SVE was used to remediate a Superfund contaminated site in Hastings Nebraska (FRTR 1995). At this site, approximately 140,000 m³ of soil was contaminated with carbon tetrachloride, peak values of which were between 1,000 and 1,500 ppm. The site had been used as a grain storage facility, with carbon tetrachloride used as a grain fumigant. SVE was selected as the most applicable remediation technology and was used to remove 275 kg of carbon tetrachloride from three soil strata.

Remediation took place over 11 months (including pilot testing phase, lasting 2 months) at a total cost of US $370,000 (£260,000). The comparatively long cleanup time was due to the large volume of soil to be treated (which precluded *ex situ* treatment methods), combined with low air permeability values for each soil strata.

2.4.2 CASE STUDY 2: HANFORD NUCLEAR SITE, WA.

Waste containing carbon tetrachloride, used in plutonium extraction processes was discharged into soil at the Hanford Nuclear Site in Washington State between 1949 and 1973. Studies of inventory suggested that a total of approximately 1000 tons of carbon tetrachloride was discharged, creating an 80 m thick plume over an 11 km² area. Peak carbon tetrachloride concentrations in soils were recorded as 7 ppm (parts per million).

In situ SVE, combined with groundwater pump and treat was used to remediate the highest contaminated areas of the plume. A total of 83,500 kg was removed from soil, 80,000 kg from the vadose zone using SVE and 3,500 kg from groundwater. Although in this site cost benefit studies showed that both SVE and groundwater pump and treat were not effective at meeting remedial goals, the remediation methods used were shown to be effective for remediating carbon tetrachloride (Goswami 2000). At present, regulators are investigating alternative innovative technologies including *In situ* Redox Manipulation.

These case studies demonstrate the successful application of SVE to soil contaminated with carbon tetrachloride and helped support the choice of SVE for the remediation at the demonstration site.

2.5 DEVELOPMENT OF *EX SITU* SOIL VAPOUR EXTRACTION

2.5.1 *EX SITU* SVE CASE STUDY

In 1997, xylene contamination was discovered on the site of an oilfield services company in Alberta, Canada. Feasibility studies showed that *in situ* SVE was not suitable for the site, although xylene could be treated by SVE. Due to time constraints an *ex situ* SVE remediation scheme was determined the best available option, when combined with steam injection. As Plate 2.1 shows, a treatment bed was constructed with air injection pipes at the base (left). Once the soils were placed in the treatment bed, it was sealed and steam was pumped through the soil and through vapour phase granular activated carbon vessels (right). The use of steam injection resulted in a shorter treatment time and successful remediation.

Plate 2.1: Hot Air Enhanced SVE, Alberta, Canada.
(Photo: Joe Ross, Remedx Remediation Services Ltd)

2.5.2   *IN SITU* VERSUS *EX SITU* SVE

Ex situ SVE is a development of *in situ* SVE. Instead of the soil being treated in its natural state, the soil is excavated for treatment. A treatment bed is constructed above ground and lined with an impermeable membrane while an array of venting slotted pipes is placed at the base of the bed and manifolded to a conventional SVE system. Excavated soils are then placed in the treatment bed and covered with an impermeable cover. The SVE system is then operated as normal.

Both applications of SVE *in situ* and *ex situ* have their own advantages and disadvantages. Which remediation technique is most suitable depends heavily on the nature of the site, operational constraints and contaminant types.

2.5.2.1   Advantages of *Ex situ* SVE and Disadvantages of *In situ* SVE

Ex situ SVE's greatest advantage over its *in situ* counterpart is that the remediation is not limited by the heterogeneity of the subsurface. This has great implications for the treatment of contaminants.

In situ SVE is often limited by the structure of the soil, poor pore connectivity and porosity can limit the transport and therefore rate of removal of VOCs from the soil matrix. This combined with the presence of preferred flow paths can result in incomplete treatment of the soil mass.

In situ vapour extraction is also limited by the natural thickness of the vadose zone, which may be variable throughout the duration of treatment, soil below the piezometric surface cannot be treated by SVE. Vacuums created by SVE equipment always raise the water table, the amount it is raised depends on the vacuum applied and the hydraulic properties of the soil. The thickness of the vadose zone can be reduced or maintained artificially during *in situ* SVE by groundwater pumping; this requires treatment and disposal of abstracted water and relevant licensing arrangements with local authorities.

Ex situ SVE can break up soil structures to any required degree and therefore can engineer soil according to the contaminant properties and the requirements of the remediation. Increased air permeability of the soil will result in shorter treatment times. Settlement of soil and rearranging of soil particles may occur during remediation leading to a soil structure less suited to SVE, this problem can be overcome by turning the soil as necessary to maintain optimum soil properties.

Verification of treatment of soil by *in situ* SVE can also be very difficult, and prediction of treatment times is less accurate for *in situ* techniques.

Ex situ techniques enable monitoring during treatment to be carried out at any stage so estimates of duration of treatment and contaminant mass removal are easier. Areas of soil not suitable for treatment are readily identified and can be sent for further treatment and disposal off site if necessary. Alternatively, extended treatment times can be used for soils that are more difficult to treat. The treatment bed is generally lined so that any leachate produced during treatment can be easily collected and treated. The treatment bed is also capped, therefore less contaminated water is produced during the remediation works due to the fact that no rainfall enters and percolates through the contaminated soil.

2.5.2.2 Disadvantages of *Ex situ* SVE and Advantages of *In situ* SVE

The main disadvantages of *ex situ* SVE as opposed to *in situ* works stem from the need to excavate soils. For an *in situ* system no costs are incurred for excavation, depending on site conditions and volume of soil to be treated, these costs may be substantial for an *ex situ* system.

If the groundwater table needs to be lowered to increase the volume of the treatment zone during *in situ* operations, the water can simply be pumped out, this is more difficult when excavation is taking place at the same time.

The excavation of soils also means that normal business cannot continue on site during treatment, *in situ* treatment on the other hand is comparatively non-disruptive.

As SVE is focused on volatile chemicals, there is a large risk from excavation to treatment that emissions to the atmosphere will occur. Proper working practices may reduce emissions but not to the same level as working *in situ*. This problem applies to the safety of site personnel and the general public beyond site boundaries.

In addition, CTC and CFM exhibit photochemical ozone creation potential (POCP) and emissions are harmful to the ozone layer (leading to stratosphere ozone depletion).

The amount of space required for an *ex situ* treatment system is also considerably larger than that needed for an *in situ* system as both the area of excavation and the treatment bed may be extensive.

The main advantage of the *in situ* technique is the absence for a need to excavate. However, since the remediation is *in situ* there is less control over the soil media. Factors such as soil stratification pneumatic/air permeability and contaminant properties play a large role in the success of a SVE scheme. *Ex situ* SVE is not dependant on the *in situ* soil media properties.

3.   SITE DESCRIPTION

3.1   SITE LOCATION AND TOPOGRAPHY

The subject site is part of a former chemical works and is irregular in shape measuring approximately 400 m by 250 m and covering an approximate area of 10 ha. The site layout is shown in Figure 3.1 and Figure 3.2.
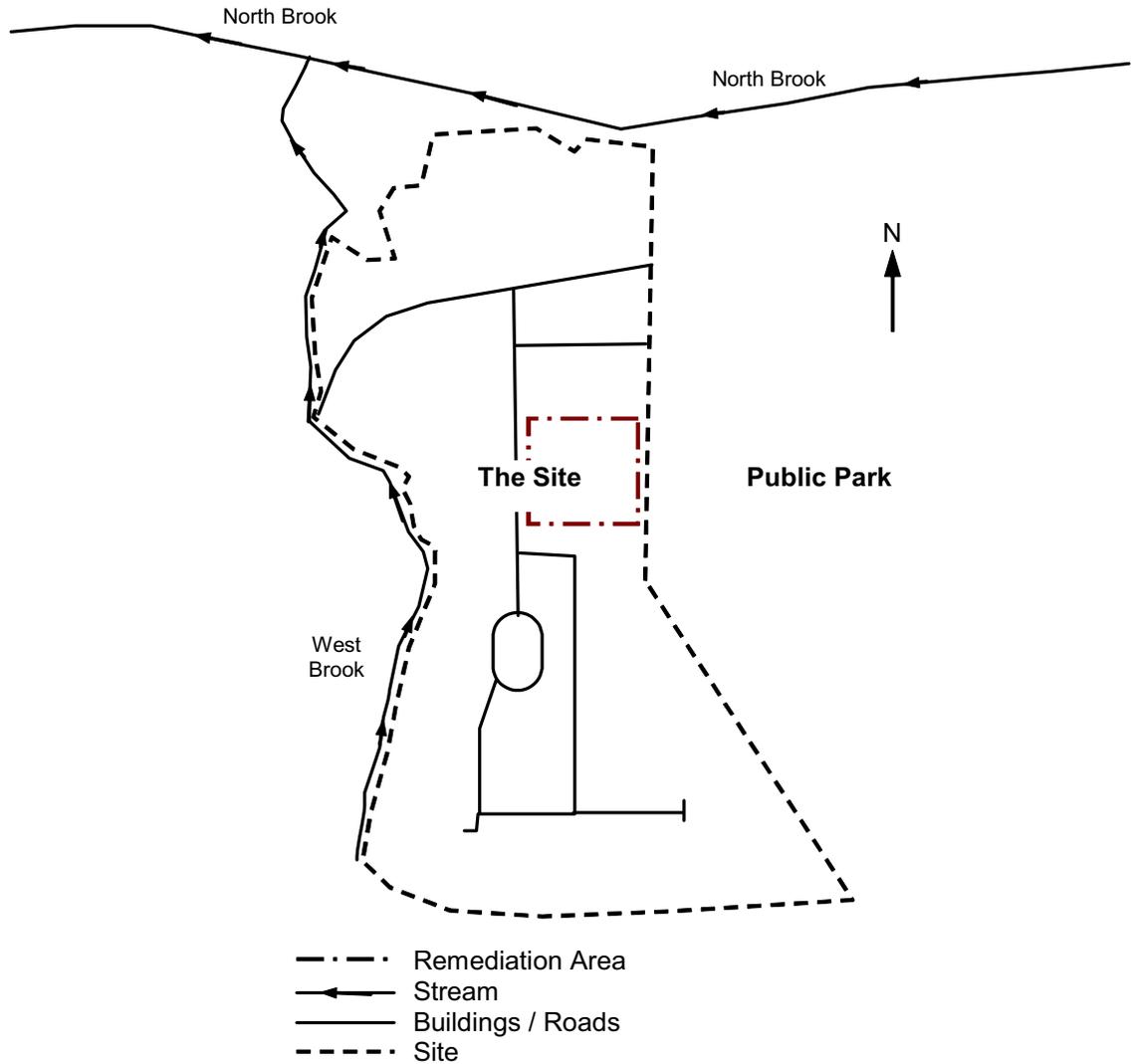
Figure 3.1: Site Layout (not to scale).

The site lies on flat ground at an elevation of approximately 22 mAOD . To the north of the site is an area of grassland and rail sidings, beyond which is a stream, North Brook. To the east, the site is directly bordered by a drainage ditch (East Ditch) beyond which is a former Landfill (now remediated by capping and development of a public park), which itself includes a former lagoon for liquid waste.

To the south of the site is residential housing and small industrial developments while to the west, the site is bounded by a further stream, West Brook, beyond which are allotments and residential properties. West Brook is at an elevation of approximately 17 mAOD , with an approximate 4 m to 5 m high bank along the brook's eastern side where it forms the western boundary of the site.

3.2 SITE HISTORY

The history of the site and surrounding area has been taken principally from previous reports and is summarised below:

- 1880 Ordnance Survey map: The site is shown as farmland;

- 1899 Ordnance Survey map: A Salt Works (salt pans) is located in the northern area of the site and a Brick Works and Brick Field are situated in the south. A Bleach Works is shown to the north of North Brook and a Chemical Works is shown to the east of the site comprising soda ash, sulphuric acid, saltcake and bleaching powder plants;

- 1903 Ordnance Survey map: Additional salt pans shown in outline in the NE of the site and lime beds (old, existing and new) are shown to the east of the site;

- 1930s: The salt works located in the north of the site were closed and dismantled;

- 1939 to 1944: Construction of the works on site commenced on the south bank of North Brook with chlorine and by-products plants comprising tropical bleach, hydrochloric acid, sulphur dichloride (2 plants), monochlorobenzene and an oil distillation plant. Ethylene, thiodiglycol (syrup), chlorinated rubber and carbon tetrachloride (CTC) plants, boiler house and hydrogen compressor were built between the limebeds and West Brook. During the war years (1939 to 1945) the site was operated under the instructions of the Ministry of Supply;

- 1977 to 1989: site was demolished with the exception of the Chlorinated Rubber Plant;

- 1993: The Chlorinated Rubber Plant was closed and demolished;

- 2002 to 2003: Remediation of the Chlorinated Rubber Plant Bulk storage area on the site (the subject of this report).

Chlorinated Rubber was produced from the direct chlorination of synthetic rubber. The reaction was carried out in a solution of rubber in carbon tetrachloride to produce chlorinated rubber particles, which were separated and dried to a powder. The carbon tetrachloride (reportedly containing chloroform as an impurity) was imported from other sites. The Chlorinated Rubber Plant was located in the centre of the site and occupied a relatively small parcel of land measuring approximately 60 m by 60 m (0.36 ha). The historical layout of the plant is known from historical site plans which assisted identification of the location of potential contaminant source areas.

Drain
Stream
Building / Road / Tank
Approximate Extent of Remediation Area
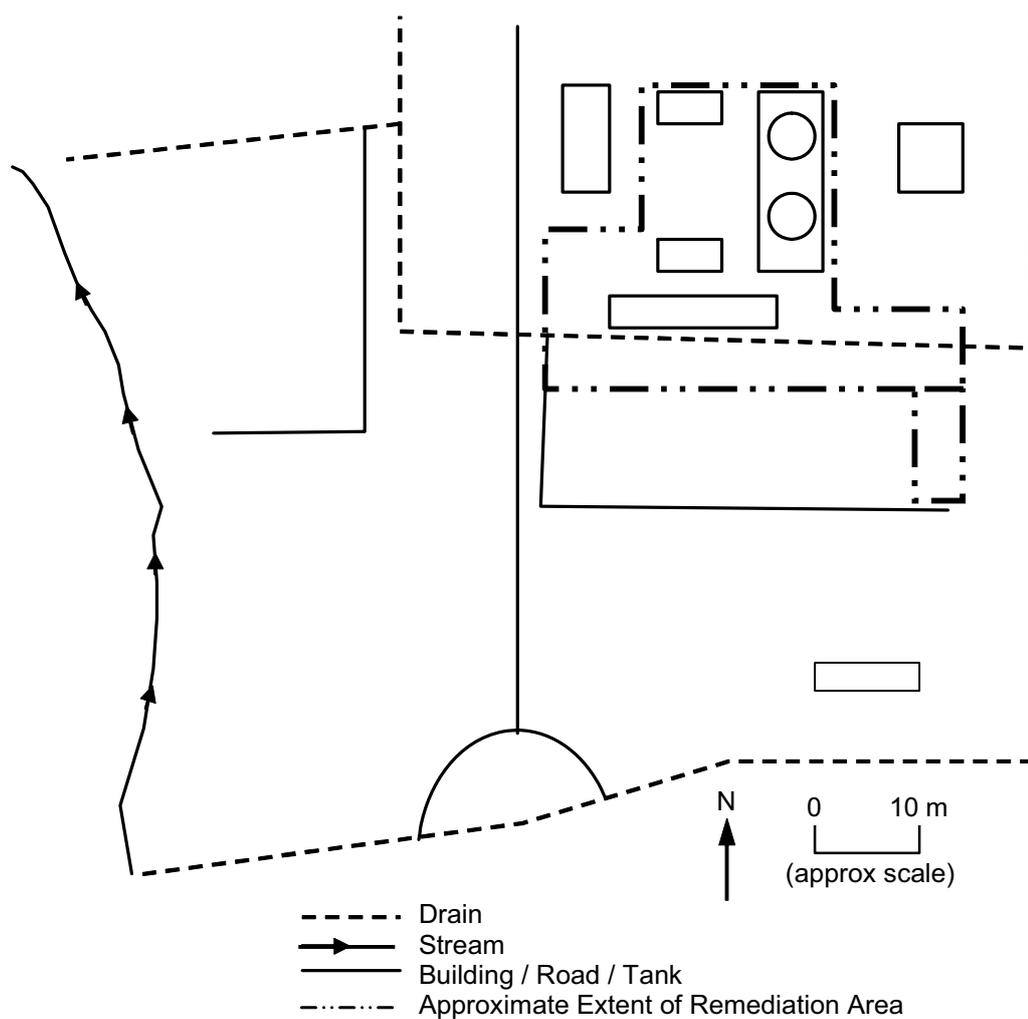
Figure 3.2: Historical Site Layout.

3.3 SUMMARY OF EARLIER ENVIRONMENTAL INVESTIGATIONS AND REPORTS

Numerous investigations, assessments and other works related to ground and groundwater contamination have been carried out on the site and surrounding areas by MJ Carter and Associates and ABB (see references). The reports of the work relevant to the former chemical works comprise: -

- Former Chlorinated Rubber Plant, Soil and Groundwater Assessment;

- Report on the Options for Remediation and Development of the Former Chemical Works Site;

- Assessment of the Impact on Groundwater and Surface Water of the Contaminants Present at the Former Chemicals Works;

- Assessment of the Risk to Groundwater, Surface Water and Future Site Users from the Contaminants Present at the Former Chemical Works;

- Former Chlorinated Rubber Plant Hotspot Investigation;

- Multi-Phase Vacuum Extraction Pilot Test: Results and Assessment, Former Chlorinated Rubber Plant.

Former Chlorinated Rubber Plant; Soil and Groundwater Assessment; Environmental Setting; September 1992

The report examined historical and published records of the geology and hydrogeology of the Former Chlorinated Rubber Plant and identified off site targets that may potentially be at risk from any on site contamination.

Assessment of Soil and Groundwater Contamination Stage I – Historical Review, Former Landfill Site; January 1996

The Historical Review (or desk study) covered the Former Landfill and surrounding land including the Former Chemical Works. The review describes site features, historical operations, summarises previous investigations and provides a preliminary hazard assessment.

Report on the Options for Remediation and Development of the Former Chemical Works Site; May 1996

The report reviewed options for the remediation of the site, including the Former Chlorinated Rubber Plant, with the objective of minimising long-term environmental liabilities and returning the site to a condition suitable for the development for light industry. The report is based upon data presented in the Historical Review and investigation data from the period between 1990 and 1996.

Interpretative Report of the Ground Investigation at the Former Landfill and Chemical Works; February 1997

The report provides an interpretation of a ground investigation carried out on the site and adjacent areas in September 1996. The investigation had been designed to address future remediation and potential redevelopment of the site and to outline the specification and engineering requirements for remediation of the main landfill. The fieldworks comprised the installation of 27 boreholes, the excavation of 69 trial pits and dynamic probing on the landfill. Soil, groundwater, surface water and soil vapour samples were taken and analysed.

Assessment of the Impact on Groundwater and Surface Water of the Contaminants Present at the Former Chemical Works; February 1997

The report provides an assessment of the risks presented to groundwater and surface water (i.e. controlled water receptors) by the presence of contamination on the Former Chemical Works. The assessment used data on groundwater and surface water quality from the investigations described above.

Assessment of the Risk to Groundwater, Surface Water and Future Site Users from the Contaminants Present at the Former Chemical Works; July 1998

The report described the distribution of contaminants at the site and an assessment of potential risk to environmental receptors and future site users. The future use was proposed to be a public open space developed under a scheme with public sector support.

Former Chlorinated Plant Hotspot Investigation; June 2001

This report describes a site investigation carried out in April 2001 to investigate VOC contamination in the Former Landfill northwest toe ditch and to delineate CTC contamination in the Former Chlorinated Rubber Plant area. The investigation comprised soil gas, soil and surface water sampling and analysis. VOCs were measured in soil gas in 1 m deep probe holes at 65 locations within a 40 m radius of trial pit TP9 (1996 Site Investigation – see above). Nine trial pits were excavated in locations with high VOC readings and soil samples were taken from each trial pit and were analysed for VOCs. Surface water samples were taken from the Former Landfill toe ditch (the length adjacent to the Former Chlorinated Rubber Plant) and were analysed for pH and VOCs.

It was concluded that it was likely that the VOC contamination of the toe ditch was caused by the migration of contamination present in the ground at the Former Chlorinated Rubber Plant. It was also concluded that it was unlikely that the source of contamination in the toe

ditch was leachate from the Former Landfill. A recommendation was made that an area of approximately 850 m² should be excavated to a depth of between 2.0 m and 2.85 m and that the arisings should be removed for disposal. This recommendation was made to remove the CTC hotspot and was not a risk-based remedial target.

3.4   DRAINAGE

Present drainage on the site is associated with an adjacent landfill (now remediated as a leisure amenity / public park through capping and landscaping). Surface water runoff from the Park flows in open ditches along the east boundary of the Site and then flows in a surface water culvert under the site in a westerly direction to discharge into West Brook at a former outfall (No. 1) on the western boundary of the site.

Leachate drainage from the Park flows in a 450 mm diameter concrete drain in a northerly direction to discharge into North Brook immediately upstream of a rail crossing. The leachate discharge operates under an Environment Agency (EA) consent. In addition, a pumped foul sewage drain from an adjacent active Works is routed through the northern section of the site and discharges into the public sewer. There are no details on the exact route of this pumped drain.

Historically, drainage from the central and southern sections of the site discharged into West Brook through three separate outfalls, Numbers 1, 2 and 3.

It is reported that this drainage was isolated (but not removed) during the demolition of the Chlorinated Rubber Plant. Plant drains discharging into the surface water culvert were also blocked. However, the main drain to Outfall 1, which discharges surface water from the Park and the site was live during the project.

3.5   GEOLOGY AND HYDROGEOLOGY

Site investigations indicate that the site is underlain by made ground overlying a sequence of glacial deposits. According to published sources, the glacial deposits are up to 18 m thick and overlie approximately 500 m of Mercia Mudstone deposits. Beneath the Mercia Mudstone is the Sherwood Sandstone. The glacial deposits and the Mercia Mudstone are considered non-aquifers. The Sherwood Sandstone is a major aquifer of regional importance although it is not exploited in this area.

The made ground occurred at variable depths but average occurrence was 0-0.5 m. The composition was variable including hardcore beneath former roadways, former pipe trenches filled with concrete/brick demolition rubble, and submerged concrete structures. Viscous organic product containing chlorinated hydrocarbons was also present within the made ground and upper sand (see Plate 7.3) which, when sampled, indicated concentrations of VOCs of over 10,000 mg/kg. Prior to remediation, an unknown volume of this material (which is thought to have been an intermediate of the site process and contain chlorinated rubber) was present in the former Chlorinated Rubber Plant above ground bulk chemical storage area.

The glacial deposits principally comprise stiff sandy or gravelly clay (i.e. typical boulder clay deposits). Two significant water bearing sand lenses have been identified by the investigations to date within two sand horizons at different depths.

An upper sand lens is present beneath the former Chlorinated Rubber Plant which is generally 1 m to 2 m thick and to be found at the top of the glacial sequence, immediately below the made ground. This lens appears to be continuous westwards from the former Plant location towards West Brook. It is possible that the sand lens outcrops in the eastern bank of West Brook, although this has not been confirmed. It is assumed for the purposes of the remedial goal calculations (see Section 5.1) that this sand lens is continuous westwards from the Plant to West Brook. Unconfined groundwater is present in this shallow sand lens at a depth of <1 m. The groundwater in the sand lens beneath the Plant appears to be flowing westwards towards West Brook at a maximum hydraulic gradient of 0.05. The

saturated thickness of the sand lens is 1 m to 2 m and it is assumed that the sand lens is in hydraulic conductivity with the brook, although a direct hydraulic connection has not been proven.

The second significant sand lens is beneath the northern part of the site, but does not appear to be fully continuous beneath the Plant. This deeper sand lens is up to 2.5 m thick and lies within the boulder clay sequence at an elevation of between 13 mAOD to 16 mAOD, i.e. at depths of 6 m to 9 m below ground level. This lens appears to be continuous northwards towards North Brook.

The deeper sand lens is water bearing and is likely to be fully saturated and possibly semi-confined. The groundwater in this sand lens flows northwards towards North Brook. It is assumed that the sand lens is in hydraulic conductivity with North Brook, although as with West Brook and the shallow sand, a direct hydraulic connection has not been proven.

An east-west orientated schematic geological cross section through the site is shown in Figure 3.3.
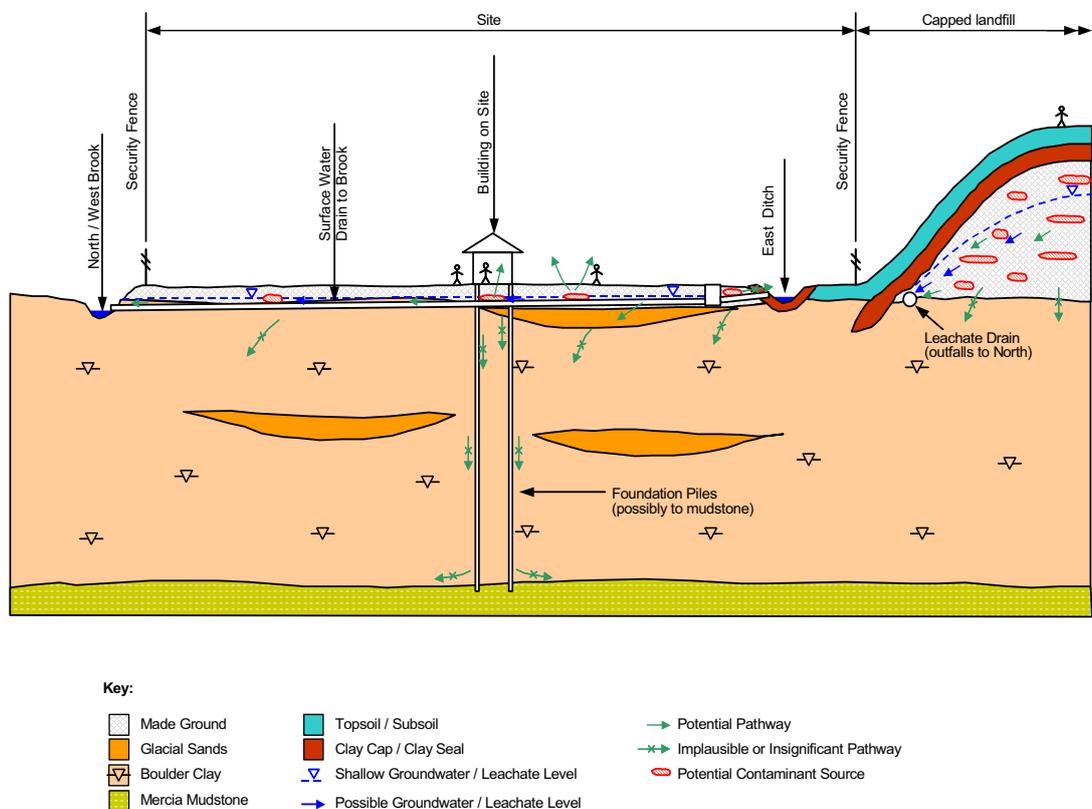
Figure 3.3: Geological Cross Section.

3.6   NATURE AND EXTENT OF CONTAMINATION

3.6.1   SOIL CONTAMINATION

Soil concentration data from several phases of investigation were available at the outset of the remediation project to characterise the contaminant distribution. They are presented in Figure 3.4.

Key

Depth (m)	
CTC (mg/kg)	
CFM (mg/kg)	

TP1

0.4 m	0.8 m
0.21	2.66
0.02	2.64

TP2

0.3 m	2.0 m
0.17	0.78
0.01	3.54

TP3

0.4 m	1.7 m
110.5	65.3
1.42	7.27

TP4

0.4 m	1.6 m
35.51	0.42
3.20	3.95

TP9 (1997)

0.3 m	0.6 m	1.6 m
16,984	131.9	0.12
146.7	4.32	0.16

TP9

0.4 m	1.2 m
6,134	17.1
44	0.18

MW2

0.5 m
250
<MDL

SV1

0.5 m
6,920
<MDL

MW4

1.0 m
5.7
<MDL

TP5

0.4 m	1.6 m
4.54	200.4
0.71	14.65

TP8

0.3 m	1.4 m	2.0 m
7,961	4,602	27.65
478.9	176.1	18.57

MW3

1.0 m
850.0
<MDL

SV3

1.0 m
0.84
<MDL

TP7

0.4 m	1.0 m	1.4 m
0.49	154.6	3.4
0.07	5.91	2.81

TP6

0.4 m	1.1 m
5.28	8.31
0.43	43.59

Approx. Scale: 0 — 10 m

Figure 3.4: Initial Soil Concentrations of CTC and CFM.

Inspection of Figure 3.4 indicates that the made ground and shallow sand horizon were impacted with concentrations of CTC and CFM up to concentrations of 16,984 mg/kg and 479 mg/kg respectively. Evidence from TP9 (1997), TP8, TP7 and MW4 indicates that the concentrations of contaminants reduces by at least 1 order of magnitude below a depth of 2.0 mbgl.

3.6.2 GROUNDWATER CONTAMINATION

Due to the scope of earlier investigations and restrictions imposed by the programme, groundwater contamination was not fully characterised prior to the start of the remediation project. During soil investigations, groundwater was observed to be seeping into trial pits at low rates. Hence, while any shallow groundwater was known to be contaminated with VOCs, detailed characterisation of shallow or deeper groundwater did not take place.

Shallow groundwater was assumed to be an active contaminant migration pathway to one of the key site receptors, West Brook, as described in Section 5.1.

3.6.3 INITIAL MASS OF CONTAMINANT PRESENT

Soils data for the former CTC tankage area were analysed to estimate the mass of total VOCs present in the defined 'remediation volume' prior to remediation. The data were manipulated in a number of different ways to give an indication of the likely range of VOC mass present. The impacted area was divided into two layers (upper and lower) in a grid pattern to give two sets (layers) of cells of discrete volume as shown in Figure 3.5. For dimensions of the upper and lower layers, see Appendix 1.
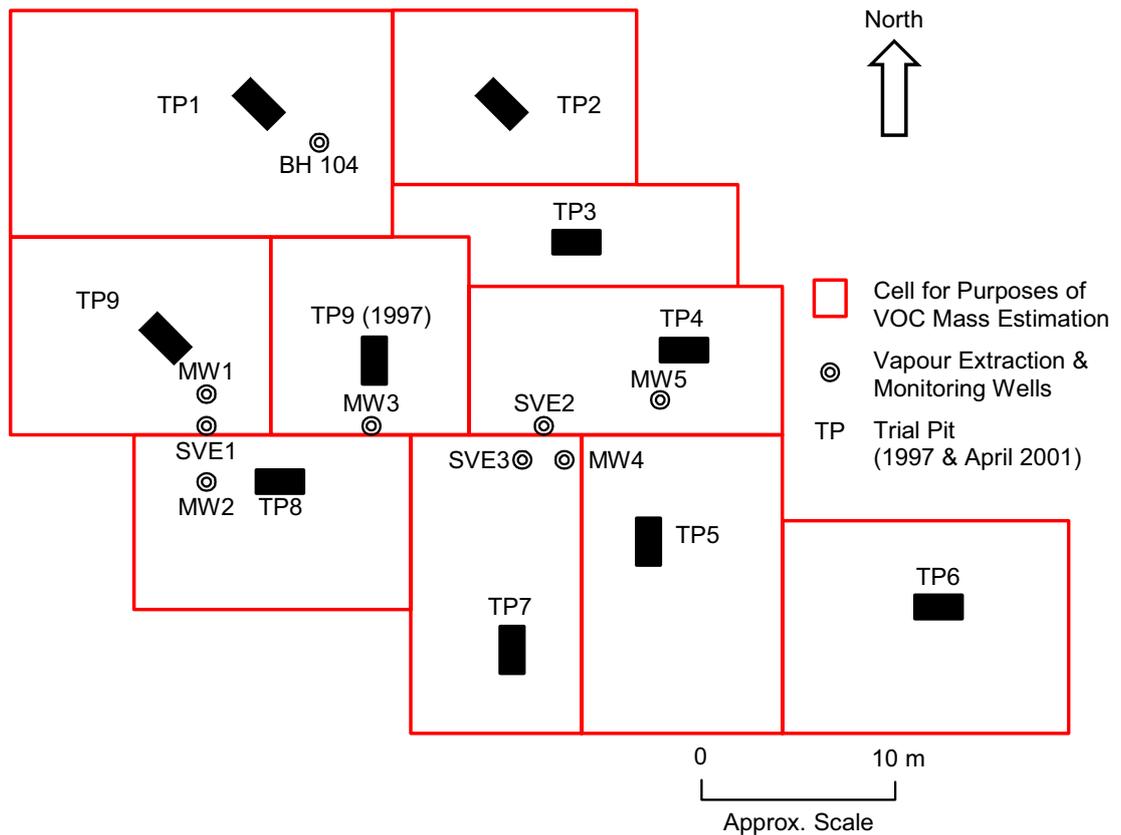
Figure 3.5: Contaminant Distribution Grid.

The average concentration of each cell was calculated using the available site investigation data to allow computation of the estimated mass in each cell (assuming that this average concentration was representative of all the soil in that cell). Finally, the average concentration of VOCs in each cell was multiplied by the volume of soil in each cell to give the estimated mass of VOCs in each cell, these were then totalled to give the total estimated mass of VOCs present.

This methodology for estimation of the initial mass of contaminant present gave a total mass estimate of approximately 2,850 kg of VOCs based on the initial remediation volume of approximately 1,600 m³. The final volume of soil excavated for the remediation project was estimated at 2,293 m³, therefore, if the average concentration of VOCs in the initial soil volume (1,600 m³) is assumed for the final volume excavated, the initial mass present prior to remediation of the final excavated volume becomes 4,140kg (see also Appendix 1).

The uncertainty associated with these results and a discussion of the likely initial mass present are discussed further in Section 10. Data tables used in estimates of the initial mass present can be found in Appendix 1.

3.7   CONCEPTUAL SITE MODEL

A conceptual site model is presented in Figure 3.6. Key receptors were considered to include future site occupants, neighbouring residents and surface water features (West Brook and North Brook).
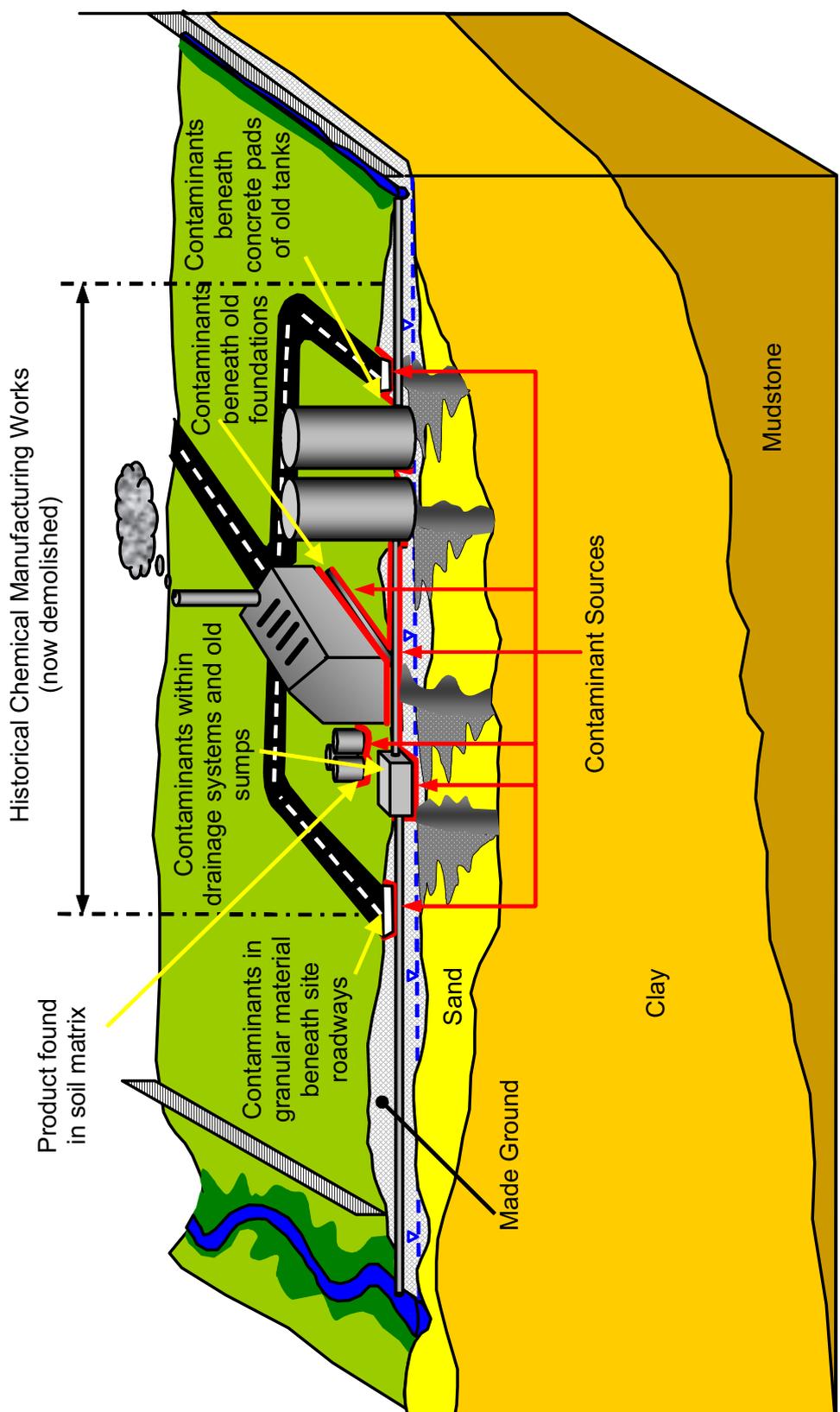
Figure 3.6: Conceptual Site Model.

Historical Chemical Manufacturing Works (now demolished)

Product found in soil matrix

Contaminants beneath concrete pads of old tanks

Contaminants beneath old foundations

Contaminants within drainage systems and old sumps

Contaminants in granular material beneath site roadways

Contaminant Sources

Made Ground

Sand

Clay

Mudstone

19

4. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

4.1 INTRODUCTION

This section outlines a number of support issues relating to the remediation project including regulatory approval, contract agreement, Health and Safety, work plans and Quality Assurance/Quality Control.

4.2 REGULATORY APPROVAL, COMPLIANCE AND LICENSING

The following regulatory issues were addressed during the project:

- The soil treatment system was regulated by a Mobile Plant Licence under the Waste Management Licensing Regulations;

- Planning permission was granted for the engineering operations associated with the remediation work. As part of this, CTC and CFM vapour site action levels and noise limit levels for the SVE plant were agreed with the Local Authority Environmental Health Department;

- An exemption from the Waste Management Licensing Regulations was granted to allow replacement of remediated soils into the original excavation (on the grounds of ecological benefit provided by the remediation in terms of reduction of VOC input into West Brook);

- Site Specific Target Levels (SSTLs) for environmental protection (of West Brook) for CTC and CFM were agreed with the Environment Agency.

4.3 CONTRACT AGREEMENT AND PROJECT TEAM

The Client and landowner commissioned ABB Engineering Services (ABB Eutech at the time of the work) to manage all aspects of the project including delineation of the volume to be remediated, liaison with the regulators, air dispersion modelling, hazard studies and the Construction Design and Management (CDM) roles of planning supervisor and principal contractor. ABB Engineering Services (ABB ES) commissioned Remedx Ltd, the main contractor, to carry out the remediation.

Vacuum equipment was supplied by Ground Remediation Systems while the treatment bed was prepared and lined by Environmental Lining Systems.

Soil and groundwater sample analysis was carried out by Alcontrol Ltd while dust and Tenax samples were analysed by Scientific Analysis Laboratories.

4.4 HEALTH AND SAFETY (INCLUDING NUISANCE)

Management of health and safety on the project covered the following key areas:

- CDM Regulations;
- Hazards of Construction;
- Hazard Studies 2 and 3;
- Exposure of on site workers to chemicals including decontamination procedures;
- Exposure of the public (off site) to chemicals (including odour) and dust;
- Noise;

- Vehicle movements and the potential for contamination to be transported off site by vehicles.

4.4.1 CDM REGULATIONS

As previously mentioned, the project was carried out under the CDM regulations. ABB provided the Form 10, appointments register, the pre-tender Health and Safety plan and principal contractor Health and Safety plan while Remedx provided detailed working plans and method statements. ABB and Remedx also carried out site inductions, toolbox talks and Health and Safety audits during the project.

4.4.2 HAZARDS OF CONSTRUCTION

The 'Hazcon' methodology was originally developed by ICI but has been adapted by ABB for use on projects involving significant sitework. The process uses a series of guidewords which must be assessed by the Hazcon team to identify potential hazards associated with the proposed sitework and develop mitigation measures.

4.4.3 HAZARD STUDIES 2 AND 3

ABB's Hazard Study Methodology comprises 8 stages, covering essential safety, health and environmental protection issues that need to be addressed during plant life, including the initial feasibility studies, through the project execution process, to established process operation, and later periodic review of operational plant. The methodology, which was developed while ABB ES was part of ICI (i.e. prior to 2001), has been widely adopted throughout the process industries, strongly influencing the development of "HAZOP – Guide to Best Practice" (I. Chem. E., 2000). The methodology comprises a systematic approach to identifying the hazards that can arise in the process. Hazard Study 2 is a 'top down' approach to be used at initial stages and to affect or influence the design while Hazard Study 3 is a 'bottom up' approach to test the final draft design against deviations in the intended operation to ensure the process remains adequately safe.

4.4.4 EXPOSURE OF ON SITE WORKERS TO CHEMICALS INCLUDING DECONTAMINATION PROCEDURES

In response to the hazard of exposure of site workers to VOCs detailed working plans were developed to minimise the mass of VOCs released during excavation. Trigger concentrations were set and Personal Protective Equipment (PPE) was specified which ultimately included positive pressure full face respirators.

Full decontamination procedures were developed including access and egress from the site using clean and dirty zones and a hygiene unit.

4.4.5 EXPOSURE OF THE PUBLIC (OFF SITE) TO CHEMICALS (INCLUDING ODOUR) AND DUST

Following completion of a specific assessment of the potential for VOCs to be released by the remediation using Atmospheric Dispersion Modelling System, ADMS (Cambridge Environmental Research Consultants, 2002), action levels were specified on site that would result in a simulated exposure of the public to concentrations above Environmental Assessment Levels (EALs). Monitoring carried out by Remedx included use of Photo Ionisation Detectors (PIDs) present at the treatment bed, the excavation area, boundary monitoring on a 2 hourly basis, fixed point continuous monitoring at the site boundary closest to residential property and personal monitors to provide retrospective data. In addition, Tenax tubes were present at site boundary monitoring stations to provide averaged VOC concentrations during the period of sitework (see also Section 9). These monitoring stations also monitored dust concentrations.

The ADMS assessment also included evaluation of odour, which was a particular concern of the local authority. It was concluded that, provided the toxicologically based action levels were complied with, odours would not cause an issue to off site receptors.

4.4.6 NOISE

As part of the planning consent, a background noise survey was carried out and limits were set on the operation of the SVE system prior to its specification.

4.5 LABORATORY ANALYTICAL METHODS AND QA/QC

The following laboratory analysis was carried out:

- VOCs by GC/MS associated with soil sampling during the pre-remediation site investigations;

- VOCs by GC/MS associated with soil sampling during remediation in order to delineate the base and lateral extent of the volume of soil to be remediated;

- VOCs by GC/MS associated with soil sampling in the treatment bed to provide verification of the effectiveness of the treatment;

- VOCs by GC/MS associated with passive carbon absorption tube VOC (Tenax) monitors.

When sampling the base and sides of the excavation, given that only 5 g of soil sample is used for GC/MS VOC laboratory analyses, the use of a headspace sampling system was implemented. For each sampling location, three sample sets were taken (each set containing one bag and one jar) – the headspace of the three bag samples were checked for headspace concentration by PID and the laboratory sample jar of the corresponding highest result was submitted for laboratory analysis. This methodology was designed to collect the sample with the highest concentration of VOCs (i.e. to be conservative).

At the completion of the specified treatment period, a treatment cell was sampled at five locations (a strip windrow or cell in the treatment bed contained approximately 30 m³ of treated soil). Samples were collected from two elevations within the Strip, on a grid pattern using hand augers. One half of each sample was headspace tested on site using a PID. From the headspace tests the two highest reading samples were identified (again, a conservative approach). The second half of each of these two samples was sent to a chemical testing laboratory for analysis – hence the approximate laboratory sample density was 1 sample for every 15 m³ backfilled.

4.5.1 SAMPLE HANDLING

Proper handling of samples is critical to ensure that they remain stable and representative of the *in situ* conditions.

All soil and water samples were stored on site and in the laboratory in accordance with BS 6068 Section 6.3 'Water quality, sampling guidance on the preservation and handling of samples'. Cool-boxes, ice-packs and appropriate sampling containers were used for storing the samples. Trip blanks and duplicates were included in the analysis programme.

To minimise sample degradation, samples were:

- Collected using a hand auger with minimal disturbance in order to reduce VOC loss prior to analysis;

- Sufficient to completely fill the container, such that air space was excluded as far as possible;

- Stored on site and transported in cool boxes to maintain a temperature of 4°C;

- Transported to the laboratory as quickly as possible after sampling.

4.5.2 CHAIN OF CUSTODY

Once a sample was collected, the sample container lid was secured and a waterproof adhesive label affixed. The label included sample identification, detailing sample location and depth, and time, date of collection and samplers initials.

Chain of custody records accompanied samples dispatched from the site for testing. These comprised a list of sample types (soils, groundwater), sample depth and location, time and date of sampling and analysis requested. The sampler also noted the type of material, e.g., made ground, clay etc. and any visual or olfactory evidence of potential contamination.

4.5.3 QUALITY ASSURANCE PLAN

All sampling adhered to strict quality assurance/quality control (QA/QC) requirements to ensure high quality data. These QA/QC protocols included the following:

- Conformance with the stated requirements of the various work plans, including the method of obtaining samples, number and type of sampling containers with precise identification, sample preservation techniques and approved holding times, sample identification codes and documentation procedures;

- Clear labelling of all samples using appropriate identifiers such as identifying sample number, sample location, sample depth, sample date and time, name of sampler, requested analysis and sample preservation technique;

- Use of standard chain of custody (COC) records to document transfers of samples from point of sampling through to the laboratory.

4.5.4 QA/QC REVIEW OF ANALYTICAL RESULTS

Analytical results as reported by the laboratory were subject in the report to a thorough QA/QC review. This review included the following discussion to assess the accuracy of analytical results:

- Holding Time Review - Check for excedances of prescribed holding times;

- Elevated Detection Limits - identify samples with elevated detection limits (above the numerical standards used to assess the significance of the data) as a result of sample dilution or small sample volume;

- Review of Gas Chromatograms: VOC (and if necessary Semi Volatile Organic Compounds (SVOC)) chromatograms were reviewed to assess the presence of unidentified significant peaks (i.e. above the base line).

5.   REMEDIATION DESIGN

5.1   ENVIRONMENTAL RISK ASSESSMENT

Agreement of site specific target levels (SSTLs) with the Environment Agency (EA) was based on a 'controlled waters risk assessment' (using EA R&D document P20 methodology, Environment Agency, 1999).

Using the Tier 3 soil model, this assessment methodology is essentially a spreadsheet-based back-calculation to simulate a potential source-pathway-receptor pollutant linkage. A 'compliance point' is defined within which it is proposed an 'allowable' mass of contaminant may discharge due to leaching from contaminated soils and subsequent groundwater flow. An equilibrium soil concentration for a contaminant can then be calculated for a specific migration pathway. This soil concentration is then adopted as the SSTL below which the target concentration at the compliance point will not be exceeded based on the assumptions within the model.

In this case, the contaminants were carbon tetrachloride (CTC) and chloroform (CFM), the migration pathway was westerly shallow groundwater flow to West Brook as groundwater baseflow and the point of compliance was set at 85 m from the bulk storage area within West Brook (this distance is the shortest distance from the bulk storage area to the brook – see also Figure 3.1). Limited dilution in West Brook was included (with EA agreement) to take account of the zone of baseflow discharge and the size of the stream.

The target concentrations for CTC and CFM at the compliance point (West Brook) were set at the EA-defined Environmental Quality Standard (EQS) for inland surface waters:

- Carbon tetrachloride EQS = 0.012 mg/l;

- Chloroform EQS = 0.012 mg/l.

Three simulations or calculations were carried out using different sets of parameters (worst case, best case and most-likely case). The calculated soil remedial goals for carbon tetrachloride ranged from 26 mg/kg to 240 mg/kg. The 'most-likely' dataset was considered to be the most applicable as it took average or mid range values for the most sensitive parameters. This gave a remedial goal for CTC of 123 mg/kg. The calculated soil remedial goal for CFM using the 'most-likely' dataset gave a remedial goal of 31 mg/kg.

The SSTLs for CTC and CFM were agreed by the EA and adopted for the remediation project.

5.2   DELINEATION OF REMEDIATION VOLUME

Once the SSTLs were agreed with the EA, pre-remediation contaminant data were used to define the 'Initial Delineation Volume' of soil to be remediated.

The surface boundary of the initial excavation area was 940 m², which if extended to an average depth of 2 metres would result in a soil volume to be remediated of 1,880 m³.

This 'Initial Delineation Volume' was revised following the first phase of excavation in November 2002. The resulting 'Revised Delineation Volume' of 2,480 m³, which was delineated following the 1st phase of excavation, was then adopted as the volume of soil to be remediated.

The validation sampling was implemented to confirm that the final extent of the base and sides of the excavation were correctly defined between soils with contaminant concentrations above the SSTLs inside the defined volume and soils with contaminant

concentrations below the SSTLs (outside the defined volume). Final volume verification is discussed in Section 10 (Mass Balance).

6. DESIGN AND INSTALLATION OF *EX SITU* SVE SYSTEM

6.1 INTRODUCTION

This section outlines the design of a pilot test (using *in situ* SVE) and describes a full scale system using *ex situ* SVE. The steps in the design process are described, including initial field scale pilot testing, re-appraisal of the remedial approach and development of an *ex situ* SVE approach to the remediation.

6.2 PILOT TESTING

6.2.1 INTRODUCTION

To give confidence that a selected remediation technique can treat soils and/or groundwater to meet remediation and economic targets, pilot testing is a useful step. It is arguable whether field scale pilot testing is required for all *in situ* remedial schemes; however on many occasions it is highly desirable, especially where the remediation project is large or where the contaminant or ground conditions are not in the normal experience of the practitioner. At the site a pilot trial was designed to test the application of SVE in the actual field conditions and was justified by the size of the remedial project and the toxic nature of the contaminant carbon tetrachloride.

SVE had been selected as it was believed the contamination at the plant met the two key requirements for successful application of the technique. The physico-chemical properties of CTC and CFM make them ideal compounds for SVE. The ground conditions at the site were assessed from borehole logs from previous site investigations. It was believed that the fine sands reported would also allow soil vapour to be recovered from suitably installed wells.

6.2.2 OBJECTIVES OF PILOT TESTING

Pilot testing was undertaken to validate the proposed remedial approach and to obtain information on the following parameters:

- The radius of influence of the SVE wells;
- The air permeability of the soils at the pilot test site area;
- The optimum vacuum rate applied to the SVE wells;
- The resultant flow rate of the wells; and,
- The mass removal rate of contaminants over time.

6.2.3 HEALTH, SAFETY AND ENVIRONMENT ISSUES OF FIELD SCALE PILOT TESTING

The pilot testing work did not fall under the Construction (Design and Management) Regulations (1994), however in-house Health Safety and Environment procedures were followed. As a matter of course these required full risk assessments and method statements to be undertaken for all work activities planned at the site. The method statements and accompanying risk assessments were developed under Environment Agency (EA) mobile plant licensing arrangements then in force (Index of Working Plan Specifications) presented in the Environment Agency's Working Plan Guidance and Specifications Volume 3 (Draft 4), 'Mobile Plant Licenses – Remedial Treatment of Contaminated Soils', Environment Agency, 1998.

The control and monitoring measures described in the site specific working plan and risk assessment were put into effect. There were three main sources of hazard present during the vapour extraction pilot test, these included:

- VOC vapours from the substrate or, once extracted, from the plant;

- Contaminated groundwater abstracted from the plant; and,

- Electricity from the plant.

The main contaminants, CTC and CFM are classified as human carcinogens (see also Section 9). For this reason, careful measures had to be taken to reduce any risk of exposure, including exposure from groundwater, which is known to contain CTC and CFM. Potential exposure pathways for these VOCs are listed in Table 6.1, together with steps taken to minimise risks.

Table 6.1: Potential Human Exposure Pathways and Risk Minimisation Measures

Dermal contact with VOCs	
Hazard	VOCs can be adsorbed through the skin
Risk Minimisation	Appropriate PPE worn, including:
	Gloves (must be nitrile if handling contaminated materials),
	Chemical resistant boots (with reinforced soles and toe-caps),
	Safety glasses (when handling liquids or near pressurised air streams),
	Visors and safety helmets (when working near water discharge pump and hoses),
	Protective overalls to be worn, preferably disposable Tyvek-type.
Ingestion of VOCs	
Hazard	VOCs can be ingested through poor hygiene practices
Risk Minimisation	No smoking, eating or drinking on site,
	Change of footwear upon exit from contaminated areas of site,
	Wash hands and face upon exit from contaminated areas of site.
Injection of VOCs	
Hazard	VOCs can be injected after piercing the skin.
Risk Minimisation	Appropriate PPE worn, including:
	Gloves,
	Safety boots (with reinforced soles and toe-caps),
	Safety glasses (when handling liquids or near pressurised air streams),
	Visors and safety helmets (when working near water discharge pump and hoses),
	Protective overalls to be worn, preferably disposable Tyvek-type.

To manage the exposure of workers to contaminant vapour, the Health and Safety Executive (HSE) publication EH40/2002 was referred to for setting Occupational Exposure Standards (OESs) and Maximum Exposure Limits (MELs) for each of the two contaminants, CTC and CFM, during the pilot test. Maximum exposure levels and Occupational Exposure Standards are defined in EH40/2002 and given in Table 6.2.

Table 6.2: Occupational Exposure Standards

Level	EH40 Definition
Maximum Exposure imits (MELs)	The maximum concentration of an airborne substance averaged over a reference period, to which employees may be exposed to inhalation under any circumstances.
Occupational Exposure Standards (OELs)	The concentration of an airborne substance, averaged over a reference period, at which, according to current knowledge, there is no evidence that it is likely to be injurious to employees if they are exposed by inhalation day after day to that concentration.

It should be noted that OELs and MELs have now been replaced by workplace exposure limits.

It was expected that on site VOC vapour concentrations from the contaminated soils were likely to generate vapour concentrations in air in excess of MELs, therefore protective facemasks were specified in the excavation area.

Continuous monitoring of the atmosphere near the working area was undertaken using a handheld photo-ionisation detector (PID), fitted with an 11.7 eV lamp and calibrated with a known concentration of isobutylene. This instrument could not differentiate between different VOCs, thus the PID response was assumed to be CTC or CFM as there was no contaminant specific response factor for the PID to convert readings to an equivalent concentration of CTC or CFM. The occupational exposure limit for both is 2 parts per million (ppm), as detailed in EH40/2002. If the concentration measured on the PID during the work was recorded at 2 ppm, works ceased, and measures were taken to mitigate the problem and ensure the safety of those on site.

The site investigation identified carbon disulphide to be present in small quantities in the soil. Unlike CTC and CFM, carbon disulphide is potentially explosive. This risk meant that if the Lower Explosive Limit (LEL) for carbon disulphide were reached within the soil vapour being extracted from the sub-surface, then an explosion could be caused, as the SVE was not intrinsically safe. The LEL concentration for carbon disulphide is 1% by volume, or 10,000 ppm. To protect against this the inlet VOC concentration to the plant, as read by the PID was not allowed to exceed 2,000 ppm without works ceasing and mitigation methods being adopted, such as increasing dilution air into the SVE system.

6.2.4 PILOT TEST SETUP AND OPERATION

To perform the pilot test, three new vapour extraction wells were installed. The installation and design of the three installed vapour extraction wells can be seen in Figure 6.1 and 6.2.

In addition to the SVE wells, five two-inch multi-level monitoring wells were also installed. These monitoring wells were installed so that each vapour extraction well had three monitoring points within 5 m, the closest monitoring boreholes to which were 10 m away. Monitoring wells were installed into different strata to establish soil properties in different soil types present.
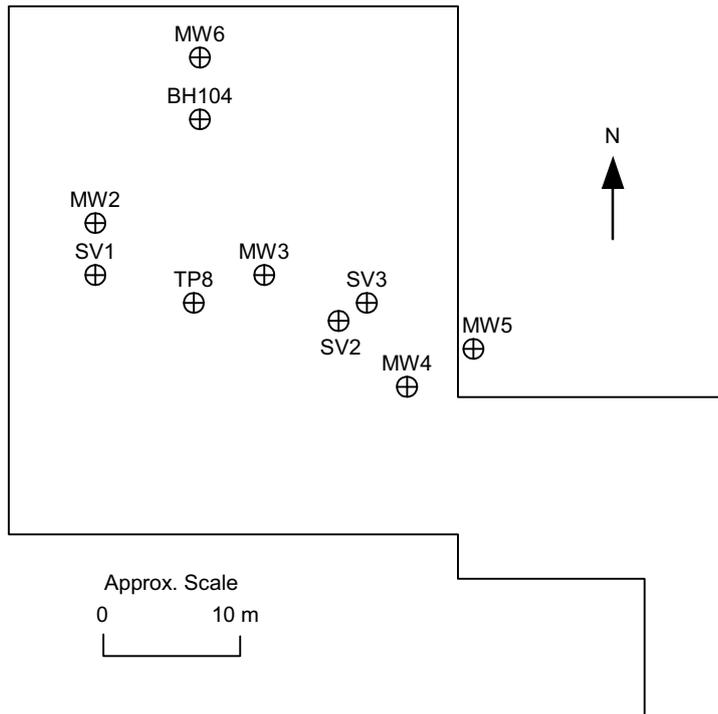
Figure 6.1: Layout of Vapour Extraction and Monitoring Wells.

Figure 6.2: Typical SVE Well Borehole Log and Well Configuration (well: SVE1).

The main plant unit for the vapour extraction test was mounted in a trailer and consisted of an oil ring vacuum pump, a side channel vacuum pump, a moisture separator and a fluid transfer pump. All motors were controlled either manually or through level switches via a panel. Granular activated carbon (GAC) was used for treatment of all vapour and liquid discharges from the plant. Treated liquids were discharged to an existing site sewer and vapours discharged to atmosphere. The layout of the vacuum extraction test is shown below:
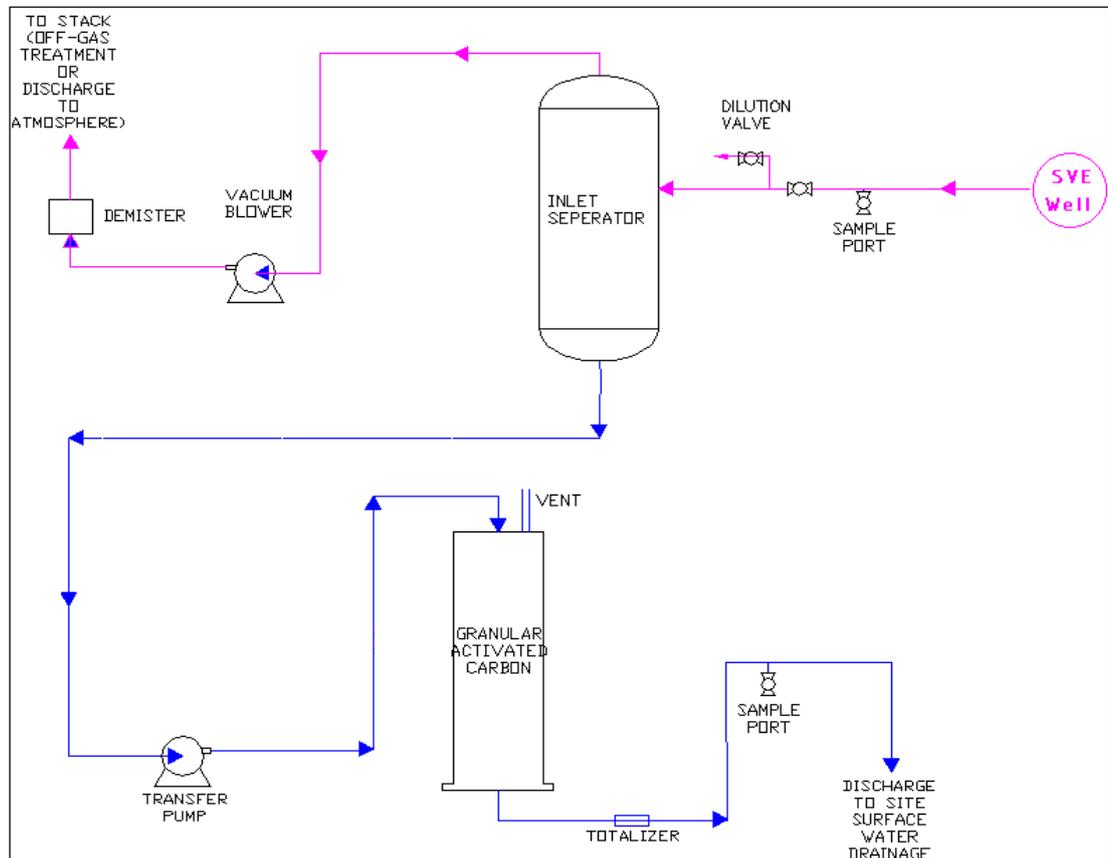
Figure 6.3: Schematic of Vapour Extraction Test Treatment.

Vapour extraction tests were carried out on each of the four SVE wells for the following periods:

Table 6.3: Vapour Extraction Test Times.

Vapour Extraction Well	Vapour Extraction Test Time (hours)
SVE 1	36
SVE 2	72
SVE 3	15
BH 104	1

By controlling the extraction rate of the vacuum applied to the well and monitoring the vapour flow rate indicated by the hot wire anemometer, the maximum possible flow rate from each of the wells was determined.

Once this flow rate was identified, a stepped vapour extraction test commenced. Similar to a groundwater extraction step test, this involved adjusting the flow rate in steps, gradually increasing the flow rate of vapour extracted until the predetermined maximum was reached. The induced vacuum in each of the monitoring wells were monitored throughout this test

with magnahelic vacuum gauges. This monitoring allowed the radius of influence of the SVE well to be determined and the air permeability of the substrate to be measured.

Optimum flow rates for the system are important to determine for economic reasons. In many cases higher flow rates do not increase mass removal, as they are rarely the limiting factor in the system, but may increase off-gas treatment costs. An optimum flow rate/vacuum will maximise contaminant removal relative to the cost of treating the offgas (USACE 2002).

Throughout the test, a PID was used to measure VOC concentrations in the gas extracted by the SVE plant. Combining this data with flow rate, allowed mass recovery rate to be calculated using the following equation:

$$M = \frac{Q \times C \times A}{1000}$$

Where:
M   =   Mass Removal (kg/hr)
Q   =   Exhaust Gases Flow Rate (m³/hr)
C   =   Soil Vapour VOC Concentration (ppm by volume)
A   =   Correction factor for PID measurements, determined by comparison of PID and subsequent laboratory analysis data

This off-gas was then passed through vapour phase GAC vessels to adsorb VOCs. Periodically, the gas emitted from the GAC vessel to atmosphere was monitored to ensure there were no VOC emissions occurring from the plant.

6.2.5 PILOT TEST RESULTS AND CONCLUSIONS

Table 6.4 summarises the data obtained for the pilot tests of the vapour extraction wells. The full results can be seen in Appendix 2.

Table 6.4: Vapour Extraction Test Results Summary.

Vapour Extraction Well	SVE1	SVE2	SVE3	BH104
Optimum Vacuum (kPa)	30	20	N/A	N/A
Radius of Influence (m)	2.6 - 2.9	4.2 – 5.2	N/A	N/A
Air Permeability (cm²)	5×10^{-9}	5×10^{-8}	N/A	N/A
Estimated CTC Recovery Rate (kg/day)	0.5	3.0	N/A	0.75

6.2.5.1 Radius of Influence of SVE Wells

The average radius of influence from the vapour extraction wells was 3.4 m (as indicated by vacuum gauge measurement). To ensure complete treatment of soil within the contaminated area, an SVE well would need to be installed every 4.8 m, as an overlap in vacuum radius of influence was required. This well spacing would require a total of 38 vapour extraction wells.

In some instances, positive pressure values were observed in monitoring wells during the different vapour extraction tests. Although the mechanism for this is unknown, previous SVE experiences (USACE, 2002) show that this phenomenon usually occurs in interbedded strata of differing permeabilities, low permeability soils, and soils with low soil pore connectivity. Locations where these values are recorded are therefore outside the radius of influence of the vapour extraction well. These conditions are not favourable for an *in situ* SVE remediation programme.

6.2.5.2 VOC Mass Recovery Rates

Figure 6.4 shows the VOC mass removal rate with time for SVE well 2, using VOC concentrations during vapour extraction test results plotted alongside a best fit exponential decay curve. This decay pattern is typical of *in situ* SVE remediation programmes. The relatively rapid reduction in the mass recovery rates was disappointing and gave concern that there may be factors limiting the ability to draw soil vapour from within the theoretical radius of influence of the well. These graphs were used to predict average CTC and CFM removal rate from the soil.

**PREDICTED MASS REMOVAL RATE
FOR WELL SVE 2**
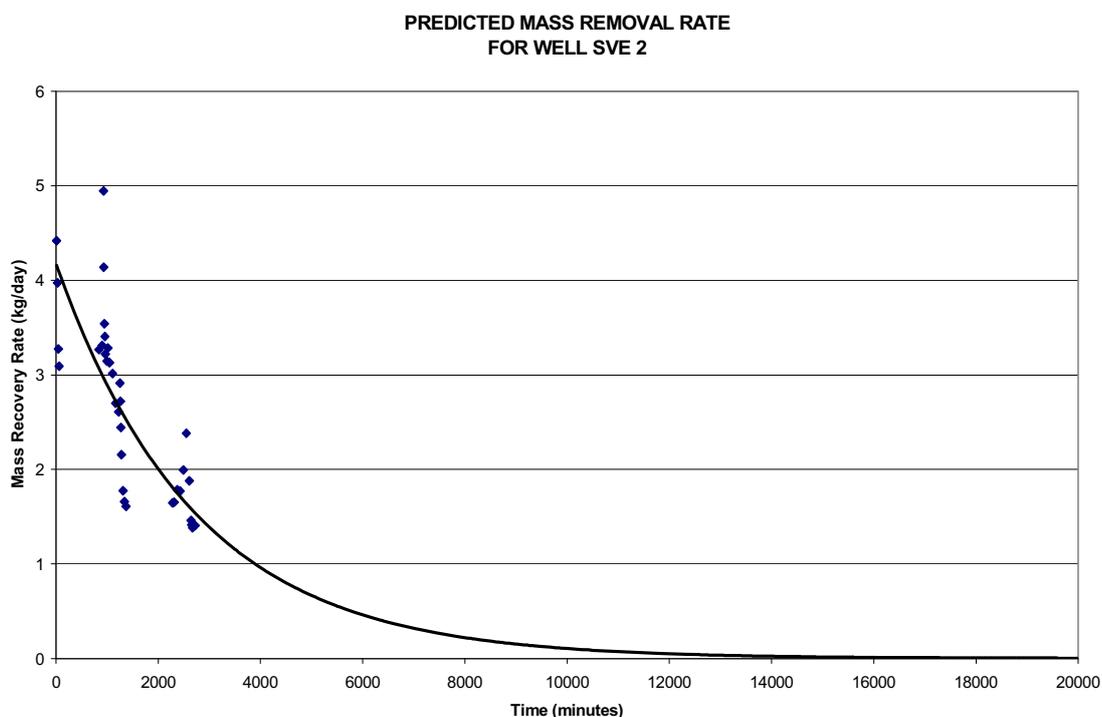
Figure 6.4: Predicted Mass Removal Rate for Well SVE 2.

The above results, combined with previous experiences of *in situ* SVE, show that none of the areas tested by the vapour extraction pilot test proved suitable for a full scale *in situ* SVE scheme. The air permeability of all vapour extraction wells from which air permeability data could be obtained was 2 to 3 orders of magnitude below the minimum recommended air permeability values for an *in situ* SVE scheme, as stated by USEPA (1996). Discrepancies arising from results from different monitoring wells were explained as an indication of high soil heterogeneity and possibly a greater influence of underground concrete structures (related to foundations of the former chemical plant) than had been anticipated. Both of these possibilities would limit the effectiveness of *in situ* SVE, through contamination isolation and short-circuiting of extracted air.

In addition, well SVE1 (borehole log presented in Figure 6.2) reported a viscous organic product containing chlorinated hydrocarbons in soils at this location. This material was considered likely to have a low air permeability and be a high concentration contaminant source. It was considered unlikely to be effectively remediated with *in situ* SVE as diffusion of carbon tetrachloride from the product would be a limiting factor.

In summary, the following factors indicated that conditions in the former plant area were not suitable for an *in situ* remediation scheme.

• Low apparent air permeability;

33

- Soil heterogeneity;

- Buried structures;

- Small vapour extraction well radius of influence;

- Low mass recovery rates;

- Uncertain distribution of contaminants, with pockets of highly contaminated viscous product.

Section 2.2 highlighted the differences between *in situ* and *ex situ* SVE systems. Using the results of the SVE pilot test and the site characteristics described in earlier sections, an appraisal of the advantages and disadvantages of *in situ* and *ex situ* SVE was undertaken and the following conclusions drawn:

- The low apparent air permeability could be resolved during excavation and placement of soils in a treatment bed, through altering the pore structure of the soils. The sands would be less compacted;

- Soil heterogeneity would be addressed through selective excavation and segregation of low permeability cohesive soils. These cohesive soils would not be placed in a treatment bed. Heterogeneity within the sands would be addressed by careful soil mixing through periodic turning of the soil during excavation and placement;

- Buried structures and highly contaminated pockets of soil could be identified visually (highly contaminated soil could also be identified using PIDs). Underground structures could be broken out and either reused if uncontaminated or sent for offsite disposal if not suitable for remediation by SVE. Highly contaminated soils could be treated separately;

- During excavation, sampling and analysis of the boundaries of the contaminated area, both laterally and vertically, can accurately delineate the remediation area. If necessary, this information could be used to extend the excavated area;

- Since the site was no longer operational, enough space was available to construct a treatment bed and set up the SVE plant.

For these reasons, it was decided that the most appropriate course of action was to construct an *ex situ* SVE plant and treatment bed on site. Soils would be excavated, sorted and segregated. Those soils suitable would be treated in an *ex situ* SVE treatment bed. Other soils would be disposed of off site or reused if uncontaminated.

6.3 DESIGN OF FULL *EX SITU* SOIL VAPOUR EXTRACTION (ESVE) SYSTEM

6.3.1 PLAN OF OPERATIONS

In summary the remediation works comprised:

- Preparation of the site for construction of the vapour extraction treatment bed;

- Construction of an *ex situ* vapour extraction treatment bed;

- Exposure of existing below ground concrete structures and confirmation of the planned excavation area by trenching;

- Free phase (viscous product) and high level soil contamination removal and segregation based on soil type and contaminant level, within part of the treatment bed prior to separate treatment/disposal;

- Removal of concrete structures and stockpile of concrete arisings;

- Pumping of water from excavations and treatment using the mobile plant followed by disposal to sewer under a temporary discharge consent;

- Excavation of bulk contaminated soils and placement in the treatment bed;

- Treatment of contaminated soils using *ex situ* SVE;

- Validation of final contaminant concentrations within the treatment bed and in the floor and sides of the originating excavation;

- Replacement of soils validated to be at concentration Site Specific Target Levels (SSTLs) for contaminants, and / or,

- Appropriate disposal of soils with levels above site action levels for contaminants;

- Removal of treatment beds and equipment from site.

6.3.2 DESIGN AND CONSTRUCTION OF TREATMENT BED

The area designated for the temporary works of the treatment bed lay to the south of the former plant area at the site. The treatment bed was designed to allow:

- All soils within the bed to be tracked from their point of excavation to their position in the treatment bed;

- Effective treatment of the contaminated soils;

- Isolation of the contaminated soil from the surrounding environment.

Features of the design to achieve this are summarised in Table 6.5 and shown in Plates 6.1 to 6.3.

Table 6.5: Treatment Bed Design Features.

Design Feature	Purpose
HDPE lined treatment bed laid onto engineered base with sand blinding layer	To ensure that contaminated soils and soil water were isolated from the non-contaminated soils below the treatment bed.
Treatment bed included bunded sides	To contain soil and soil water and collect any precipitation falling on the treatment bed, which may become contaminated through contact with contaminated soils and thus form a leachate.
Robust materials used in design	To allow the treatment bed to withstand the placement, excavation and treatment of two bed volumes of soil by heavy earthmoving equipment without being damaged or destroyed.
Vapour extraction pipe network	To allow SVE during the placement of contaminated soil within the bed to minimise vapour emissions to the atmosphere.
Waterproof treatment bed covering	To control moisture content of the soils within the bed and minimise the water drawn through the soils and recovered by the SVE system.
Geotextile membrane over vacuum extraction pipe work	To act as filter to reduce the quantity of sand drawn into the SVE pipe work and to provide a marker to avoid pipe disturbance when the treatment bed was to be emptied.

Plate 6.1: Construction of Treatment Bed Base.

Plate 6.2: Construction of Treatment Bed Base and Containment Bunds.

The treatment bed was designed to have an estimated capacity of approximately 860 cubic metres of contaminated soil, with a fill depth of 1.5 m and battered sides within the bed bunds. It had the following main components:

- Bed base containing bund constructed using compacted stone (50 mm Department of Transport (DOT), type 1);

- High Density Polyethylene (HDPE) liner, 2 mm thick, with welded seams, providing a chemically resistant and waterproof base and sides to the bed;

- SVE pipe network at the base of the bed, covered with a geotextile (HY-TEX, LF25/25).

The treatment bed was constructed using a DOT type 1 crushed stone for the base and bund walls. The bed was graded with a slope (1:200) to the centre where a sump was constructed to collect precipitation for subsequent treatment.

The liner was constructed from two rolls of 2 mm HDPE, each being 6 m wide and 112 m long. These were welded along one long central seam running the length of the treatment bed. The width of liner overlapped the bed bunds formed from compacted crushed stone. It was expected that welds would be required at the corners of the bed, but this proved unnecessary as the liner had sufficient flexibility to form itself satisfactorily to the underlying profile of the bund sides. The liner was secured by overlapping it into an anchor trench on the outside of the bed bund (see Plate 6.3). The anchor trench was then filled with stone, so the liner could not slip. Installation was conducted by specialist contractors who also supplied the liner.

Plate 6.3 shows the vapour extraction pipe array while Figure 6.5 shows a cross section through the bund and vapour extraction pipe configuration. This was composed of slotted vent pipes within the treatment bed base, and the vapour collection manifold, constructed in PVC and HDPE, connected to the SVE plant. The pipe connections were solvent welded and taped. PVC and HPDE were considered suitable for temporary works where they were exposed to the contaminant vapours. The pipework was sized such that friction head-loss was kept to a minimum, with the connecting manifold pipe diameter being increased towards the centre where the connection to the SVE plant was made. A gate valve was used to control the flow from each arm of the venting array. These valves allowed detailed control of the vapour flow from each section of the treatment bed. A sampling port was also provided for each venting arm.

Plate 6.3: HDPE Liner and Vapour Extraction Pipe Array.

CONTAMINATED
SOIL IN ONE
METRE THICK BED

SVE
MANIFOLD
PIPING

GEOMEMBRANE
COVERING SVE
PIPE ARRAY

30°

CONTAMINANT
RESISTANT
MEMBRANE

CRUSHED STONE BED
BASE, WITH 25 MM
SAND BLINDING LAYER
WITH 0.5 M HIGH
CONTAINING BUND

ANCHOR TRENCH FOR
MEMBRANE, BACKFILLED
WITH CRUSHED STONE
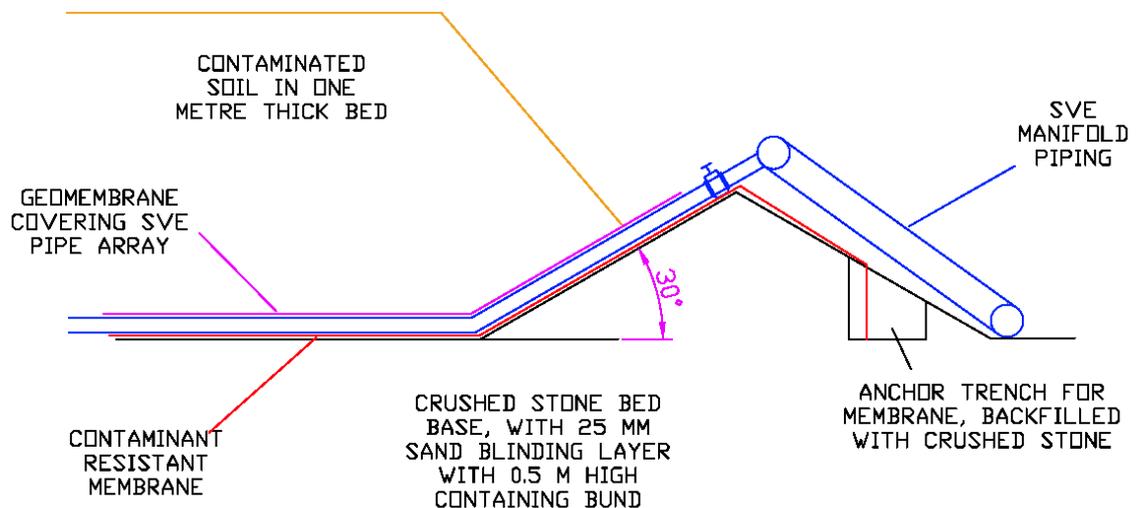
Figure 6.5: Cross Section Through Bund Showing Vapour Extraction Pipe Configuration.

6.3.3   VAPOUR EXTRACTION PLANT

Figure 6.6 illustrates the components of the SVE plant. The principle is identical in all but scale to that used in the *in situ* SVE pilot test. The inlet to the plant was via a 2 cubic metre capacity moisture separator vessel fitted with automatic water transfer pump. The plant had an extraction capacity of 1000 cubic metres per hour at standard pressure, from four regenerative type vacuum pumps. These pumps were mounted in parallel acting on common inlet manifold leading from the moisture separator.

The same hazards present during the pilot test (see Table 6.1) were present during the full-scale test and similar protective measures were taken.

The off-gas treatment from the SVE plant was operated in a manner to minimise the likelihood of fugitive emissions of vapour phase contaminants to atmosphere. The two 2.5 tonne capacity vapour phase granular activated carbon vessels were connected in series with flexible hoses. The "lead" vessel, the vessel first to receive soil vapour for treatment, was backed up by the second, lagging granular activated carbon vessel filled with virgin carbon. In this way, the backup vessel always had the maximum adsorptive capacity available. Once the lead vessel's adsorptive capacity was spent and breakthrough occurred, the second lagging vessel was in place to continue treatment. This gave time for the lead vessel to have its spent activated carbon replaced. Once it was replenished, the old lead vessel was put in line as the lagging vessel, thus maintaining the protection of having a virgin carbon vessel offering maximum adsorbtive capacity in reserve.
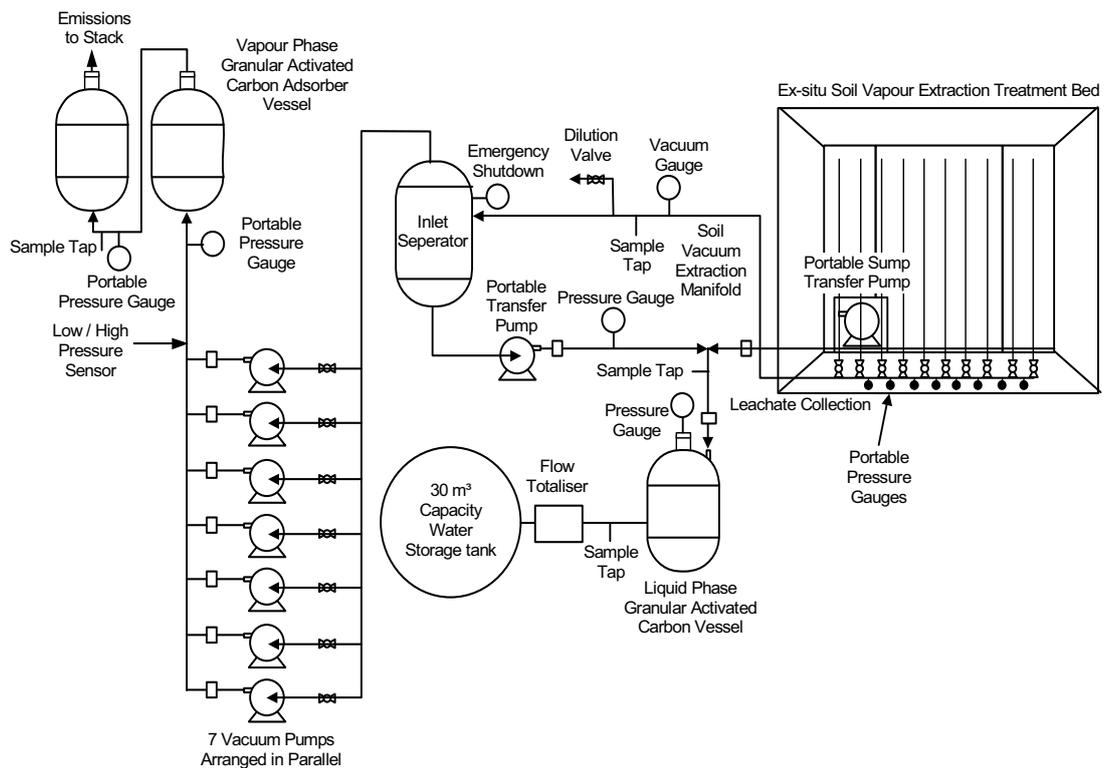
Figure 6.6: Schematic of Vapour Extraction and Water Treatment System

6.3.4 WATER TREATMENT PLANT

Three sources of water were recovered and had to be treated prior to disposal:

- Water pumped from the excavations;

- Water vapour from soil vapour drawn into the plant;

- Precipitation falling into the treatment bed collected by the sump.

Water droplets entrained in the vapour during ESVE from the treatment bed were separated from the extracted vapours in the moisture separator. Water collected by the moisture separator was automatically pumped to the sump in the treatment bed. Rainfall collected within the treatment bed was also collected within the bed sump and was periodically pumped to the water treatment plant. Water from the excavation was pumped directly to the plant (see Figure 6.6).

All recovered water was treated in a simple system comprising a 1 m^3 capacity sand filter and two 2 m^3 capacity liquid-phase granular activated carbon adsorber vessels operated in series in the same manner as the vapour phase carbon treatment. Once treated, the water was pumped through a flow totaliser to a 32 cubic metre capacity holding tank where it was stored before discharge to foul sewer, under a temporary discharge consent.

6.3.5 EXCAVATION AND TREATMENT BED FILLING

To reduce construction costs, the treatment bed was sized such that the anticipated volume of soil would be treated in two batches, necessitating the treatment bed to be filled and emptied twice, referred to as 1st fill and 2nd fill.

A concern during the excavation of contaminated soils was the fugitive release of VOCs to the atmosphere. It was unavoidable that excavation and subsequent handling would disturb and expose the soil causing a release of VOCs to the atmosphere. The fugitive emissions rate was minimised as far as possible by measurement of VOC concentrations in air, low excavation rate and reduction of the quantity of soil exposed to atmosphere (see also Section 7.3).

6.3.5.1 Sequence of Work

The excavation work was undertaken in the following sequence:

- Exposure of concrete structures;

- Identification of contamination 'hot spots' adjacent to former concrete structures;

- Identification of redundant drainage where it entered and left the excavation area, subsequent excavation and removal of drainage at these points and the backfilling of the pit with compacted clay. All these locations were surveyed and put onto as-built drawings;

- Excavation of identified hot spots and placed in the treatment bed;

- Break out of identified concrete structures;

- Excavation of soils, segregating cohesive soils;

- Validation of soil quality in the base and sides of the excavation;

- Removal of infiltrating groundwater as required.

6.3.5.2 Identification of Contamination 'Hot Spots' Adjacent to Former Concrete Structures

Previous site investigation work had identified that viscous product contamination may be present adjacent to some concrete structures. This product was observed in the backfilled concrete pipe trench for one of the concrete slabs. Careful excavation around the concrete structures identified was undertaken using a narrow excavator bucket. The soils excavated were isolated and either drummed for disposal, or placed in a designated treatment bed cell.

6.3.5.3 Redundant Drainage Identification

Redundant drainage was identified from historic drawings. It is possible that these drainage runs could potentially have acted as a pathway for liquid or dissolved phase contaminants disturbed during the excavation. To prevent this, old drainage runs were isolated and, where applicable, removed.

6.3.5.4 Break Out of Concrete Structures

Once the concrete structures had any soil contaminants in contact with them removed, they were broken out. This was undertaken using a 30 tonne excavator with a concrete breaker. Concrete was assessed as uncontaminated if headspace tests showed that there was no VOC present on a sample of the crushed material. This concrete was then stockpiled in the

Concrete Stockpile Area, for later re-use. Any voids created had their sides battered to eliminate a falling hazard.

6.3.5.5 Soils Excavation

Once the concrete structures have been removed, the excavation area was free of known obstructions to allow soils to be excavated and placed in the treatment bed. The soil excavation was very tightly controlled and closely recorded. A working method was adopted such that all soils excavated would be traceable in the treatment bed.

6.3.5.6 Excavation Grid

Control of the excavation was based on defining the excavation area by use of a grid, and division of the treatment bed into strips. The excavation was divided into grid squares sized 4 m by 4 m. Each grid square had a unique coordinate of a letter followed by a number i.e. B3. Theoretically the grid defined a volume of soil equal to one completely filled strip in the treatment bed (36 m³ once bulking was allowed for). The treatment bed was to be filled by placing 100 mm thick layers in each strip in turn. Each strip would accommodate 4 m³ to fill it to a depth of 100 mm. Therefore the specified site dump truck was to have a 4 m³ capacity. The dump truck would be filled each time from the excavation with a known volume, with one dump truckload being delivered to a single strip. The excavation was conducted one grid square at a time. The excavation depth was 2 m, giving a volume per grid square of 32 m³ *in situ*. Simple record keeping tracked the exact strips in which soils from each grid square were placed.

6.3.5.7 Rate of Soil Excavation

The rate of excavation was assessed as follows:

- That 800 cubic metres could be treated in the bed at any one time;
- That this would take 200 dumper truck loads to fill if each dumper had a 4 cubic metre bulked capacity (3.6 cubic metres *in situ* if 10% bulking was allowed for);
- That this gave 40 dumper truck loads per day if filling took one week;
- Thus the cycle time for excavation and dumper loading, return haulage time between excavation and treatment bed would be 12 minutes. If haulage time was 5 minutes, then excavation rate would be 3.6 *in situ* cubic metres per 7 minutes. This equals approximately 0.6 *in situ* cubic metres per minute.

This is a slow rate of excavation but is consistent with the vapour control methods outlined in Section 7.2.

6.3.5.8 Soil Quality Validation

Once an area was excavated, the soil quality in the base and sides of that part of the excavation could be sampled and analysed. One half of each sample was used for head space testing on site using a PID. The second half of each sample was sent to a chemical testing laboratory for analysis.

The laboratory analysis suite included soil VOCs by GCMS with reporting of CTC and CFM only.

The SSTLs below which soils were to be classified as treated were:

Carbon tetrachloride 123 mg/kg
Chloroform 31 mg/kg

If the laboratory results were below the SSTLs then the excavation limits tested would be the excavation's final extent. If the laboratory analysis results showed values above the SSTLs,

then instructions from the Engineer would be sought with respect to extending the excavation beyond the planned limits.

6.3.5.9 Excavation Water Management and Treatment

The permeability of the sands into which the excavation was to be formed was shown to be of low permeability (air permeability 10^{-8} to 10^{-9} cm²). It was expected that there would be little flow of groundwater into the excavation from the undisturbed naturally occurring soils. Some perched water inflow to the excavation from former drainage and other utility corridors was to be expected, but not of a sustained nature. If the excavations were to be left for a prolonged period (over two weeks) groundwater flow would be expected to begin to fill the excavation. However, for a continued excavation programme over a one week period, groundwater inflow was unlikely to be a concern and a relatively low excavation dewatering pumping and treatment capacity would be sufficient.

Precipitation falling within the excavation was likely to be the greatest demand on the excavation dewatering plant. The excavation was to be dug with a sump located to capture collected water. This was to be pumped out periodically as required. Water was to be pumped using a portable pump, either diesel motor driven or electrical with portable generator. This would pump water via a 50 mm diameter flexible braided hose to the site water treatment plant. The same system was to be used to pump water from the soil treatment bed water collection sump.

7. IMPLEMENTATION OF *EX SITU* SOIL VAPOUR EXTRACTION

7.1 INTRODUCTION

The implementation of *ex situ* vapour extraction comprised the following cycle:

- Excavation of VOC contaminated soils and placement in the treatment bed;

- Operation of the treatment bed;

- Verification of soil treatment success or failure;

- Determine fate of treated soils in each cell of the treatment bed, i.e. re-use as fill, further treatment within the bed, or off site disposal to landfill;

- Emptying of the treatment bed cells not requiring further treatment and placing of soils in the excavation or sending them for disposal.

Of key importance during the excavation and treatment bed filling was the attempted minimisation of fugitive VOC emissions.

7.2 CONTROL OF EXPOSURE TO VAPOURS

7.2.1 BASIS OF VAPOUR CONTROL

A VOC vapour dispersion modelling assessment (using ADMS version 3.1) was prepared in advance of the works to attempt to predict vapour behaviour during excavation at the site. This report proposed that the most effective method for controlling the vapour exposure of off site residents was to control VOC emissions at source in addition to setting site boundary action levels, which if exceeded, would result in suspension of work. This was adopted as the basis for VOC vapour emission management.

7.2.2 ZONING

The working area was classified into a vapour control area (Zone 1) and a vapour awareness area (Zone 2). These zones were derived from the dispersion modelling assessment which carried out vapour plume predictions.

7.2.2.1 Zone 1

This was termed a control zone, as within this area, a maximum allowable Working Vapour Trigger Concentration was set. Any exceedence of this Working Vapour Trigger Concentration for a period exceeding 1 minute resulted in a cessation of work and a change in operating methods. In any circumstances the vapour trigger concentration was to be no greater than 20 ppm, which had been selected based on maintaining the highest protection factor for respiratory protective equipment (RPE). This concentration would be that read on a hand-held PID (calibrated with response factor for carbon tetrachloride) measured at head height anywhere within Zone 1.

7.2.2.2 Zone 2

This was termed a vapour awareness zone. Within this area it was possible that vapour concentrations may have exceeded 2 ppm, but at its boundary, vapour concentrations were always less than or equal to 2 ppm. It was considered likely that vapour concentrations would be below the 8 hour Time Weighted Average (TWA) Maximum Exposure Limit (MEL) value of 2 ppm for much of the time in Zone 2, and thus RPE was not required to be worn at all times, but was available.

The dispersion modelling assessment indicated that if the maximum VOC concentration in air could be kept equal to or below 2 ppm in the area designated Zone 2, then even in the worst case atmospheric conditions modelled (2 m/s wind speed towards the nearest housing with F-Stability; for details see Section 9) there would be no risk of exceeding the Environmental Assessment Level (EAL) of 0.6 ppm for carbon tetrachloride in air at the nearest housing, or exceeding 2 ppm on nearby public access open space.

7.2.3 WORKING VAPOUR TRIGGER CONCENTRATION

The method of excavation was continuously assessed to ensure that the vapour trigger concentration was not exceeded. The generation of a specific vapour concentration in air was directly linked to the rate of VOC mass emitted to atmosphere at any time. Thus by reducing the actual mass of VOC emitted, it was attempted to reduce the consequent vapour concentration at the point of excavation (see below).

7.3 CONTROL OF VAPOUR EMISSIONS

The excavation works were planned such that they could be adapted to reduce VOC emissions (either emission rate or total mass release) from soil by:

- Reducing the rate of soil excavation at any one time. This was achieved by using a smaller bucket fitted to the excavator, by taking smaller 'bites' of soil, or by digging more slowly;

- Reducing the quantity of contaminated soil exposed at any one time. This was achieved by keeping contaminated soils to which access was not immediately required covered by moveable sheeting or uncontaminated soils.

In the event, the monitored levels of VOCs were adequately controlled by reducing the dig rate.

Plates 7.1 to 7.3 illustrate the excavation operation.

Plate 7.1: Controlled Excavation.

Plate 7.2: Excavation of Remediation Area.

As a precautionary measure, if members of the public were present adjacent to the site boundary near the excavation, excavation work ceased until they had moved on.

7.4 CONTROL OF EXCAVATION

The method of excavation working required close co-operation between the excavation team made up of the banksman, the excavator operator, the dumper driver and the supervising scientist. In addition, a technician with a hand-held PID, monitored VOC concentrations in Zone 2. Communication between the excavation team was through voice activated radio transmitter-receivers, each fitted with throat microphone and earpiece.

In Zone 1, the banksman continuously operated a hand-held PID with 11.7 eV lamp calibrated to measure VOC concentrations directly as carbon tetrachloride. This enabled him to make judgements as to the excavation method required to keep vapour concentrations below the working trigger concentration.

Plate 7.3: Use of PID to Measure VOC Concentration Following Exposure of Viscous White Product Containing Chlorinated Hydrocarbons.

Equipped and operating in this manner, the excavation team was able to operate a system of work such that vapour emissions were controlled in real time in a safe manner.

During the excavation in Zone 1 a maximum VOC concentration of 225 ppm was recorded as a transitory spike. This only lasted a few seconds. Other similar spikes were observed but at much lower concentrations, generally below 20 ppm.

7.5 EXCAVATION STATUS AT END OF WORKING DAY

At the end of each working day the excavation was left in a condition to minimise any vapour release when the site was unoccupied. Any exposed areas of contaminated soil were covered with clean soil or polythene sheeting. Vapour monitoring continued for one hour after the completion of the excavation works in any one day.

7.6 PERSONAL PROTECTIVE EQUIPMENT

All personnel on site were wearing PPE which included body suits, hard hats and gloves. Respiratory Protective Equipment was also worn and is described below.

7.6.1 RESPIRATORY PROTECTIVE EQUIPMENT

Initially, the Respiratory Protective Equipment (RPE) comprised half face (orinasal) respirators equipped with a CEN A2 VOC filter and CEN P3 particulate filter chosen for works in the vapour control zones. Information regarding the life of these cartridges was used to calculate the need for weekly replacement, assuming a (conservative) continuous working concentration of 20 ppmv of CTC. The maximum exposure limit (MEL) for CTC was

2 ppm. The orinasal respirator had a protection factor of 10. This allowed it to be worn in air with a concentration of 20 ppmv carbon tetrachloride without exceeding the 2 ppmv 8 hour TWA.

During the first week of excavation, one of the excavator drivers working in Zone 1 reported a headache and being able to smell VOC vapours. It appeared that the orinasal masks may not have been providing sufficient respiratory protection and they were replaced by the Protector Tornado T7 powered respiratory protection system comprising full face masks with Tornado ABE1 PSL filter suitable to remove all VOCs.

7.6.2   PROTECTION FACTOR

The mask protection factor for the powered Protector Tornado with T-7 full face mask had an assigned protection factor of 40. This theoretically allows it to be worn in air with a concentration of 80 ppmv carbon tetrachloride without exceeding the 2 ppmv 8 hour TWA. However good practice dictates that credit should only be taken for an Assigned Protection Factor (APF) of 10, therefore 20 ppm continued to be set as the working level in line with the guidance received.

7.6.3   FILTER LIFE

The filter cartridges used had a life of 45 to 50 minutes in an atmosphere of 5,000 ppm carbon tetrachloride. The maximum working concentration of 20 ppmv set would ensure that vapour cartridges did not fail during a working week. Thus each cartridge was replaced once per week and a register for filter issue and change was operated.

7.6.4   RESPIRATOR TRAINING, MAINTENANCE AND CLEANING

All site staff issued with masks were given instruction on good practice use of the mask, simple maintenance required and decontamination/cleaning at the end of each working day. A facial fit test was also performed for all personnel issued with RPE.

7.7   TREATMENT BED FILLING

7.7.1   FILLING SEQUENCE

The treatment bed was filled in accordance with the method statement. The SVE system was operating during the filling sequence and its operation was coordinated with the filling process.

The treatment bed was divided into cells running across the bed. These were sequentially numbered from the end nearest to the excavation area on site. A rolling process was established to fill the bed starting from the end nearest to the excavation area. Two strips were used at a time. The filling sequence commenced with Cell 1 and proceeded along the bed.

The gate valves on the SVE venting pipe network were opened on all lateral slotted pipes in cells being filled. All other gate vales remained closed. Thus the entire vapour extraction capacity of the plant was initially concentrated on the cells being filled.

Soils were tipped into the end of each cell and spread carefully and slowly across the length of the strip by an excavator using a toothless bucket. This continued until a depth of soil of 100 mm was in place across the cell. This initial fill of sand acted as a blinding layer to protect the underlying pipes and geotextile layer. Further soil was then placed in the cell until it was filled (Plate 7.4).

Plate 7.4: Filling of the Treatment Bed.

7.7.2   RECORD KEEPING

Records were kept detailing the fate of each area of soil excavated. The following details were recorded:

- Date and time of placement;

- Cell number in the treatment bed;

- Location block from which the soils were excavated, given as coordinates and depth interval;

- Estimate of VOC concentration in soil from headspace PID readings.

7.8   PLANT OPERATION AND CONTROLS

7.8.1   OPERATING PARAMETERS

The SVE plant operated 24 hours each day, 7 days per week. The plant had the following operating parameters that could be adjusted to control its performance:

- Number of slotted venting pipes in the base of the treatment bed connected to the inlet manifold (these venting pipes could be isolated as each one had its own gate valve);

- Number of vacuum pumps operating (each vacuum pump could be switched off individually and isolated by its own in line gate valve). There were two types of vacuum pump, single stage and two stage centrifugal pumps. The two stage pumps could generate a higher vacuum;

- Dilution air could be added before the vacuum pumps if the applied vacuum and flow rate from the treatment bed required reduction without taking any of the vacuum pumps out of line. This could be done to reduce VOC concentration reaching the vacuum pumps, or to completely bypass the treatment bed but leaving all vacuum pumps running during maintenance.

The container housing vacuum pumps and activated carbon vessels are shown in Plate 7.5.

Plate 7.5: Container Housing Vacuum Pumps and Activated Carbon Vessels.

7.8.2 SVE PLANT ALARMS

The SVE plant was protected by the following three automatic shut down systems:

- High level switch in moisture separator vessel. This operated if the moisture separator filled with water and thus prevented any liquid reaching the pumps;

- High pressure switch in the outlet manifold. This would operate if there was a pressure build-up after the outlet manifold. This could occur if there was a blockage in the pipe work or in the carbon vessels. The plant would shut down preventing any pressure build up across the rest of the system. Such a pressure build up could result in a hose failing or becoming uncoupled from the activated carbon treatment, resulting in untreated vapour discharge;

- Low pressure switch in the outlet manifold. This would operate if there was a pressure drop after the outlet manifold. This would occur if the hose connecting the carbon vessels failed or was removed resulting in plant shutdown, again preventing untreated vapour discharge.

In the event of an alarm triggering, the plant would automatically shutdown and an amber flashing light situated on top of the container would operate.

7.8.3 OPERATING MODES

The design of the treatment bed and SVE plant allowed flexible operation not only in applied vacuum and flow rate but also in the ability to focus on certain cells within the treatment bed, perhaps where the highest soil VOC concentrations were located. Several high soil concentration cells could be treated simultaneously or the whole SVE plant could be applied to one cell at a time in a cyclical fashion for one day at a time.

7.9 SVE OPERATION

To ensure personnel protection from leaks in the SVE plant, the system was run prior to the addition of soils to the treatment bed. The commissioning and first week of operation saw variations in the SVE operating parameters as difficulties with water recovery were dealt with. The main SVE objective was to achieve a vacuum with a high flow rate through the soils within the treatment bed. It was found that this required a minimum applied vacuum of 0.1 Bar at the SVE plant inlet. The plant was designed to operate at different flow rates by utilising different combinations of vacuum pumps. However, it was found during the commissioning phase that maximum flow from all pumps was effective, even when only a few treatment cells were connected to the SVE system.

The mass of VOCs recovered through the SVE system was monitored by means of direct PID readings from the head of the SVE manifold. These readings were used to calculate the cumulative CTC mass recovered by the system (see Section 10).

When required, spent activated carbon was pumped into drums for off site disposal using a vacuum system.

7.10 WATER TREATMENT

During the first phase of excavation little groundwater was encountered. Between the completion of the first treatment bed fill and the second phase of excavation, significant quantities of water accumulated in the excavation void. Although there was a slow but steady flow of groundwater into the excavation, much of the water accumulated was from precipitation, either falling directly into the excavation, or from surface and shallow drainage features present in the made ground and shallow natural soils.

A water treatment plant was set up as detailed in Section 6.3.4.

Treated water was discharged to the foul sewer under consent from the local water company.

Operating parameters of concern within the discharged water were suspended solids, chemical oxygen demand, dissolved phase VOC concentrations and a range of other chemicals. The discharge was regularly sampled and analysed for VOC content.

The water treatment system had a maximum flow capacity of 20 m³/hr. Approximately 1750 m³ of water were treated and discharged to the foul sewer during the project.

Approximately 160 m³ of water was also taken for off site disposal due to very high suspended solids preventing it being treated on site.

7.11 REINSTATEMENT OF SUCCESSFULLY TREATED SOILS

The treated soils from the bed were reinstated into the excavation void under a waste management licensing exemption. This was undertaken in two phases. The first fill of the treatment bed was reinstated during 30th October to the 1st November 2002. This was followed by the reinstatement of the second treatment bed fill during the 4th to the 7th of January 2003.

Only soils below the clean-up criteria for CTC and CFM were reinstated. No geotechnical testing was undertaken on the reinstated soils.

Prior to the commencement of the reinstatement, concrete arisings previously verified as uncontaminated, were placed into the bottom of the excavation to stabilise the base of the excavation, prior to the placement of the treated sand. In addition to the concrete, it was also necessary to import approximately 600 tonnes of crushed stone to provide a base across the rest of the excavation. The treated soil from the treatment bed was placed into the excavation with minimum compaction. The remaining void was backfilled with stockpiled

soils that were already on site prior to these remedial works. All of the stockpiles were chemically tested to verify that they were below the relevant target levels.

7.12 DISPOSAL OF SOILS FAILING TO MEET REMEDIATION TARGET CONCENTRATIONS

The soils that underwent the remedial programme were chemically tested as described below. Only one cell in the treatment bed (C14) of the second excavation failed to meet the remedial target concentrations. This soil (approximately 30 m³) was disposed of to an appropriate landfill with the other soils that were not suitable for treatment.

7.13 DISPOSAL OF SOILS NOT SUITABLE FOR TREATMENT

During the excavation phases of the remedial programme, soil that was deemed unsuitable for treatment was stockpiled and samples sent for laboratory analysis prior to disposal to landfill. This soil generally consisted of clay and concrete arisings from underground structures. Approximately 2,300 tonnes (approximately 1,375 m³) of this material was disposed of to a suitably licensed landfill.

After the first phase of work a white viscous product seeped slowly from one side of the excavation. This material was thought to be an intermediate of the former plant process. Chemical analysis showed that it had high concentrations of CTC. The material was removed using a mini-digger into 205 litre drums for off site treatment and disposal.

7.14 DECOMMISSIONING

The remedial plant was switched off on the 3rd January 2003 and decommissioning began. The plant was removed from site on the 7th January 2003 and bed dismantling began. The site was cleared and demobilised completely by the 28th January 2003.

8. PERFORMANCE MONITORING

8.1 INTRODUCTION

This section describes the monitoring carried out during the project including parameters for the SVE system, air quality, general site data and the treatment bed.

8.2 SVE SYSTEM MONITORING

The SVE system was monitored for two primary reasons; to estimate VOC mass removal efficiency and allow adjustment of operating parameters to maximise this, and to ensure the safe operation of the plant.

The parameters that were monitored for the duration of the *ex situ* SVE operation are detailed in Table 8.1.

Table 8.1: Parameters Monitored During the SVE Operation.

Parameter	Instrument	Frequency
Treatment bed venting pipes vacuum	Magnahelic gauge	As Required
Treatment bed venting pipes velocity	Digital anemometer	As Required
Inlet manifold velocity	Digital anemometer	Daily
Inlet manifold vacuum	Magnahelic gauge	Daily
Outlet manifold pressure	Magnahelic gauge	Daily
Outlet temperature	Digital thermometer	Daily
Lead carbon vessel outlet pressure	Magnahelic gauge	Daily
Lagging carbon vessel outlet pressure	Magnahelic gauge	Daily
Lead carbon vessel inlet velocity	Digital anemometer	Daily
Lead carbon vessel outlet velocity	Digital anemometer	Daily
Lagging carbon vessel outlet velocity	Digital anemometer	Daily
Lead carbon vessel inlet VOC by PID	PID	Daily
Lead carbon vessel outlet VOC by PID	PID	Daily
Lagging carbon vessel VOC by PID	PID	Daily
Dilution valve setting	Record percentage open	Daily
Water present in inlet moisture separator	Record volume with bucket	Once Per Week (min.)
Security of hoses and fittings of SVE plant	PID and manual check	Daily
Exhauster flow rate	Digital anemometer	Daily
Air quality (VOCs)	Roving PID (15 locations)	4 times daily
Air quality (VOCs)	Tenax and adsorption tubes	Continuous for 8 hr TWA
Air quality (VOCs)	Logging PID at site fence	Continuous for 8 hr TWA
Air quality (dust)	Filter packs	Summer Months

8.3 AIR QUALITY MONITORING

8.3.1 REAL TIME EXCAVATION AND TREATMENT BED AREA

The site VOC vapour emission monitoring was monitored as follows:

- Real time excavation and treatment bed monitoring, by hand-held PID operated by Banksman;

- Real time Zone 1 monitoring by roving hand-held PID operated by technician, readings taken every two hours at fixed stations.

8.3.2 TENAX TUBES

A programme of air quality monitoring was implemented during the works. This used passive Tenax adsorptive carbon tubes, placed at five permanent monitoring points around the site to monitor low levels of VOCs in the atmosphere. These tubes were exposed for a week to allow a long term average exposure to be calculated. The results were calculated to provide the 8 hour (hr) Time Weighted Average (TWA). The TWA was then compared to the Occupational Exposure Limit (OEL) of 2 ppm taken from the Health & Safety Executive publication EH40/2002.

8.3.3 ROVING PID

During the excavation phases of the work, four daily rounds of instantaneous readings were taken using a PID at twelve stations around the site. The locations of the monitoring stations are presented in Figure 9.4 as P0 – P11.

The results show that the guidance levels of 2 ppm were not exceeded at any of the stations further than 10 m from the excavation. The PID was calibrated to isobutylene at least twice daily.

8.3.4 LOGGING PID

A PID with data logging capabilities was placed on the boundary of the fenced area of the site. The PID data logged the concentrations of VOCs in the air during an 8-hr working day during the excavation phases of the site. The results show that the OEL of 2 ppm was not exceeded at the monitoring location.

8.3.5 ACTIVE ADSORPTION TUBES

Active carbon adsorption tubes were also used to monitor the exposure of CTC to the workforce during the excavation works. The results were calculated to provide the 8 hr TWA. The TWA was then compared to the OEL of 2 ppm taken from EH40/2002 to provide retrospective confirmation of the concentrations present in the workers breathing zone.

8.3.6 DUST MONITORING

During the summer months of the remedial programme, total dust was recorded at five locations across the site. The dust monitoring locations are shown in Figure 9.4. The results showed no significant concentrations of dust at the site boundary. A limited amount of dust suppression was required due to heavy plant on haul roads.

8.4 ODOUR MONITORING

The odour threshold for CTC is approximately 41 ppm. Hence, if the above control measures were to be operated there should be no chance of CTC odours being noticed at the site boundary, or anywhere outside Zone 1.

8.5   DAILY SITE LOG

A daily site activity log was kept. This recorded:

- Personnel on site;
- Equipment on site;
- Visitors;
- Activities undertaken;
- Health and Safety matters;
- Contact with general public or complaints;
- Contact with other 3rd parties (local authority, EA, members of the public).

In addition daily vapour and weather reports were produced and referenced in the log.

8.6   MASS RECOVERY THROUGH SVE SYSTEM

The main aim of the remedial scheme was to maximise recovery of VOCs within the SVE system.

A response factor calculated from laboratory vapour analysis and then applied to direct readings from the PID was used in the field.

8.6.1   USE OF ON SITE PID FOR MEASURING VOC CONCENTRATIONS

The volatile mass recovery rate was estimated from a semi-quantitative measurement of VOC vapour concentration using a PID, combined with the volumetric flow of exhaust gas from the SVE vacuum pumps (measurements being taken before the vapour phase carbon treatment vessels).

The volumetric air flow was calculated from the measurement of velocity of exhaust gas using a hot wire anemometer. This velocity, multiplied by the cross sectional area of the duct gives the volumetric flow rate.

The PID readings were converted to a VOC concentration, in mg/m^3, using a PID response factor (see Section 8.6.2). The response factor was derived from at least two laboratory analyses of vapour samples of known volume taken at known PID readings.

Once the VOC concentration in the exhaust from the vacuum pumps was known, together with the volumetric flow rate, the VOC mass recovery rate was calculated. Data were collected from the SVE system (at least weekly) and the mass recovery rate calculated. The total VOC mass recovered was then estimated for the period between the measuring dates.

8.6.2   DERIVATION OF THE SITE SPECIFIC PID RESPONSE FACTOR

Vapour samples were collected from the sample/monitoring point before the vapour phase carbon treatment vessels using an "SKC Sidekick" pump calibrated on site using an "SKC 303 Bubble Airflow Meter". Two carbon tubes were placed in series to eliminate the potential for VOC breakthrough. Time taken for sampling along with a sampling rate in l/min allowed a total volume sampled to be calculated in m^3. All VOCs in this volume of air were collected by the carbon tubes and analysed in the laboratory. The analysis of these samples showed quantities of VOCs in this known volume of air in µg. This information allowed correlation between VOC in air in $µg/m^3$ and the recorded PID reading taken during sampling. This correlation is the response factor of the PID for that composition of vapour. This procedure was followed on a number of occasions, and the PID readings were plotted against the calculated VOC concentration in $µg/m^3$ giving a straight line 'calibration' chart from which to convert semi-quantitative PID readings into vapour concentrations. The straight line drawn

was assumed to pass through the origin, thus the PID response factor was calculated from the slope of the line.

8.6.3 EQUATIONS USED TO ESTIMATE VOC MASS RECOVERY

The VOC concentration (mg/m^3) and flow (m^3/hr) allow a mass recovery rate to be calculated (mgVOC/hr converted to kg/day). This is outlined in the following equations:

Volatile Organic Compound (VOC) Concentration (mg/m^3) = Cn x RF   [Eqn.1]

Cn = Average of 2 consecutive PID concentrations
RF = Response Factor

The averaging of two consecutive readings (Cn) gave a mid-range estimate for mass recovery during a time period.

Response Factors (RF) were calculated by comparing analysis of vapour samples collected in the pilot testing with PID concentrations from the same sample.

The estimated total VOC mass recovered, derived from PID readings was cross-checked with the estimated mass of VOCs adsorbed onto the vapour phase granular activated carbon (the carbon VOC mass loading being estimated from laboratory analytical results of samples of spent carbon).

$$\textbf{Total Mass (kg)} = \frac{\textbf{P x C x t x 60}}{\textbf{1 x 10}^6}$$ [Eqn.2]

$$\textbf{Mass Recovery Rate (kg/day)} = \frac{\textbf{P x C x 60 x 60 x 24}}{\textbf{1 x 10}^6}$$ [Eqn.3]

P =   Pump flow rate, (m^3/s) at atmospheric pressure;
C =   VOC concentration, (mg/m^3);
t =   Elapsed time period, (minutes)

The mass recovered in a monitoring period was calculated by allocating the mass recovery rate for the time period halfway between the current and previous monitoring dates and halfway between the current and projected next monitoring period.

The VOC recovery data, as routinely measured in the off-gas from the treatment bed, are presented in Figure 8.1 and 8.2, which show the cumulative CTC mass removal from each fill of the treatment bed.
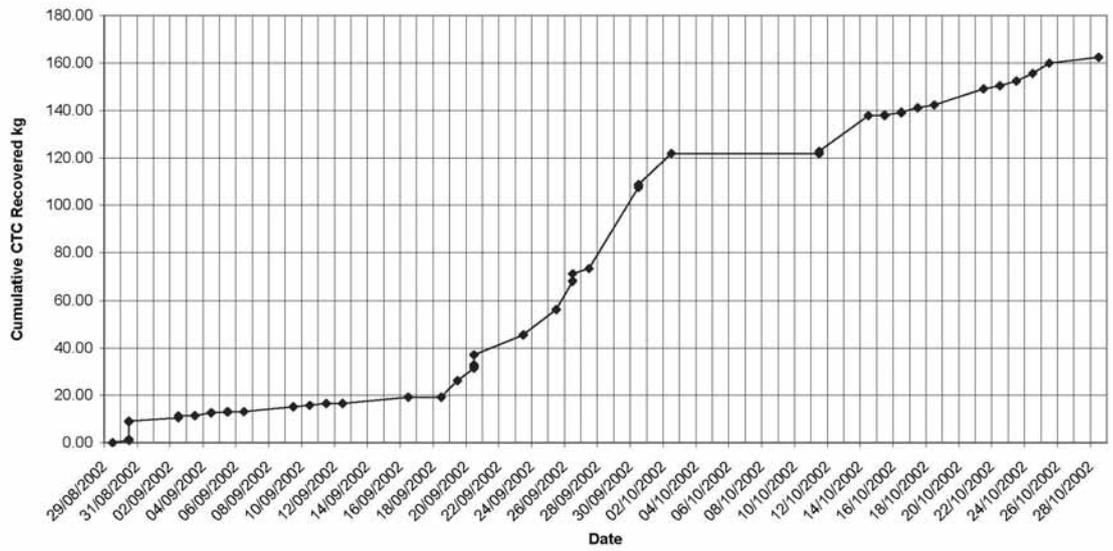
Figure 8.1: Treatment Bed Fill 1 Cumulative Mass Recovery.
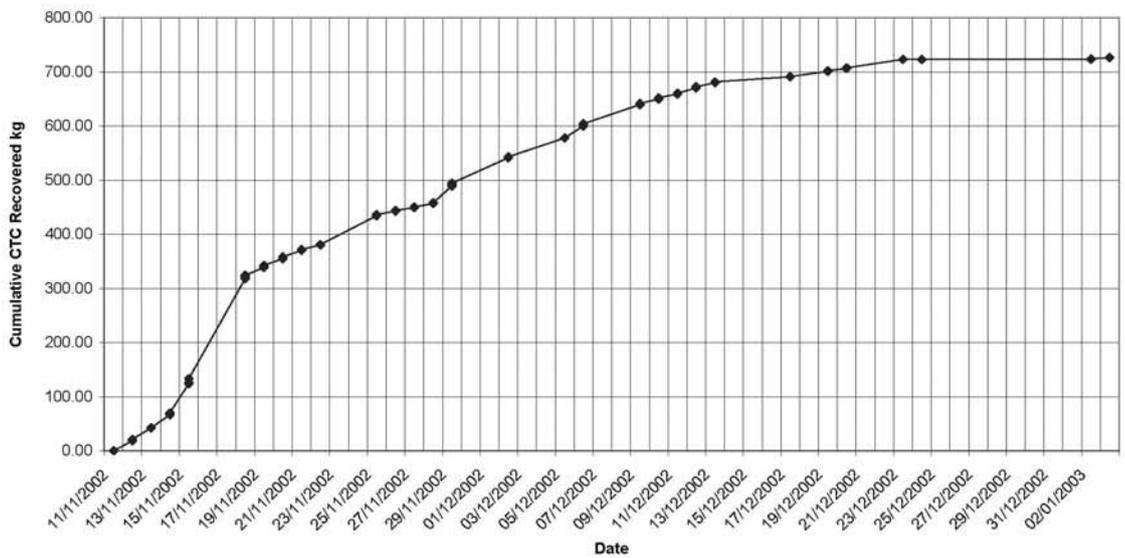
Figure 8.2: Treatment Bed Fill 2 Cumulative Mass Recovery.

Estimated totals of 122 kg and 726 kg of CTC were recovered by the SVE system during the first and second treatment bed fills, respectively.

8.7 VALIDATION OF FINAL TREATED SOIL CONTAMINANT LEVELS

The soils present in the treatment bed were periodically tested for VOC content by conducting head space tests with a hand-held PID. This data series allowed estimation of the time to remediation completion for each bed fill. The results of these headspace tests were used as a qualitative measurement to observe the overall trend in concentration reduction. Once the concentrations of VOCs had been established in each soil cell and sufficient reduction observed, the decision was made to undertake soil sampling for chemical analysis.

Soil sampling was undertaken on each individual cell. The sample was selected by taking five duplicate soil samples from each cell. Three of these soil samples were taken from just below the surface while the remaining two were taken from depth. One set of soil samples was then analysed on site by headspace testing and the results recorded. The duplicate soil sample with the highest headspace test result from each cell was then sent for laboratory analysis for speciated VOCs.

The bed was sampled on the 18th October 2003. The results are summarised in Table 8.2. On completion of the first treatment cycle, only soil samples from C2 and C13 failed the clean-up criteria of 123 mg/kg CTC. Soils from within these cells remained in the treatment bed for further treatment during the second bed filling. Soils from all other treatment cells were backfilled into the excavation under the remit of the waste management licence exemption.

On planned completion of the second excavation and treatment cycle, soil samples representative of six cells failed the clean-up criteria of 123 mg/kg for CTC. For this reason it was decided to run the treatment bed for a further 3 weeks before re-sampling the failed cells. The cells that passed the clean-up criteria were also treated for an extra 3 weeks to obtain further mass reduction. Only the soil in cells that had failed the initial analysis was re-tested prior to their reinstatement. Both cells C2 and C13 that initially failed the clean-up criteria from the first excavation now passed.

Of the second set of analysis only C14 failed the clean-up criteria as detailed in Table 8.3. Soils from this cell were removed to a suitably licensed landfill under duty of care procedures. The soils from the remaining cells were reinstated.

Table 8.2: Excavation Bed Analysis.

Cell No.	Treatment Bed Fill Cycle						
	1st		2nd				
	Carbon Tetrachloride Concentration (mg/kg)	Chloroform Concentration (mg/kg)	Carbon Tetrachloride Concentration (mg/kg)		Chloroform Concentration (mg/kg)		
			1st sample	2nd sample	1st sample	2nd sample	
C1	68.9	3.7	Cell Not Used		Cell Not Used		
C2*	757.7	4.61	3.6		0.02		
C3	7.8	0.13	0.1		<0.001		
C4	23.7	0.12	0.2		0.01		
C5	20.8	0.15	2.0		0.07		
C6	1.2	0.06	1.8		0.08		
C7	0.7	0.05	6.9		0.15		
C8	1.7	0.04	0.2		0.05		
C9	7.8	0.06	15.2		0.07		
C10	0.7	0.04	96.5		0.14		
C11**	70.2	0.36	453.6	47.5	1.96	0.95	
C12	84.1	1.49	111.5		0.03		
C13*	767.4	1.13	76.1		0.08		
C14**/***	1.3	0.01	295.6	211.5	3.81	3.95	
C15	1.2	0.02	56.1		0.19		
C16**	5.9	0.04	176.0	75.0	1.32	0.38	
C17	51.2	0.22	77.0		0.21		
C18**	19.5	0.19	200.9	69.1	0.84	0.07	
C19**	5.9	0.1	123.9	77.6	0.27	0.23	
C20**	24.0	0.3	199.0	68.8	0.36	0.10	
C21	47.0	0.48	13.1		0.03		
C22	6.6	0.09	80.7		0.17		
Mean Concentration	22.5	0.38	44.0		0.15		

*   1st fill sample exceeded SSTLs, soils remained in treatment bed for treatment during the 2nd phase of testing

**   2nd fill 1st sample exceeded SSTLs, soils remained in treatment bed for further treatment prior to 2nd sample

***   2nd fill 2nd sample exceeded SSTLs, soils in this cell sent off site for treatment and disposal

Table 8.3: Second Excavation Bed Analysis.

Cell	Concentration CTC (mg/kg)
C11	47.5
C14	211.5
C16	75.0
C18	69.1
C19	77.5
C20	68.8

9. AIR DISPERSION MODELLING

9.1 BACKGROUND

The remediation project was designed to reduce the quantity of VOCs which were present within the ground at the subject site. By their very nature the substances to be removed are readily vaporised and so easily lost to the atmosphere. These losses were expected to occur as the contaminated ground was being excavated, during transportation to the treatment beds, and during turning operations on the beds.

Before site works commenced, dispersion analysis of the likely vapour releases allowed the setting of local monitoring limit levels (i.e. site action levels) below which Environmental Assessment Levels (EALs) would not be exceeded at local residential areas.

Monitoring of the airborne concentrations of VOCs during the site works allowed post-project estimates of the quantities of VOCs emitted to atmosphere. Using this data, the total quantity of VOC present and the efficiency of the remediation process could be estimated.

9.1.1 PHYSICAL PROPERTIES

The main contaminants in the ground were carbon tetrachloride (CTC) and chloroform (CFM). The excavations revealed several pockets of viscous organic product containing chlorinated hydrocarbons, which were identified and removed for off site treatment and disposal.

Table 9.1: Physical Properties of CTC/CFM Mixture Used in the Dispersion Analysis.

Property	Value	Units
Molecular weight	154	kg/kmol
Conversion factor µg/m³ to ppb	0.16	

9.1.2 TOXICOLOGICAL PROPERTIES

Air quality Environmental Assessment Levels (EALs) rather than Occupational Exposure Limits (OELs) apply over non-industrial areas, and are set at levels which are a fraction of the OELs in order to protect the most vulnerable in society, who may be exposed to the emissions 24 hours a day rather than the 8 hours a day for employees on site.

At the time of the project, OELs were defined as either Occupational Exposure Standards (OESs) or Maximum Exposure Limits (MELs) for both (long term) 8 hour time weighted average (LTEL) or short term 15 minute average (STEL) exposures.

Hourly and annual average EALs are based on fractions of the LTEL and STEL limits as specified in Integrated Pollution and Prevention Control Horizontal Guidance Note 1 (Environment Agency, 2003). The fractions were dependent on whether the chemical had a MEL or OES defined.

Table 9.2: Derivation of EALs.

Basis	Long term EAL (as an annual avg.)	Short term EAL (as a one-hour avg.)
OES 8 hour time weighted average	OES / 100	-
MEL 8 hour time weighted average	MEL / 500	-
OES STEL 15 minute average	-	OES STEL / 10
MEL STEL 15 minute average	-	MEL STEL / 50

For those substances without a defined STEL, a figure of three times the 8 hour time weighted average is used as the STEL.

There are no 'long term' or 'short term' EALs that apply to off site potential exposure, therefore, the hourly average EAL for continuous emissions was judged to be the most appropriate limit value to apply, even though the potential emissions from the remediation were likely to be of only limited duration (circa 4-6 weeks).

The view was taken that due to the limited duration of the emissions, occasional exceedences of the EAL during this period would probably be regarded as acceptable.

9.1.2.1 Carbon Tetrachloride (CTC)

CTC is toxic by inhalation. Very high exposures may cause abnormal heart rhythm and can prove suddenly fatal. Repeated exposures to lower concentrations may produce adverse effects on the liver and kidneys as well as in the short term producing anaesthetic effects. When rats have been repeatedly exposed to CTC, liver cancer has occurred.

Unusually for toxic volatile organic compounds, CTC does not have a MEL defined. Because toxicity studies have demonstrated that there is a safe concentration below which long-term damage to the liver and kidneys of humans is unlikely, CTC has an OEL defined. Humans are unlikely to contract cancer providing concentrations do not significantly exceed the occupational exposure limit. This is 2 ppm (13 mg/m³), expressed as an 8 hour average.

No 15-minute STEL is defined and hence, based upon HSE guidance (HSE 2003), it is assumed that it can be represented by a value of three times the 8 hour average concentration i.e. 6 ppm (39 mg/m³). The corresponding off site hourly average EAL is one tenth of the 15 minute average STEL i.e. 0.6 ppm (3.9 mg/m³). Since the releases were only likely to occur for a short period, then the calculation of annual average concentrations for comparison against annual average EALs is inappropriate.

The odour threshold for CTC quoted by Woodfield & Hall (1994) is 41 ppm (280 mg/m³). It should be noted that CTC is one of the few chemicals for which the odour threshold is higher than the OEL, therefore odour is not sufficient warning to site personnel of exceedence of the STEL.

9.1.2.2 Chloroform (CFM)

The toxic effects arising from high concentrations of CFM are similar to those of CTC. Very high concentrations may cause an abnormal heart rhythm and prove suddenly fatal. Lower concentrations that are still above the OEL may cause anaesthetic effects.

Very high and repeated exposures may produce adverse effects on the liver and kidneys. High doses of CFM have led to cancers of these organs in animals, as well as abnormalities in embryos and foetuses. None of these effects are expected to occur in humans, provided exposure is maintained at or below the OEL.

The OEL for CFM is the same as for CTC, 2 ppm (9.9 mg/m³) as a LTEL (8 hour average). There is no specific STEL, and so, again a figure of 6 ppm by volume (30 mg/m³) has been used. The hourly average EAL is 0.6 ppm by volume (3 mg/m³).

There is a wide variation in quoted odour thresholds for CFM. Woodfield & Hall (1994) suggest a low figure of 0.667 ppb (0.0033 mg/m³). The US-EPA (1990) suggests 14 sources of CFM odour threshold data, with a range from 0.6 to 1413 ppm. From the list of research projects quoted, the work of Dravnieks is probably the best known and reliable. He suggests an odour threshold of 276 ppm (1350 mg/m³) for CFM, a figure well above the OEL.

9.1.3 TOPOGRAPHY

The subject site is situated in an area with no substantial topographic features such as large buildings or hills which would adversely affect the wind flow field across the site.

The site is in a semi-rural location with reclaimed ground to one side of the site, and a mixture of suburban housing and agricultural land surrounding it. The aerodynamic roughness length for the dispersion modelling was therefore taken as 0.3 m.

The nearest residential area is around 200 m to the south west of the excavation area. The site boundary (in a south-westerly direction) is around 100 m away from the excavation area.

9.1.4 METEOROLOGY

Wind speed and direction data for the site were collected using a Davis Instruments anemometer which was mounted at approximately 3.5 m above ground. Other data collected included temperature, relative humidity, barometric pressure and rainfall.

The anemometer recorded data at 30 minute intervals reporting wind direction to a resolution of 22.5° on a compass rose (accuracy: ± 7°) and wind speed in the range 0.9 to 78 m/s (accuracy: ± 5%).

The closest Meteorological (Met.) Office observatory is located approximately 30 km from the site and records wind speed (at the standard reference height of 10 m), wind direction to a resolution of 10°, temperature, and cloud cover every hour.

Over the period the site data was recorded (August 2002 to February 2003) 22.5% of the site wind speed / direction observations were recorded as 'error values'. During this period the site observations were not compared with local Met. Office observations. Only after the site station had been dismantled was the site data compared.

Figure 9.1 gives a comparison based on 6-hourly averages of wind directions, which shows a significant offset between the site and Met. Office data which could not be resolved by analysis of topographical features such as hills or buildings which may have caused a permanent deflection. The conclusion was therefore that the site anemometer had been misaligned with North, and that there was an estimated -50 degree offset in the site observations, i.e. the site anemometer north was pointing towards the North-West.
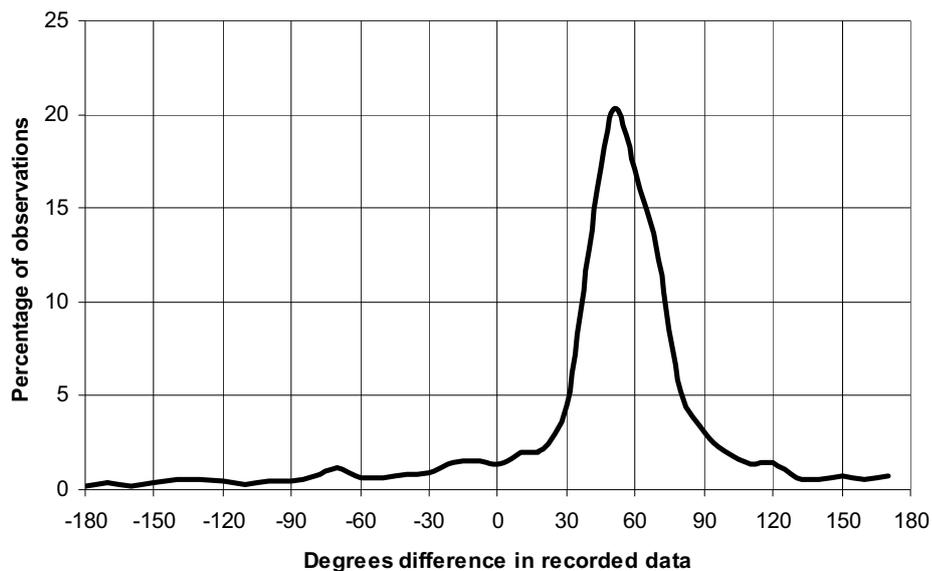
Figure 9.1: Comparison of Met. Office with Site Recorded Wind Direction Data.

The site wind speed observations were therefore corrected in direction and to the standard reference height of 10 m using the approximation of a vertical logarithmic wind speed profile in neutral atmospheric conditions. This results in a multiplication factor between the site and Met. Office data of 1.46. A comparison of the corrected observations is given in Figure 9.2.
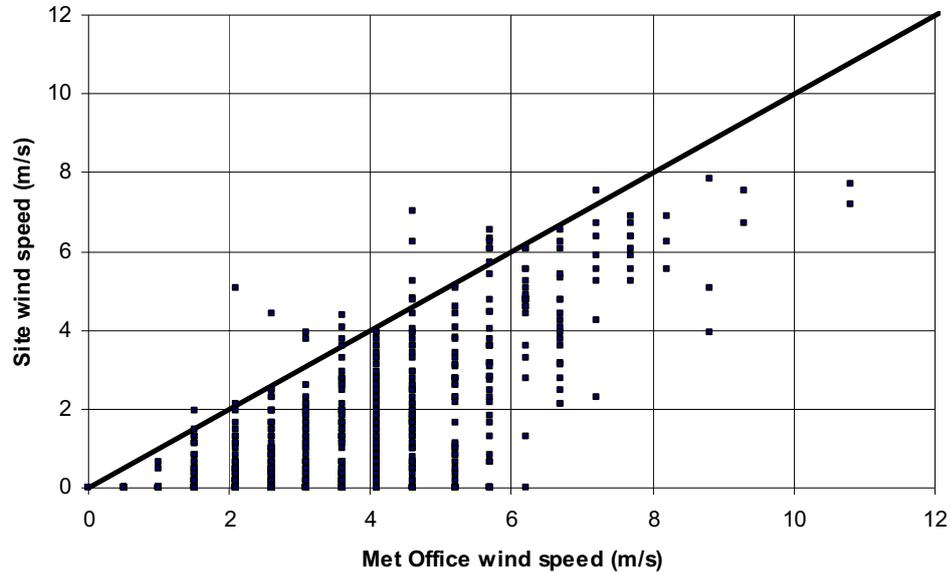
Figure 9.2: Comparison of Site Recorded Wind Speed Data with Met. Office Data.

From the above it is apparent that the site anemometer was generally under-reading the wind speed. This is to be expected as the lower height of 3.5 m and the comparatively high start speed 0.9 m/s would lead to all wind speed below approximately 1.5 m/s being recorded as zero.

The temperature data for the site and Met. Office are compared in Figure 9.3.
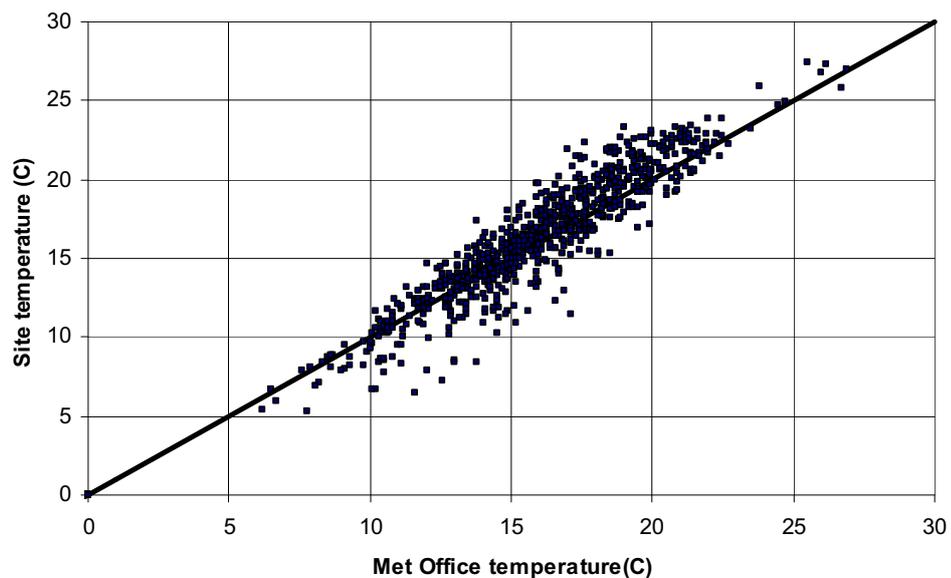
Figure 9.3: Comparison of Site Recorded Temperature Data with Met. Office Data.

It can be seen that there is a good correlation between the site temperature and that recorded by the Met. Office.

Based on the above comparisons, a composite meteorological data set was created using the most reliable data from each of the data sets. The wind direction and speed were therefore taken from the Met. Office data, while the site temperature was taken from the site data.

9.1.5 DISPERSION MODEL

UK-ADMS (Atmospheric Dispersion Modelling System) v 3.1 was used for the dispersion calculations. ADMS is now the most widely used dispersion model in the UK and is accepted by industry, consultancies and regulators.

UK-ADMS v3.1 can model the effects of multiple concurrent ground level area sources, on an hour by hour basis, when using the appropriate meteorological data. This allows the effects of time varying temperature, wind and weather to be taken into account when calculating average airborne concentrations.

9.2 PRE-PROJECT ANALYSIS METHODOLOGY

A pre-project analysis of likely dispersion of VOCs was used to determine the maximum concentrations allowable on site such that the OEL would not be exceeded beyond the site boundary, and the EAL would not be exceeded at the location of nearest residential housing.

The two main VOCs of concern were CTC and CFM. Based upon initial soil sample results, maximum concentrations of CTC on the western side of the area to be remediated, were up to 17 g per kg of soil, with typical values in the region of 5-10 g/kg.

The mass ratio of CTC to CFM in the samples was in the region of 35:1. As the ratio of CTC to CFM was high, and the OESs for both substances are the same (2 ppm), a reasonable approximation for the modelling was to assume that all the released chemical was CTC.

Initial estimates of the quantity of soil to be excavated, and the duration of the excavations gave a mass excavation rate in the region of 9 kg/s for an 8 hour working day. Assuming the worst case scenario that all the VOCs were lost to atmosphere before being covered over in the treatment beds this would give a maximum release rate of 150 g/s based on the highest soil concentrations.

The dispersion was analysed for a series of typical UK wind-weather conditions determined by wind speed measured 10 m above grade and a Pasquill-Gifford stability category as detailed below:

- 2 m/s B-stability, representing a typical hot summer's day with little cloud cover. These conditions are termed unstable atmospheric conditions and occur for typically 7% of the time in the UK;

- 5 m/s C-stability, conditions representing a warm spring afternoon or a summer morning with only a slight cloud cover. These conditions are termed slightly unstable conditions and occur for around 5 – 10% of the time in the UK;

- 5 m/s D-stability, representing a typical windy and cloudy day and termed neutral atmospheric conditions. These conditions occur for typically 50 – 70% of the time in the UK;

- 3 m/s E-stability, representing slightly stable weather conditions, representing evenings with little cloud cover. These conditions occur for typically 5-10% of the time in the UK;

- 2 m/s F-stability, representing a cold winter's evening with little cloud cover (stable atmospheric conditions). These conditions typically occur for 15% of the time in the UK.

9.3   PRE-PROJECT ANALYSIS RESULTS

For both CTC and CFM, the acceptable concentration levels beyond the site boundary were not defined by odour threshold data. Instead, emission rates were required to be controlled so that concentrations remain below the STEL at the site boundary, and the hourly EAL off site.

Based on the worst case emission levels and a total loss before remediation, the airborne concentrations of VOCs would exceed the EAL over the residential areas and the OES on site under all wind-weather conditions analysed. For more typical soil concentrations the EAL over the residential areas and the OES on site would only be exceeded under stable wind-weather conditions.

In practice however, the soil was likely to be transferred from the excavation area in lumps – most of the CTC and CFM will be contained within the lumps of soil and only free phase material on the surface will evaporate.

As an indication of the likely emission rate, it was assumed that each lump of earth weighs 9 kg – the excavation rate per second. Then, assuming the bulk density is 1.7 tonnes per cubic metre and the lump is spherical, the radius of the lump is calculated to be 0.11 m. If there is a 0.1 mm thick film of CTC over 20% of the area of the lump of soil, and this all evaporates, then 4.7 g/s would be released to atmosphere.

With this lower estimated emission rate, concentrations over the nearest residential area are predicted to be below the hourly EAL of 0.6 ppm and within the site boundary concentrations are predicted to be below the OES of 2 ppm.

However, as the concentrations are still not negligible, and the uncertainty in the emission rate was high, on site monitoring of CTC concentrations was deemed necessary. Close to the excavation, it was impossible to predict by dispersion modelling the concentrations that would be experienced, so it was recommended that all personnel involved with excavating the soil should have respiratory protection.

From analysis of the concentrations estimated for the site boundary and the residential areas, it was found that this ratio concentration was in the order of 3.6 to 5.6 for a range of wind-weather conditions. Based on a conservative estimate it was assumed that the concentration over the nearest housing would be a factor of 3 lower than that measured at the site boundary. It was therefore concluded that concentrations at the site boundary should not exceed a figure of 1.8 ppm (rounded up to 2 ppm) for periods longer than an hour.

A 2 ppm limit value was imposed for the site boundary monitoring. Should the site boundary monitor register more than 2 ppm, site excavations were to be halted until levels reduced.

Post-project analysis of the logged data from the site boundary monitor showed that the limit value had not been exceeded during the site works.

9.4   POST-PROJECT ANALYSIS METHODOLOGY

The aim of the post-project dispersion analysis was to determine the mass of VOC 'emitted' to atmosphere during the excavation and remediation phases of the project.

Estimation of the VOCs 'emitted' to atmosphere, along with initial and final soil sample concentrations, and the quantity of VOCs collected in the remediation bed filters allowed the mass balance of the remediation process to be estimated.

VOC MONITOR DATA COMPILED

Monitoring at the excavation and treatment bed was designed to detect peak concentrations which could cause ill-health effects as a result of acute exposures. This was performed using a series of PIDs. The monitor locations (P0 to P11) are shown below in Figure 9.4 and described by the following:

- Excavator location at treatment bed;

- Excavator location at excavation;

- Roving 2 hourly boundary monitoring;

- Fixed point continuous monitoring (P0).
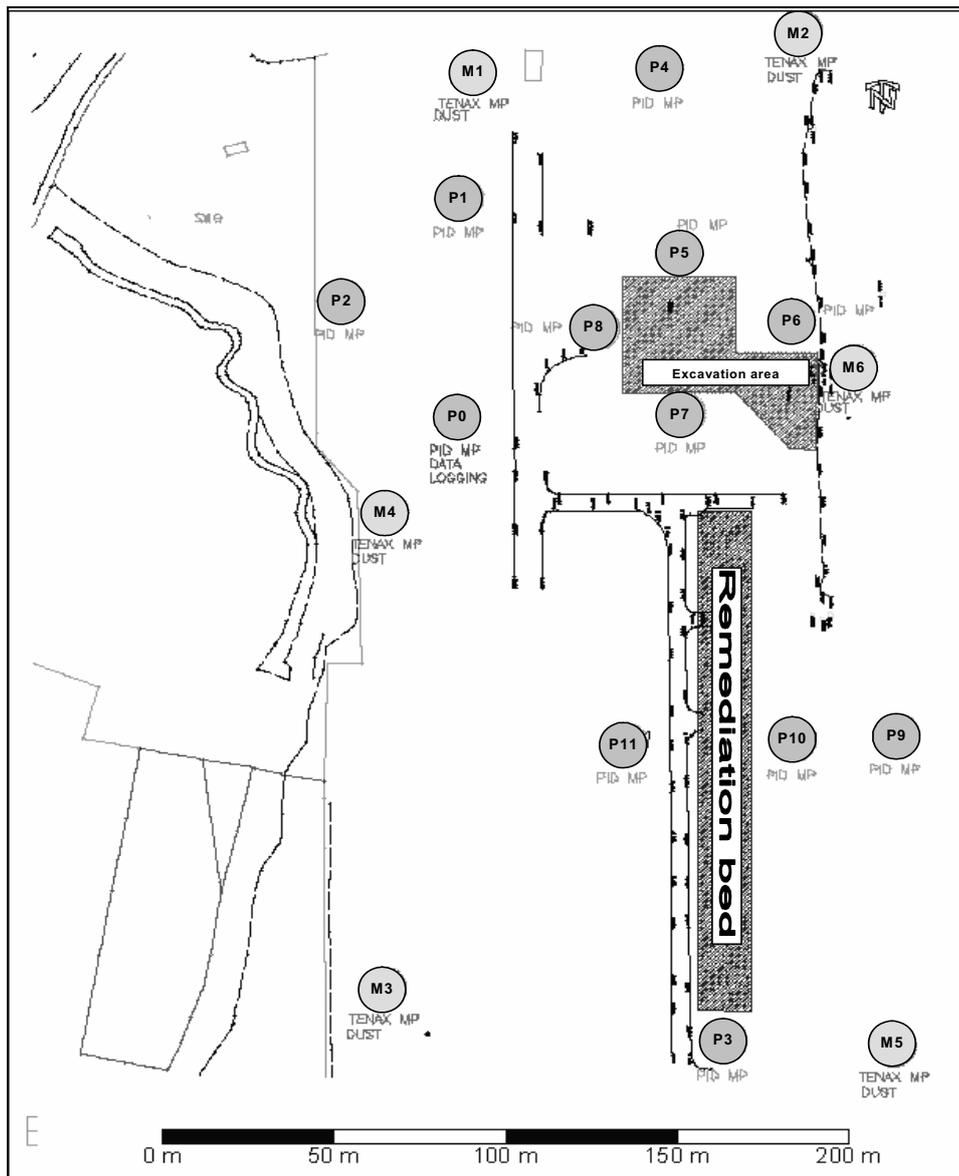
Figure 9.4: Location of Vapour and Dust Monitoring Points.

This real time monitoring was also carried out for all workers at zones where peaks or prolonged exposures are at their highest. The only worker whose (moving) work location did not have the permanent presence of a PID was the dumper driver, however, the dumper drivers' exposure was expected to be lower than the exposures at the treatment bed and

excavation. Hence, if the concentrations were acceptable at both the excavation area and the treatment bed, they would also be acceptable for the dumper driver.

A number of passive absorption tube VOC (Tenax) monitors were also located around the site. These are shown in Figure 9.4 as M1 to M6. These were placed at approximately 1 m above ground level, and were exposed for up to 1 week before being sent for analysis.

The exposure durations and total VOC content of the Tenax monitors were used to calculate an average airborne concentration of VOCs for the exposure period. The data formed the basis for the back calculation of the source terms for the dispersion analysis, and hence the quantities of VOC 'emitted' to atmosphere from the excavation and remediation beds.

9.4.2 'SOURCE TERMS' BACK CALCULATED

In order to back calculate the source term data from the monitor measurements, the following factors were taken into account on an hour-by-hour basis:

- The meteorological data were analysed as described in Section 9.1.4, for the wind direction, wind speed and temperature;

- Based on the temperature and the saturated vapour pressure of CTC a volatility factor was estimated, to account for the increased vaporisation rate at higher temperatures. This gave an increase in evaporation rate of a factor of 3 between 0 and 30°C;

- The 'sources' were defined as being in one of six locations. The excavation area was divided up into 3 areas, as was the remediation bed. By using a combination of these areas the location of the activity could be defined for each hour. The excavation cell areas were based on the south-east corner, and the rectangular block divided into northern and southern sections. The remediation bed was divided into thirds as north, central and south areas;

- An activity factor was defined to account for the working hours on the site. This accounted for the start times, lunch breaks and finish times, and was based on the sitelog of when either excavation or bed turning was logged as occurring. From early 'headspace' tests of ground samples it was determined that the bulk of the evaporation / emission from the samples occurred in the few seconds following breaking up of the sample, so it was considered reasonable to assume that the emission rates outside of excavation / bed turning times would be negligible;

- The number of cells which were excavated during the day was included as an average for the day. No detailed record was kept of the actual number of cells excavated in each hour.

The factors detailed above were used as multipliers for weekly average 'base' concentrations which represented the 'total CTC present' for each of the excavation and remediation areas for each of the weeks analysed.

9.4.3 ITERATIVE SOLUTION FOR 'BEST FIT' TO MONITOR DATA

A basic input file was created for Atmospheric Dispersion Modelling System (ADMS) which defined the three cell and three strip source locations, their shapes, areas and heights (ground level). The monitor locations were given as point receptors, and the background pollutant parameters defined for CTC. The week specific data was detailed externally as a variable emission rate (VAR) file, and a meteorological data (MET) file. This allowed the ADMS input (APL) file to be left as a general skeleton.

The source terms were calculated based on the factors detailed above using a Microsoft Excel spreadsheet, which created the VAR file in the format required by ADMS.

Once the VAR file had been created, the spreadsheet then ran the ADMS calculation using the specified MET and VAR data. On termination of the calculation, the results file was read directly back into the spreadsheet for comparison with the measured monitor data.

The source term parameters, chiefly the weekly average 'base' concentrations, were then adjusted, and the calculation program run again until a best fit with the monitor data at M1-M6 was achieved.

9.5 POST-PROJECT ANALYSIS RESULTS

The mass emission rates were estimated on an hour-by-hour, and week-by-week basis, and hence the total mass 'emitted' to atmosphere was calculated.

Figures 9.5 to 9.9 show the wind rose for each week modelled, using the Met. Office convention of wind data aligned with the direction the wind is blowing from.

Surrounding the wind rose in the approximate direction of the monitors (M1 to M6) are the monitored (actual) and estimated (estim.) hourly average concentrations.

Where no data was recorded by the monitor, 'ND' is noted as the concentration.

M1	µg/m³
Actual	67
Estim.	0.6

M3	µg/m³
Actual	18
Estim.	0

M5	µg/m³
Actual	53
Estim.	57

M2	µg/m³
Actual	204
Estim.	194

M4	µg/m³
Actual	28
Estim.	0

M6	µg/m³
Actual	ND
Estim.	8154
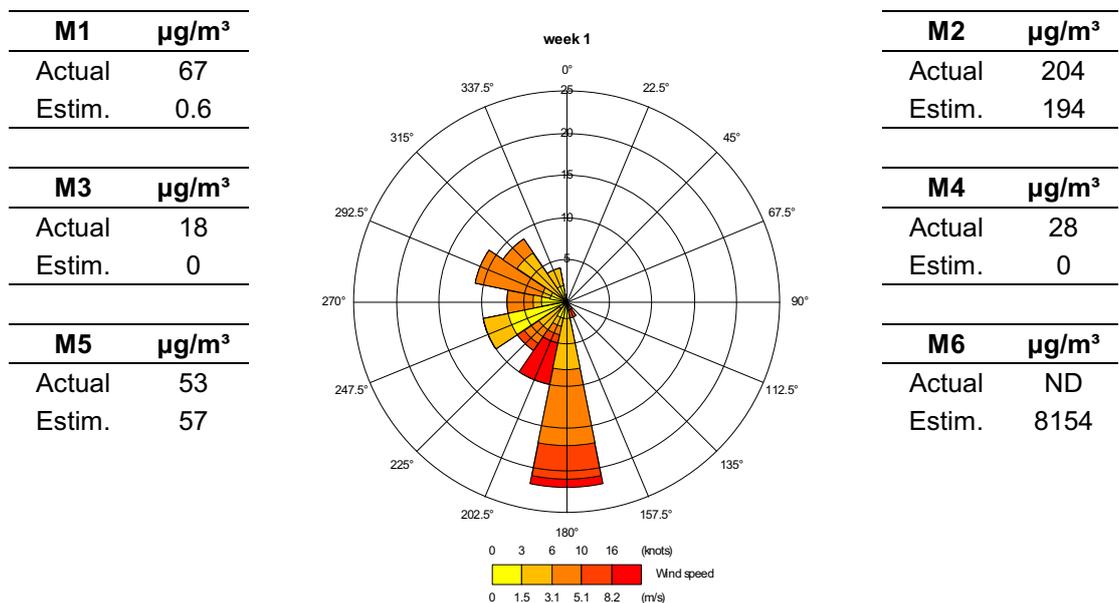
Figure 9.5: Week 1 Dispersion Results.

The total mass evaporated in week 1 was estimated as 1180 kg.

The fit of the source term data was determined by the M2 and M5 monitors. As there was no M6 monitor data recorded that week, verification of the high concentration in that direction was not possible.

The M3 monitor concentration noted above is effectively a zero reading, as the value recorded was the analytical detection limit.

The M1 and M4 monitors recorded concentrations, although the estimated concentrations were negligible. It is likely this is a result of local wind variations, which the dispersion model is unable to account for, or that contaminated ground may have been transported past these locations on their upwind side.

M1	µg/m³
Actual	26
Estim.	25

M3	µg/m³
Actual	17
Estim.	20

M5	µg/m³
Actual	12
Estim.	0
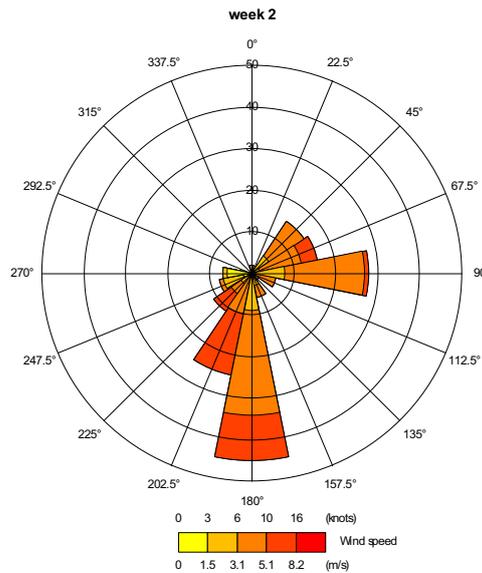
M2	µg/m³
Actual	50
Estim.	19

M4	µg/m³
Actual	9
Estim.	17

M6	µg/m³
Actual	265
Estim.	24

Figure 9.6: Week 2 Dispersion Results.

The total mass evaporated in week 2 was estimated as 184 kg.

The fit of the source term data was determined by the M1 and M3 monitors. The data for monitors M4 and M5 has been extrapolated based on the data available, as these monitors were removed two days into the week.

The M6 monitor recorded high concentrations, while the estimated concentrations were negligible. It is likely this is a result of local wind variations, which the dispersion model is unable to account for, or that contaminated ground may have been transported past the location on the upwind side.

M1	µg/m³
Actual	44
Estim.	32

M3	µg/m³
Actual	133
Estim.	130

M5	µg/m³
Actual	746
Estim.	50
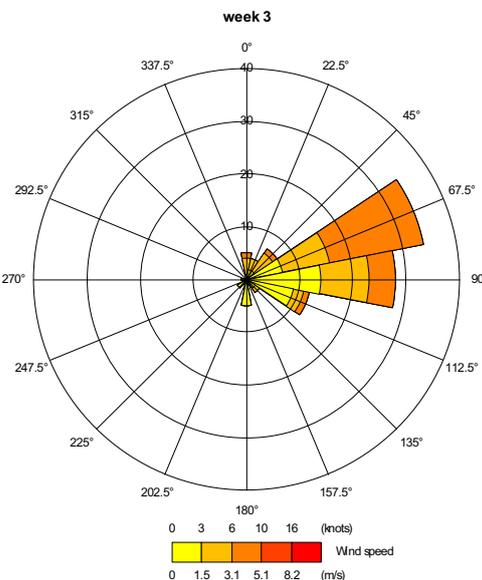
M2	µg/m³
Actual	28
Estim.	42

M4	µg/m³
Actual	251
Estim.	42

M6	µg/m³
Actual	224
Estim.	46

Figure 9.7: Week 3 Dispersion Results.

The total mass evaporated in week 3 was estimated as 297 kg.

The fit of the source term data was determined by the M1, M2 and M3 monitors.

The M4, M5 and M6 monitors recorded a high concentrations, while the estimated concentrations were small. It is likely this is a result of local wind variations, which the dispersion model is unable to account for, or that contaminated ground may have been transported past the location on the upwind side.

M1	µg/m³
Actual	136
Estim.	27

M3	µg/m³
Actual	ND
Estim.	0

M5	µg/m³
Actual	13
Estim.	0
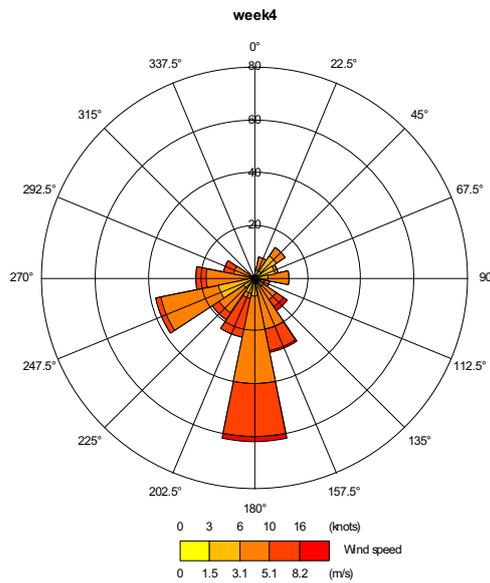
M2	µg/m³
Actual	ND
Estim.	55
No data	

M4	µg/m³
Actual	86
Estim.	0

M6	µg/m³
Actual	544
Estim.	547

Figure 9.8: Week 4 Dispersion Results.

The total mass evaporated in week 4 was estimated as 1060 kg.

The fit of the source term data was determined by the M6 monitor, which was reliant almost entirely by the emission rate from the excavation area, with virtually no contribution from the remediation bed.

M1	µg/m³
Actual	ND
Estim.	70

M3	µg/m³
Actual	27
Estim.	0

M5	µg/m³
Actual	21
Estim.	20
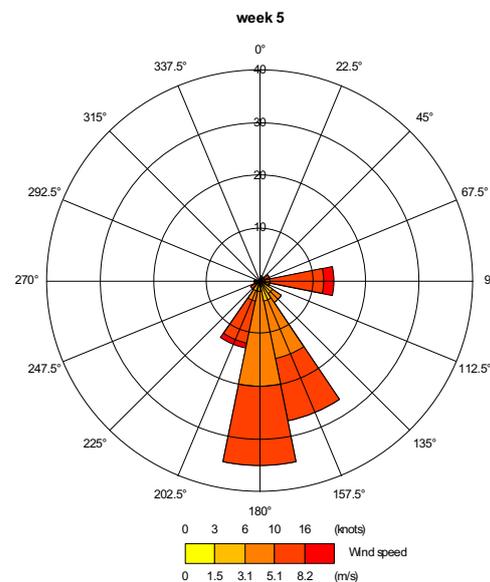
M2	µg/m³
Actual	359
Estim.	362

M4	µg/m³
Actual	208
Estim.	0

M6	µg/m³
Actual	ND
Estim.	346

Figure 9.9: Week 5 Dispersion Results.

The total mass evaporated in week 4 was estimated as 710 kg.

The fit of the source term data was determined by the M2 and M5 monitors, which were reliant on the emission rate from the excavation area and the remediation bed respectively.

Although the wind was recorded as blowing in the direction of M4 during week 5, this did not occur at the time any excavation or bed turning activity was occurring, and therefore was not attributed with any emissions.

A summary of the estimated mass emissions is given below.

Table 9.3: Summary of Mass Emission Rates.

Week	Mass (kg)
1	1180
2	184
3	297
4	1060
5	710
Total	**3431**

9.6   MODELLING UNCERTAINTY

The masses detailed in Table 9.3 are based on the best fit for the measured data from the site monitors. There are however several areas of uncertainty which could give rise to significant variation in the estimates of the VOC mass 'emitted' to atmosphere.

9.6.1   WIND-WEATHER DATA

The wind-weather data for the modelling was created as a best approximation of the site conditions using the data available. It was suspected that the site anemometer was set up incorrectly, with the north reading approximately north west, as shown in Figure 9.10. This led to the discarding of the wind data from the site, and the use of the Met. Office data in its place.

This decision had a secondary effect, in that the site wind-weather data generally showed a lower degree of spread in the wind directions recorded than the Met. Office data as shown when comparing the site and Met. Office data for week 1.
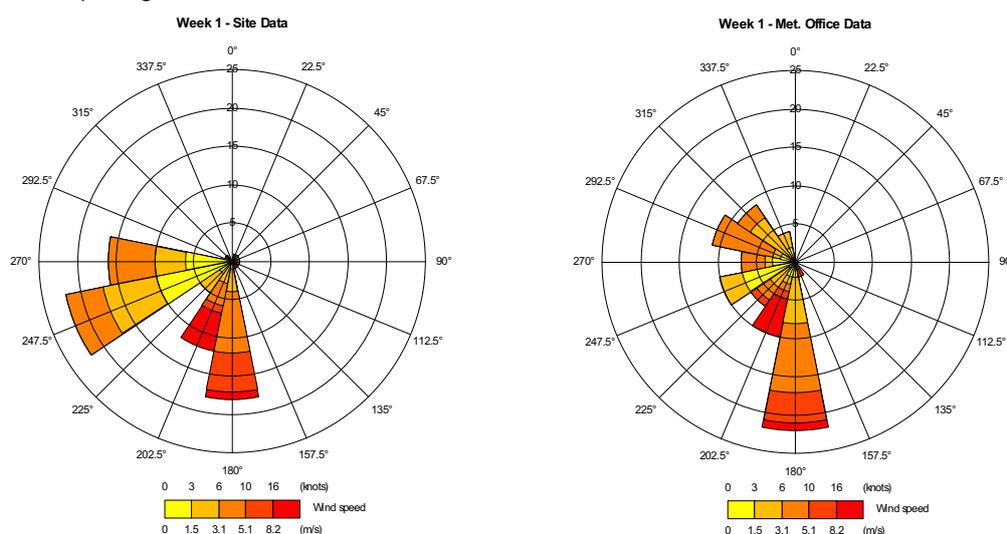
Figure 9.10: Comparison of Site and Met. Office Wind-Weather Data.

It can be seen above that the Met. Office data covers 8 segments, while the site data only covers 5. This may in turn lead to a poorer fit to the observed concentrations when data is recorded at all the monitors.

In addition to the overall spread of the data, the timings of the wind directions were also critical, as the only wind direction data that had an effect on the dispersion analysis were those that occurred during the excavation and remediation bed turning times. The time based plot of wind direction versus time for week 1 shows this in Figure 9.11.
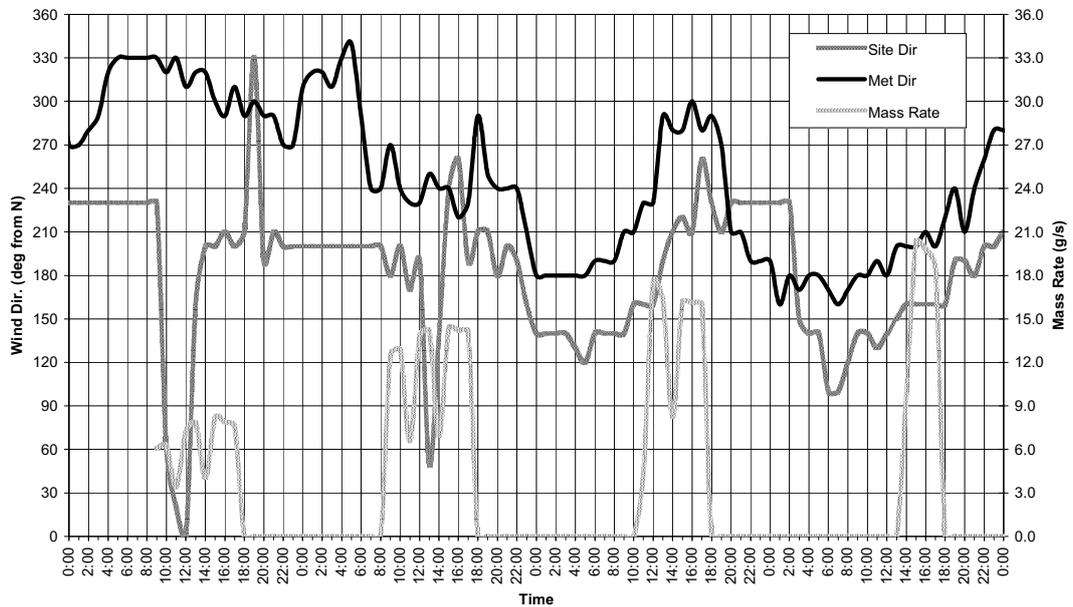
Figure 9.11: Wind Direction and Emission Rate Versus Time.

From the above, the site / Met. Office wind direction offset can clearly be seen in Figure 9.11. It can also be seen that at certain times during the emission times the wind directions are quite different.

9.6.2   SOURCE EMISSION RATES

There were a total of 6 emission sources defined for the analysis. The locations of these sources varied from roughly in between monitors M4 and M6 (the cell sources), down to monitors M3 and M5 (the remediation bed sources). The site daily log gave some details of the cells and bed areas which were being worked upon, but not the exact timings.

As with the wind-weather conditions, the timing of excavation and bed turning operations was critical to the concentrations which the monitors observed.

During the iterative solution of the emission rates, there were several possible fits for the monitor data which could be achieved, dependent upon slightly different assumptions of which source was emitting, and at what rate.

In some cases the actual and estimated data could be fitted equally well by sets of data which differed in total emissions by a factor of 2.

9.6.3   MISSING AND ANOMALOUS DATA

As seen in the results of the analysis, there were several monitor observations which were recorded as 'No Data' (ND). The reasons for no data being recorded included monitors not being available, which occurred early on in the project, and monitors being stolen from the site.

The results also showed weeks when significant concentrations were observed by the monitors when according to the wind-weather data, the wind had not been blowing in the correct direction for them to have received anything. These obviously anomalous observations indicate that there were likely to have been some site operations which

produced large amounts of VOCs, but which were not recorded as excavation or bed turning.

The possibilities for these include:

- Removal of highly contaminated chlorinated rubber products which were identified and removed for off site disposal;

- Positioning of the dumper truck used for transport of the excavated ground to the remediation bed close to a monitor while loading or unloading;

- Route taken by the dumper truck between the excavation area and remediation beds.

All of the above may also have contributed to the other monitor observations on which the back calculation of the source terms were based. Dispersion models typically have an accuracy of ± 50%, however in this case, given the assumptions in the methodology, the errors could be greater.

9.7 REVIEW OF DISPERSION MODELLING

The pre-project analysis allowed safe working limits to be set based on a scientific analysis of the actual site conditions, rather than setting arbitrarily conservative limits based on non-specific data.

The post-project analysis showed that a significant quantity of VOCs are likely to be 'emitted to atmosphere' during this type of remediation, and that this issue cannot be neglected when considering the environmental impact of the remediation works.

The post-project analysis could have been improved significantly by the following:

- Meteorological station set-up, which should include: checking the 'north alignment' of the wind direction sensor; locating the anemometer at as great a height as practicable to improve it's low-speed response; recording the direction data at smaller increments (10 degrees rather than 22.5 degrees);

- Increased number of monitors, at better locations. Ideally the distance between the monitors should be smaller than half the estimated width of the dispersing vapour plume, so any release is observed by at least two monitors. This would allow cross checking of observations, and rejection / correction of anomalous readings. The monitors should be placed as close to the site boundary fence as possible to ensure that all emissions from site activity occur from a known direction;

- Improved logging of site activities. Activities which were not logged included: the times when highly contaminated ground was broken / excavated; the times rather than days when cells were excavated, to allow better estimation of varying excavation rates.

10. PERFORMANCE EVALUATION

10.1 INTRODUCTION

Performance evaluation is presented in the following sub sections:

- Volume excavated and fate of excavated material;
- Validation Sample Results;
- Backfill of Excavation Void;
- Mass Balance.

10.2 VOLUME EXCAVATED

As described in Sections 5 and 7, iterative excavation phases and validation sampling events resulted in a total volume of soils excavated of approximately 2,293 m³. This material was subsequently treated as follows:

Table 10.1: Fate of Excavated Material.

Description	Volume (m³)
Soils placed in treatment beds and subsequently backfilled following successful treatment	885
Soils placed in treatment beds which were treated but did not meet Site Specific Target Levels (SSTL) and were therefore disposed of at an off site facility	30
Soils/materials segregated during excavation including concrete (80 m³, which was crushed and reused in the backfill) and clay, contaminated pipework and rubble (which could not be treated and was disposed of at an off site facility)	1,375
Viscous organic product containing chlorinated hydrocarbons, which was placed in drums for off site treatment	3
Total excavated	**2,293**

10.3 VALIDATION SAMPLING

As described in Section 5, the excavated void of material to be remediated was validated by sampling and analysis of the base and sides of the excavation

10.3.1 VERTICAL EXTENT

On completion of the excavation to the specified depth, 16 samples were collected from the base of the excavation. The results of this sampling exercise have been supplemented with earlier data (a further 9 samples) to provide validation of the vertical extent of the excavation (i.e. confirmation that the boundary of the excavation was delineated between soils with contaminant concentration above the Site Specific Target Levels (SSTLs) within the excavation boundary and soils with contaminant concentrations below the SSTLs outside the excavation boundary). The concentrations detected in these 25 samples are listed in Table 10.2 and the SSTLs for comparison are 123 mg/kg and 31 mg/kg for CTC and CFM respectively.

Table 10.2: Validation Sampling – Vertical Delineation.

Sample No.	Depth (m)	Carbon Tetrachloride Concentration (mg/kg)	Chloroform Concentration (mg/kg)
EB1	2.0	0.03	0.16
EB2	2.0	0.15	4.20
EB3	2.0	2.39	1.09
EB4	2.0	3.13	3.54
EB5*	2.0	123.5	5.75
EB6	2.0	0.33	0.33
EB7	2.0	1.98	5.58
EB8	2.0	Not sampled	Not Sampled
EB9*	2.3	178.8	8.26
EB10	2.0	29.59	4.40
EB11	2.0	0.30	2.94
EB12	2.3	185.9	10.38
EB13	2.0	1.10	0.91
EB14	2.0	0.60	0.26
EB15	2.0	2.57	6.75
EB16	2.7	250.3	17.45
TP9 (1997)	2.6	0.03	0.01
TP1	0.8	2.66	2.64
TP2	2.0	0.78	3.54
TP3	1.7	65.34	7.27
TP4	1.6	0.42	3.95
TP8	2.0	27.65	18.57
TP103	2.1	0.15	0.32
TP105	1.5	0.08	<0.001
TP106	1.5	4.8	0.4

*at these locations, the excavation was extended to an increased depth to meet the SSTL.

These data indicate that, in all but two of the locations sampled (E12 and E16), the concentrations of CTC and CFM were below the SSTLs (i.e. a 92% compliance rate). Hence, by removing soils with concentrations of CTC and CFM above the SSTLs, the quantitative risk assessment (QRA) predicted that environmental receptors would be protected from contaminants migrating via the simulated migration pathway (i.e. the selected target concentration at the compliance point should not be exceeded due to operation of the contaminant migration pathway that was simulated by the QRA).

The mean concentrations of the soil samples collected from locations just below the base of the excavation for the purposes of validating the vertical extent of the remedial volume were 36.8 mg/kg (CTC) and 4.1 mg/kg (CFM). Hence, the vertical boundary of the excavation was defined at depths where the average concentrations of CTC and CFM were well below the SSTLs.

The two samples that exceeded the SSTLs were collected at depths of 2.3 m and 2.7 m respectively. Given that only two out of 25 samples exceeded the SSTL, it is considered likely that the extent of soil exceeding the SSTL is limited. Moreover, the depth and location of these sampling points within the clays in this area are unlikely to result in target concentrations at the identified receptors being exceeded, due to the low permeability of the clay and the lack of a contaminant migration pathway from clays at this depth to West Brook via shallow groundwater.

10.3.2   LATERAL EXTENT

On completion of the excavation to the specified dimensions, 16 samples were collected from the sides of the excavation. The results of this sampling exercise have been supplemented with earlier data (a further three samples) to provide validation of the lateral extent of the excavation (i.e. confirmation that the boundary of the excavation was delineated between soils with contaminant concentration above the SSTLs within the excavation boundary and soils with contaminant concentrations below the SSTLs outside the excavation boundary). The concentrations detected in these 19 samples are listed in Table 10.3.

Table 10.3: Validation Sampling – Lateral Delineation.

Sample No.	Depth (m)	Carbon Tetrachloride Concentration (mg/kg)	Chloroform Concentration (mg/kg)
ES1	1.5	0.06	0.01
ES2*	1.5	0.16	0.08
ES3	1.0	0.05	<0.001
ES4	1.5	6.92	0.99
ES5	0.5	67.70	0.01
ES6	1.0	1.55	0.07
ES7	1.2	0.20	0.05
ES8	1.5	2.55	<0.001
ES9	1.5	0.94	1.44
ES10	1.5	6.24	1.23
ES11	1.5	6.55	0.91
ES12*	0.5	269.7	<0.001
ES13	0.2	6.76	0.14
ES14	0.2	1.95	0.43
ES15	0.2	1.14	0.26
ES16	0.4	1.70	<0.001
TP103	2.1	0.15	0.32
TP105	1.5	0.08	<0.001
TP106	1.5	4.8	0.4

* not included in the mean calculation as they were not on the revised excavation boundary following validation testing of the initial delineation volume and extension of the excavation area.

These data indicate that, once the excavation extent had been increased following sampling and analysis during remediation (i.e. revision of the remediation volume dimensions for the final excavation void), the concentrations of CTC and CFM were below the SSTLs in all areas sampled (i.e. a 100% compliance rate). Hence, the selected target concentration should not be exceeded at the compliance point due to operation of the contaminant migration pathway that was simulated by the QRA.

The mean concentrations of the soil samples collected from locations at the sides of the excavation void for the purposes of validating the lateral extent of the remedial volume were 5.8 mg/kg (CTC) and 0.4 mg/kg (CFM). Hence, the lateral boundary of the excavation was defined at locations where the average concentrations of CTC and CFM were well below the SSTLs.

10.4   BACKFILL OF EXCAVATION VOID

The excavation was backfilled using the material described in Table 10.4.

Table 10.4: Backfill of excavation void.

Description	Volume (m³)
Material stockpiled on site (mainly from earlier unrelated works which was tested and found to be suitable for use)	950
Treated soils from the treatment bed	885
Imported hardcore and crushed concrete (originally on site)	305
Total backfilled	**2,140**

The measured excavation void was 2,340 m³. The volumes of backfill are based on site estimates, hence the difference between the two values stated.

10.5   MASS BALANCE

10.5.1   INTRODUCTION

Although the remediation project was not designed with a contaminant mass balance as an objective, for the purposes of the CL:AIRE Technology Demonstration Project (TDP), a contaminant mass balance has been attempted. Mass balance equations rely on a number of assumptions, specifically averaging various inputs and outputs from the system, in this case the parameters used were:

$$M_0 = (M_c \text{ or } M_d) + M_b + M_t + M_l$$

Where:

- Mass of contaminants present in remediation area prior to remediation (M_0);

- Mass of contaminants collected by treatment system by measuring concentration passing through total discharge air flow (M_d);

- Mass of contaminants present in activated carbon after treatment (M_c);

- Mass of contaminants emitted to atmosphere derived from extensive boundary and personal monitoring, weather data and air dispersion modelling (M_b). Personal and vapour monitoring points are situated at distances of 0-200 m from the excavation and treatment areas – see Section 9;

- Mass present in treatment bed after treatment (M_t);

- Mass removed for off site treatment and/or disposal for contaminants within materials unable to be treated with SVE (M_l).

The mass of contaminants in groundwater was ignored from both sides of the equation for the purposes of this exercise.

The relative advantages and disadvantages of using a mass balance approach to quantify the effectiveness of a remedial system are discussed below. Advantages are chiefly the ability to quantitatively measure treatment efficiency and environmental fate of contaminants undergoing treatment. Disadvantages stem from problems defining source areas and concentrations and minimising errors that may be inherent in each stage of the calculation.

10.5.2   INITIAL MASS OF CONTAMINANTS PRESENT (M_0)

The primary aim of the soil sampling conducted during this project was to accurately define the volume of soil that required excavation and treatment and latterly to ensure that any residual concentrations of VOCs were below SSTLs by sampling of excavation void

boundaries (lateral and vertical). The data collected were subsequently used to estimate the mass of contaminants in the soil as a means to measure the success of the *ex situ* SVE treatment system through mass balance calculations.

Measured site soil concentrations of contaminants exhibited a large variance (0.14 – 17,142 mg/kg) over the identified impacted area for treatment and several calculations were used to calculate the mass of contaminant present (see Section 3.6.3). In calculating the contaminant mass present prior to remediation, the excavation area was divided into cells. These were representative areas and volumes encompassing sampling points and depths from which mass calculations of contaminants could take place.

Statistical evaluation of the results confirms the high variation. If a maximum value test is run, as defined in CLR 7 (DEFRA *et al.,* 2002), it indicates that all samples over 1,000 mg/kg (5 in total) could be considered as outliers and not part of the underlying population. This confirms the presence of hotspots of contamination and does indeed corroborate field observations of visual contamination in these areas.

It is unclear what proportion of this material was removed for off site treatment / disposal and what residual concentrations remained and became homogenised within the volume to be treated. It is unlikely that entire 'cells' (calculated soil volumes) will contain a consistent concentration of CTC, especially at concentrations of 17,000 mg/kg, however, it is difficult to discount this data point on the basis of it being an outlier. If it is, and merely replaced with an average concentration, the mass of contaminants changes significantly.

Based on the calculation methodology presented in Section 3.6.3 and Appendix 1 and discussed above, the initial mass present is 4,140 kg of CTC and CFM (this has been calculated to make up approximately 98.5% of VOCs present on the site based on a total of 27 samples within 3,900 tonnes of soil (i.e. 1 sample for each 145 tonnes of soil). An additional 510 kg of VOCs was estimated to have been present in the form of viscous organic product containing chlorinated hydrocarbons, which was placed in drums and not sampled during the collection of the original 27 samples. Hence, the total estimated mass present within the volume of soil to be remediated was 4,650 kg.

Given the scale of the heterogeneity, it is considered that there was insufficient data to quantitatively determine the magnitude of the error of the initial mass present prior to remediation. However, it can be qualitatively stated that errors could be significant, relating to the following factors:

- Sampling error (loss of volatiles);
- Cell averaging (i.e. how representative of a volume cell is a particular concentration?) and how the presence of viscous organic product containing chlorinated hydrocarbons and other soil samples containing very high concentrations of CTC and CFM affected the mass of contaminant ascribed to each cell. Using the volume cell approach, these samples have a large influence on the resulting mass estimate.

Recommendations to reduce and quantify this error include:

- Collection of a statistically valid number of samples (see discussion below);
- Accurate mapping of volumes of soil type in order to determine the spatial distribution of made ground, sand, clay etc and the concentration distribution within the different types of material;
- More sampling points would be required to add a sufficient level of precision and accuracy to define the mass. Some cells of large volumes, such as TP1 contain almost 20% of the excavation volume, based on one sample location. The additional implications for time and cost need to be addressed if this level of detail were required.

The initial mass of contaminants present, as determined using the approach described above, will be affected by the following factors:

- Consistent bulk density;

- Consistent spread of contaminants (spatially, in 3 dimensions);

- Consistent geology;

- Consistent contaminant availability,

- Local influence of groundwater / capillary action;

- Error and losses associated with sampling technique.

A significant amount of time and effort is spent trying to reduce sample errors in the laboratory. However, it is well documented that the largest component of sample error is in the field, typically over 80% and higher still for VOCs. Much of this error in the case of VOCs can be attributed to contaminant mass loss during sample collection, predominantly by volatilisation as soils are physically disturbed when samples are collected, but also through biodegradation if samples are not stored correctly prior to lab analysis. Other sampling methods for VOCs, such as undisturbed sampling using coring techniques (e.g. Sorini *et al.,* 2003), and sample preservation, are becoming increasingly popular and necessary if meaningful results are to be obtained.

Problems with the heterogeneity of soil contaminants are well documented when attempting to accurately define 'contaminated land' (as defined in the legislation) and have been the subject of past (CL:AIRE 2004) and future CL:AIRE technical notes and reports. Changes in soil properties, lithology and presence of underground services are a small selection of the factors that can cause considerable variation in contaminant concentrations within a small spatial area. These site sampling issues are usually exacerbated by properties of the contaminant under investigation, such as its mobility, age and previous use within the site. The interpretation of the variation that may be observed is crucial in order to add a level of certainty (or more appropriately uncertainty) to these estimates.

Several forms of guidance put forward sampling techniques designed to produce statistically valid results, while (Ramsey *et al.,* 2002) define certain levels of acceptable error in decision making. Unless sufficient sampling is undertaken it is difficult to establish the size and nature of these hotspots and infer if they represent a significant issue.

10.5.3 MASS COLLECTED BY THE TREATMENT SYSTEM

The air inlet to the activated carbon and the vapour flow rate were used to calculate the cumulative recovered VOCs for each treatment bed fill. Results are presented in graphical form in Section 8.5.

Using this methodology, the total mass recovered by the system was estimated at 890 kg of VOCs.

An alternative approach to estimating the mass recovered by the system is to multiply the concentration of CTC adsorbed to the activated carbon by the mass of carbon used – assuming that this concentration is representative of the total activated carbon used in treatment. However, in this case, there are not enough samples of the concentration of VOCs in the activated carbon used to be able to estimate the mass recovered.

10.5.4 MASS OF VOCS EMITTED TO ATMOSPHERE DURING EXCAVATION AND TREATMENT

ADMS version 3.1 was used to calculate the mass of VOCs emitted to atmosphere during the excavation and treatment of the material (as described in Section 9). The calculated

figure was 3,450 kg of VOCs. In common with the initial mass present, it is not possible to quantify the uncertainty associated with this mass estimate. However, it can be stated qualitatively that errors, which could be significant, are likely to be associated with:

- Wind/weather data from the site weather station and the correlation with the local meteorological office station;

- Estimation of source emission rates;

- Missing observation data.

10.5.5   MASS OF VOCS BACKFILLED INTO EXCAVATION VOID

Section 8.6 presents the concentrations of VOCs within the treatment bed following treatment prior to backfill. Given that the mean concentration was 33 mg/kg and the soil volume was 885 m³ (1,545 tonnes using a bulk density of 1.7 t/m³), the total mass of VOCs backfilled was estimated to be 51 kg. This calculation results from a sampling density of approximately 1 sample per 20 m³ of treated soil. In addition, the mean concentration (and therefore the total estimated VOC mass backfilled) is likely to be an over-estimate due to:

- The sampling methodology, which was designed to conservatively analyse the sample with the highest PID concentration;

- The fact that the treatment bed operated for at least one week following the validation sampling event (during which time the laboratory analysis was carried out) prior to confirmation that the soils were suitable for backfill and treatment was complete;

- Treatment bed emptying (excavation), transport and backfilling operations may have caused further release of VOCs to atmosphere.

10.5.6   MASS OF VOCS REMOVED FOR OFF SITE TREATMENT AND DISPOSAL

On the basis of waste classification sampling results, it has been estimated that the material unsuitable for treatment comprised a total mass of VOCs of 745 kg, the majority of which was thought to have been present in the viscous organic product containing chlorinated hydrocarbons which was drummed for off site treatment and disposal.

10.5.7   DISCUSSION

Despite the uncertain nature of key parameters, inspection of the mass balance equation gives the following observations:

- If the initial mass is treated as an unknown, the methodologies employed indicate that the sum of mass emitted to atmosphere, mass collected by the treatment system, mass backfilled and mass removed off site was 5,130 kg;

- At completion of the treatment programme, 95% of the total VOC mass collected and backfilled was treated by the system, hence, once the soils are emplaced within the treatment beds, treatment was effective;

- However, based on the methodology employed, approximately 60-80% of total VOCs present within the area to be remediated prior to remediation may have been emitted to atmosphere.

This suggests that for existing remediation of VOC contaminated soils, the scale of air emissions should be taken into account in the design stage.

11. ECONOMIC CONSIDERATIONS

At the outset of the project, a number of options were considered in order to achieve the stated remediation objectives. These included excavation and disposal, low temperature thermal desorption, capping, *in situ* and *ex situ* SVE and bioremediation.

Cost estimates (±25% approximate accuracy) were assessed for a number of the options, however, *ex situ* SVE was the only remedial approach subjected to detailed cost estimates.

The final costs for the project are presented in Table 11.1 including the design, installation, commissioning and operation of the treatment system.

Table 11.1: Cost Breakdown for *Ex Situ* SVE System.

Item	£
Pilot Testing	5,500
Design and Working Plans	7,000
System Installation	110,500
SVE Unit, off-gas treatment with GAC	1,500
Supervision, Surveying and as-built drawings	27,600
Validation Soils and Water Analysis	12,500
Demobilisation	18,240
Water Storage and Transport	35,935
Total	**278,775**

This equates to a cost of approximately £65 per tonne. Initial estimates for excavation and disposal to landfill were within this order of magnitude but, on inspection of the site analytical data, waste disposal companies approached were not confident of being able to dispose of the soils due to levels of chlorinated solvent concentrations of above 1% by volume.

12.   CONCLUSIONS

The remediation project achieved the stated objectives which were:

- To remediate soils in the former bulk storage area to a standard that protects environmental receptors close to the site (i.e. the surface water drainage ditch to the east and West Brook);

- To remediate soils in the former bulk storage area to a standard that protects human health receptors in the event that the site is developed for industrial / commercial end-use;

- To carry out all work to the highest safety standard;

- To complete any remedial action within a 6 – 12 month time frame.

This has resulted in release of this land for potential development. *Ex situ* operation of the treatment system enabled more certainty in meeting the stringent programme objectives. Moreover, excavating the part of the site formerly occupied by a demolished chemical works enabled segregation and appropriate treatment and disposal of the inevitable variable material encountered (e.g. former pipe tracks, underground infrastructure, etc) – this would not have been possible based on the investigation data available at the outset of the project and would have resulted in delays if an *in situ* technique had been adopted.

Although some material did require off site treatment and/or disposal, approximately 1,550 tonnes of soil was treated and backfilled under a waste management licensing exemption – this prevented approximately 80 truck movements and also prevented the corresponding volume of soil being disposed of in a landfill (although it should be noted that some form of treatment would have been requested prior to landfill disposal).

A mass balance has been attempted using data originally collected for remediation validation and Health and Safety monitoring purposes. Errors associated with the initial mass present (calculated from soil concentrations obtained from pre-remediation site investigation) and the mass emitted to atmosphere (calculated from VOC boundary monitoring data, meteorological records and atmospheric dispersion modelling) may be significant. However, the mass balance equates to within 10%. The authors are not aware of previous attempts to estimate the mass of VOCs emitted during the excavation of VOC contaminated soils. The results presented by this mass balance indicate that 60-80% of VOCs present at the start of the remediation may have been emitted to the atmosphere during excavation and emplacement within the treatment bed. This finding has implications for anyone considering *ex situ* remediation method, such as:

- Traditional excavation and disposal;

- *Ex situ* SVE;

- *Ex situ* bioremediation.

Those considering these techniques should expect a significant proportion of VOCs to be emitted when carrying out remediation of this kind, depending on soil condition and contaminant distribution. If implementing such a scheme, particular consideration should be given to:

- VOC monitoring at site boundaries;

- VOC abatement systems if risks resulting from emissions to atmosphere cannot be managed (e.g. working in a dedicated vapour tent or an air support structure);

- Use of *in situ* remediation methods.

13. LESSONS LEARNED

As described in Section 12, the remediation project was a success and therefore a number of issues which went well deserve emphasis, these are described below.

- Safety was the highest priority on the project and the safety arrangements resulted in the project achieving an excellent safety record. This vindicated the use of the methods employed such as early communication of safety issues, use of 'Hazcon' (construction phase hazard assessment), site induction and tool box talks, regular safety auditing, a permit to work system, extensive vapour monitoring and detailed method statements and risk assessments covering all tasks;

- Early consultation with the regulator was very useful during the project planning phase, this allowed the necessary actions (mobile plant licence, temporary consent to discharge to sewer, planning permission and waste management licensing exemption) to be implemented within the project programme. These discussions were particularly useful in the context of waste legislation. At one stage during the design phase of the project, the regulators stated that no treated soil was allowed to be backfilled regardless of the concentrations of contaminants, because it would be classified as a waste. It was fortunate that planning permission and a waste management licensing exemption were obtained in good time. Improved regulation in relation to the definition of waste and potential re-use of treated materials would result in wider use of on site remediation treatment technology, which would in turn reduce the volume of material disposed of to landfill.

Remediation works were located close to residential housing and a public park. The local authority imposed stringent requirements to control nuisance (odour, dust, noise, etc) during the works through planning consent conditions. These requirements were in line with the proposals for the site for heath and safety management, but could have been onerous and costly if not taken into account in the programme.

- The project team were fortunate to have good relations with a local special interest community liaison group, which included the area of the site. This proved invaluable in assisting the project team with communication of the project to local residents. No complaints were received at any stage during the project;

- The pilot test was carried out prior to detailed design of an *Ex situ* SVE scheme. The results of the pilot test allowed the preferred remediation method to be amended. If an *in situ* system had been installed without a pilot test, it is considered that the project may have been unsuccessful due to soil heterogeneity and generally low soil air permeability.

In order to achieve a mass balance with quantified uncertainty, a dedicated sampling and analysis programme would be needed covering initial soil conditions and more detailed boundary sampling of VOCs in the atmosphere.

The project did not attempt to measure the mass of VOCs lost during soil sampling, however, such losses are likely to have occurred. Methods to reduce loss of volatiles during soil sampling include the use of driven, sealed sampling tubes which allow semi-undisturbed samples to be collected without excavation of boreholes or trial pits.

As described in Section 12, *ex situ* remediation of VOC contaminated soils appears likely to result in significant emission of VOCs to atmosphere. Detailed assessment of the nature and scale of these potential emissions are recommended prior to the final remediation design. If emissions need to be minimised, then either *in situ* remediation techniques should be considered, or vapour collection during excavation should be installed.

GLOSSARY OF TERMS

Environmental Assessment Level	This is the level which is deemed by the Environment Agency to be a maximum permissible level of a substance in the atmosphere over non-industrial areas. Within industrial areas the Management of Health & Safety at Work Act applies, which states that the airborne concentrations of substances should be within the relevant Occupational Exposure Limits
***Ex situ* SVE**	Soil Vapour Extraction (see below) carried out on soils that have been removed in bulk (e.g. by excavation) from their initial in-ground location
Henry's Law Constant	The proportionality constant between the vapour pressure of a compound in aqueous solution relative to its concentration in solution
Octanol/water partition coefficient	The ratio of the concentration of a compound in octanol to the concentration in water
Short Term Exposure Limit	These limits are set to help prevent effects such as eye irritation which may occur following exposure to a compound for a few minutes. The averaging time for a short term exposure limit is 15 minutes.
Site specific target levels	The risk-based derived concentration of contaminant dividing higher concentrations, which are predicted by the risk model to present an unacceptable potential risk to a receptor, from lower concentrations, which are predicted by the risk model to present an acceptable potential risk to a receptor.
Soil Vapour Extraction	The process of applying a partial vacuum into the soil zone in order to encourage volatilisation (of dissolved, sorbed and free phase VOCs) and extraction, usually via a network of abstraction wells.
The 'plant'	Former chlorinated rubber plant on which remediation took place
The 'site'	Former chemical works on which remediation took place
Vadose zone	Zone within soils (porous media) above the water table and capillary fringe where pores are only partially saturated and the fluid pressure is less than atmospheric.

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APPENDICES

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APPENDIX 1
SOIL CONCENTRATION DATA AND ESTIMATION
OF INITIAL CONCENTRATION PRESENT

Trial Pit No.	shallow / deep	Block area m²	Depth of top of block (m)	Thickness of block (m)	Concentration of VOC (mg/kg)	Initial soil volume estimate to be remediated in (m³)	Mass of Soil (kg)	Estimated Mass of VOCs in block (mg)	Estaimted Mass of VOCs in block (kg)	Total Volume of Block
1	s	135	0	0.4	0.2	54	91800	18360	0.02	310.5
1	d	135	0.4	2.3	5.3	256.5	436050	2311065	2.31	
2	s	70	0	1	0.2	70	119000	23800	0.02	161
2	d	70	1	2.3	4.32	91	154700	668304	0.67	
3	s	48	0	0.4	112	19.2	32640	3655680	3.66	67.2
3	d	48	1	2	73.6	48	81600	6005760	6.01	
4	s	72	0	1	39	72	122400	4773600	4.77	122.4
4	d	72	1	1.7	4.4	50.4	85680	376992	0.38	
5	s	108	0	1	5.4	108	183600	991440	0.99	194.4
5	d	108	1	1.8	216.7	86.4	146880	31828896	31.83	
6	s	108	0	0.5	5.8	54	91800	532440	0.53	151.2
6	d	108	0.5	1.4	53.9	97.2	165240	8906436	8.91	
7	s	84	0	0.4	0.6	33.6	57120	34272	0.03	126
7	s	84	0.4	1.1	55.68	58.8	99960	5566106	5.57	
7	d	84	1.1	1.5	6.6	33.6	57120	376992	0.38	
8	s	77	0	0.3	8771	23.1	39270	344437170	344.44	154
8	s	77	0.3	1.5	4936	92.4	157080	775346880	775.35	
8	d	77	1.5	2	50	38.5	65450	3272500	3.27	
9 (1997)	s	64	0	0.5	17142	32	54400	932524800	932.52	185.6
9 (1997)	s	64	0.5	0.9	136.22	25.6	43520	5928294.4	5.93	
9 (1997)	d	64	0.9	2.2	425.14	83.2	141440	60131801.6	60.13	
9 (1997)	d	64	2.2	2.9	0.14	44.8	76160	10662.4	0.01	
9	s	80	0	0.75	6554.5	60	102000	668559000	668.56	112
9	d	80	0.75	1.4	17.3	52	88400	1529320	1.53	
				Totals		1584.3	2693310	2857810571	2857.81	1584.3
				Min	0.14 mg/kg					
				Max	17142 mg/kg					
				Median	44.5 mg/kg					
				Arithmetic Mean of sample results	1609.00 mg/kg					
				Standard Deviation	4044.57 mg/kg					
								Final Remediation Volume		2293
				Average concentration of VOCs in Initial Soil Volume Estimate to be Reemediated	1061.08 mg/kg			Total Mass of soil in Final Remediation Volume		3898100
				Bulk Density	1700 kg/m³			Total Mass of VOCs in Final Remediation Volume		4136.19

Analysis of Initial Concentration of Total VOCs in Initial Soil Volume Estimate

APPENDIX 2
RESULTS OF *IN SITU* SVE PILOT TEST

SVE1
MASS REMOVAL RATE FORECAST
EXPONENTIAL DECAY

SVE2
MASS REMOVAL RATE FORECAST
EXPONENTIAL DECAY

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