

TDP Bulletin

CL:AIRE Technology Demonstration Project (TDP) Bulletins provide a summary of CL:AIRE approved Technology Demonstration Projects. TDPs have passed through the CL:AIRE application and review process, and represent demonstration for the specific conditions in which they are applied. This bulletin describes a field trial application of *in situ* radio frequency heating with soil vapour extraction to remove volatile and semi-volatile contamination from soil.

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In Situ Radio Frequency Heating (ISRFH) of Hydrocarbon Contaminated Chalk at a Former Service Station in Kent

1. INTRODUCTION

Ecologia was appointed by Total UK Ltd to conduct a trial to assess the effectiveness and the commercial viability of combining Soil Vapour Extraction (SVE) with *in situ* Radio Frequency Heating (ISRFH) technology in order to remove volatile and semi-volatile organic contaminants from soil.

ISRFH in Europe was initially developed by Helmholtz Centre for Environmental Research - UFZ, a German research centre in Leipzig, which demonstrated the potential application of this technology in a limited field trial at a former petrol station. Ecologia teamed up with UFZ in 2005 and carried out a two year research and development programme to refine the technology for commercial application.

The field trials and small-scale experiments using the ISRFH technology over the two year programme by Ecologia in Kent were used to:

- refine the electrode design;
- optimise the radius of influence of the electrodes;
- determine the heating rate of the soil;
- assess the influence of SVE on the ISRFH process; and
- calculate the energy requirement and cost to achieve the required *in situ* heating.

The results of these preliminary field trials indicated that the ISRFH technology coupled with an SVE system was capable of heating the soil effectively without incurring excessive energy costs. The process is protected by a European Patent (No.1596998) jointly owned by Ecologia and UFZ.

Previous application of ISRFH was mostly restricted to the US as part of the Superfund Technology development programme carried out in the mid to late 1990s (Lowe *et al.*, 2000). Commercial development of the technology was partially limited by the high cost of the antennae and ancillary equipment. The design of the antenna developed by Ecologia is substantially different to that reported in the US literature.

Via CL:AIRE, Total UK Ltd expressed an interest in collaborating with Ecologia to trial the technology at one of their decommissioned service stations that had been earmarked as requiring further remediation work. An aerial image of the field trial site is shown in Figure 1.

2. TECHNOLOGY DESCRIPTION

The technology uses Radio Frequency (RF) to excite polar molecules present in the soil, thus generating heat in a manner similar to that of a microwave oven. ISRFH uses a frequency of 13.56 MHz with a wavelength of 22 m, and can penetrate the soil to a much greater extent than microwaves.

Soil water plays a major role in the ISRFH process because water is the most abundant polar molecule present in the soil and is easily excited by radio waves emitted from the electrodes. The maximum energy loss for a free water molecule is at about 10 GHz; this is typically the range of a microwave oven. RF heating using frequencies of 13.56 MHz could therefore appear less appropriate than microwaves for dielectric heating due to the lower number of oscillations per



Figure 1. Aerial photo of the ISRFH system during the field trial.

time (i.e. less heat generation). However, radio waves allow a much greater penetration into the matrix of the material being heated, making this process more appropriate for *in situ* remedial applications.

There are other processes beside orientation / polarisation of water that play a greater role in RF heating than with microwave heating. RF heating has been shown to be able to heat dry materials (e.g. dry sand, zeolites) which cannot be heated by microwaves due to the absence of free water in their matrix (Roland and Kopinke, 2009).

Non-polar molecules are unaffected by an electromagnetic field and do not produce heat. Many contaminants in the soil, such as straight chain hydrocarbons, are thus not heated directly by the radio waves, but will be affected indirectly by the heat created within the soil.

ISRFH is effective in dealing with volatile contamination in cohesive, low permeability, unsaturated soils that cannot be heated efficiently using steam due to mass transfer limitations. The technology also reduces the potential for uncontrolled contaminant mobilisation generally associated with steam injection in impermeable/fissured soils. As alluded to above, as the soil dries during the heating process, the performance of ISRFH is less susceptible to reduction in soil moisture than resistive heating. In addition, due to the good penetration of the radio waves into the soil, ISRFH produces a more even soil temperature gradient than the extreme gradient generally associated with conductive soil heating based on simple heating coils/rods.

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The technology can be coupled with a Soil Vapour Extraction (SVE), or a Multi Phase Extraction (MPE), system to extract the Volatile Organic Compounds (VOCs) and Semi-Volatile Organic Compounds (SVOCs) that are mobilised by heat produced by the ISRFH system. The ISRFH system developed by Ecologia can also be easily coupled with resistive heating in order to heat both unsaturated and saturated soils simultaneously, achieving reduced energy consumption using the same piece of equipment.

3. SITE DESCRIPTION

3.1 Reasons for Selection

The Total UK Ltd site selected as the most appropriate for carrying out the ISRFH trial was a decommissioned petrol station located in Minster, Kent.

The site was selected as it was impacted by VOCs such as benzene, toluene, ethylbenzene and xylenes (BTEX) and other petroleum hydrocarbons (reported as Total Petroleum Hydrocarbon (TPH), mostly with less than 21 carbons i.e. C<21). Soil contamination was restricted to a relatively localised area (approximately 20 m diameter) on the south west corner of the former petrol station and within the unsaturated Chalk strata to a maximum depth of 10 m below ground level (bgl). The underlying groundwater had not been impacted by the contamination.

The site is located north of the east-bound carriageway of A299, Canterbury Road West, Mount Pleasant, Minster. The immediate surrounding land-use comprises residential properties and a caravan park in an adjacent chalk pit to the north-eastern boundary (the caravan park is at a lower level than the trial site, at approximately 10-12 m bgl). Agricultural land is present to the western boundary. The land surrounding the site generally slopes downward towards the south.

The site is typical of a decommissioned medium-sized petrol station in an area with high groundwater vulnerability. Underground storage tanks (USTs) had previously been removed and the excavation had been backfilled. Due to the presence of the hydrocarbon contamination, voluntary remediation was required in order to reduce potential future environmental liabilities if the site should be divested or redeveloped.

3.2 Geology

Information obtained from the British Geological Survey (BGS) maps of the regional geology indicated that Cretaceous Upper Chalk underlies the site. This was confirmed during the initial intrusive site investigation. Ground conditions encountered during site investigation works in the central, eastern and south-western area of the site comprised concrete hardstanding overlying made ground. The made ground is in turn underlain by Chalk found at approximately 0.75 m bgl. Backfill material from the earlier site excavation and decommissioning of the USTs was encountered in the western area to a depth of approximately 4 m bgl. This comprised Department for Transport Specification for Highway Works granular sub-base material Type 1 (also known as MOT Type 1).

3.3 Hydrogeology and Hydrology

The Environment Agency (EA) has classified the Cretaceous Upper Chalk underlying the site as a Major Aquifer. Information obtained from the site investigation indicated that the groundwater table was at a depth of approximately 47.3 m bgl flowing in a south westerly direction. The hydrogeological maps from the EA indicate that the site is located within the Outer Zone of a groundwater Source Protection Zone (SPZ II). An Inner groundwater Source Protection Zone (SPZ I) is reported to be located 270 m to the southwest.

Inspection of available data from the BGS on local abstraction boreholes revealed that the nearest abstraction well is located approximately 750 m to the southwest of the site. The nearest surface water feature is a pond reported to be located 948 m to the south of the site.

4. SYSTEM DEPLOYMENT

A 20 ft (6.1 m) shipping container housing the main components of the ISRFH system was provided on loan from UFZ. The container was modified to house the RF generator, which converts power line frequency into radio waves, whilst another 20 ft container houses the SVE and chiller systems.

The ISRFH energy was delivered into the surrounding soils by an array of electrodes, installed approximately 2.5-3 m apart at predetermined, discrete depths. A process layout of the ISRFH together with technical specification of the equipment used is presented in Figure 2.

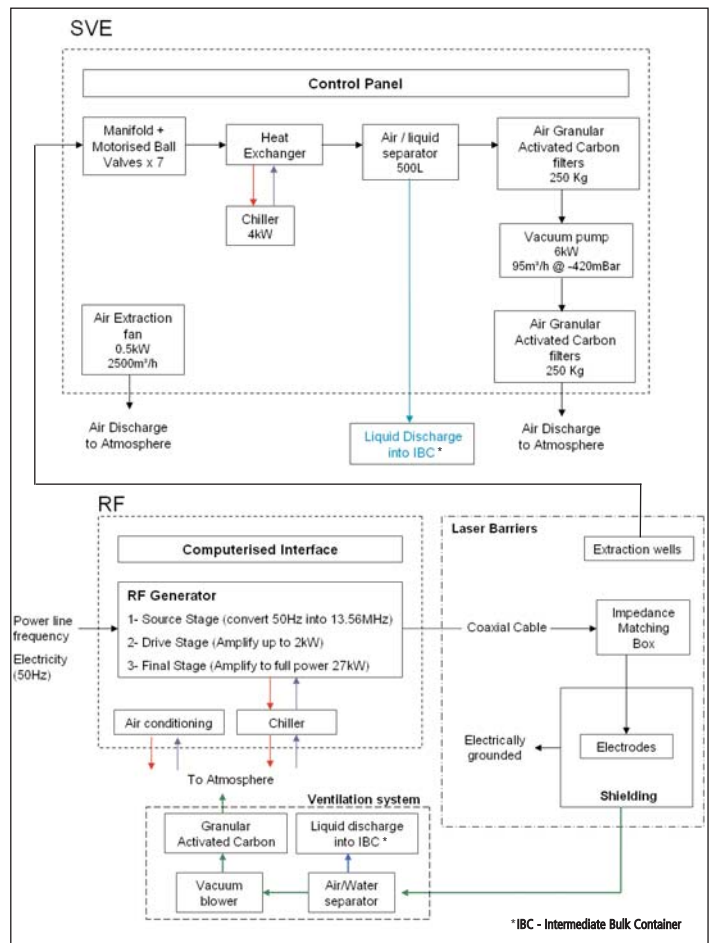


Figure 2. Diagram of the ISRFH remediation used during the remediation trial.

The SVE system was equipped with a high vacuum blower (6 kW) with a maximum flow rate of 95 m³/h @ 420 mbar gauge pressure. The system was controlled by two Programme Logic Controllers (PLCs). The PLCs were programmed to apply vacuum extraction to each of eight extraction wells in a cyclical sequence for a period of 45 minutes per well. This ensured that the maximum vacuum achievable by the system was applied to each individual extraction well and that the volatile contaminants extracted from each well were measured accurately. On-line monitoring of each SVE extraction well was achieved using a Total Volatile Organic Compound (TVOC) sensor (a type of photo-ionisation detector (PID)). This operation also required purging and sampling each SVE extraction line using a small bladder pump.

For this site, ISRFH electrodes were deployed in a triangular array between 3 m and 6 m bgl, together with eight multilevel SVE wells (screened depth 2.5-5 m bgl and 5.5-7.5 m bgl). A detailed layout of the electrodes and monitoring wells is presented in Figure 3.

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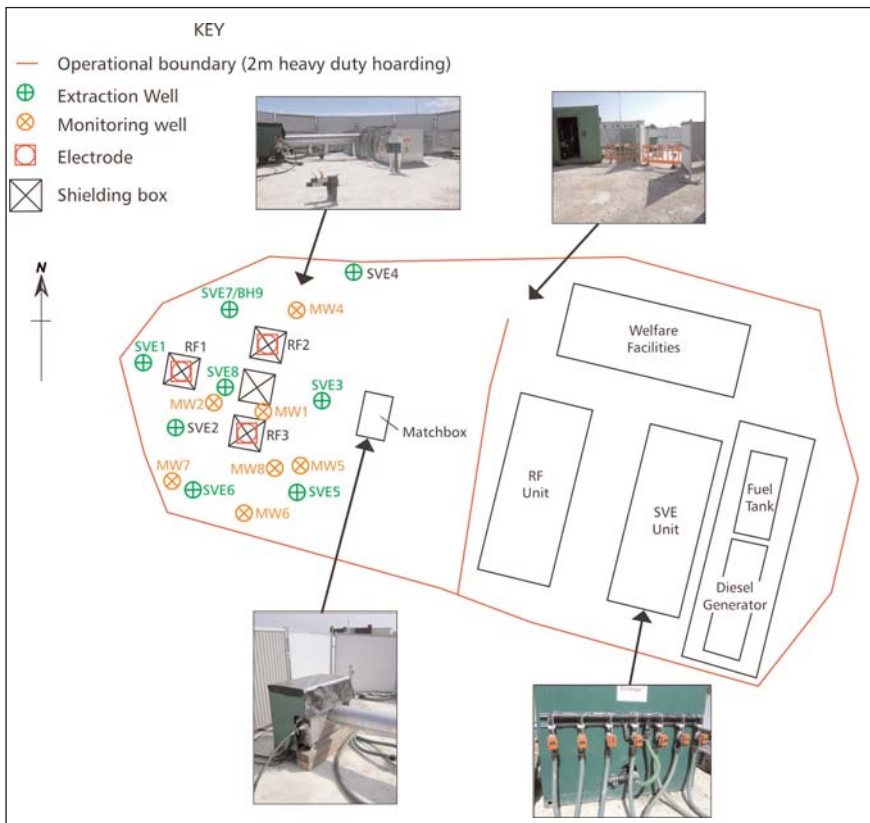


Figure 3: Map showing the position of electrodes, extraction wells and monitoring wells of the ISRFH system during the field trial.

5. HEALTH AND SAFETY, ENVIRONMENTAL PERMITTING AND STAKEHOLDER ACCEPTANCE

Prior to the commencement of the remediation operation, regulatory liaison was required in order to address the following aspects of this novel remediation system.

Electromagnetic field generated by the radio waves – The electromagnetic field generated by the electrodes is fully contained within the specialist Faraday cages, designed and built by Ecologia. Trespass by unauthorised personnel into the treatment area or access to the Faraday cages is prevented by an infrared fence which shuts down the system automatically. The system is operated remotely and it has additional safety systems associated with the on-line soil temperature sensor array which will shut down the generator in the event of excessive heat production near the electrodes or at the boundary of the treatment area.

Monitoring of the electromagnetic field – The electromagnetic intensity outside the Faraday cage is lower than that generated by a mobile telephone and below the guidance levels for time varying electromagnetic field for the general public published in the most recent International Commission on Non-Ionizing Radiation Protection guidelines (ICNIRP, 1998). This is the most restrictive guidance currently available.

Environmental permit – The field trial was exempt from an environmental permit as the volume of material treated was less than 1000 m³. However, the EA requested that an assessment following the guidelines set out in an environmental permit should be implemented during the trial. Power for the system was provided by a generator. A noise survey was carried out prior to commencement of the remediation process to assess whether the noise from the generator could affect a nearby caravan park. Sound-proofing was subsequently installed around the generator compound to meet the Local Authority's requirements. A groundwater monitoring programme was also implemented during the trial in order to ensure that the process did not cause vertical migration of the contaminants into the underlying aquifer.

6. REMEDIATION PERFORMANCE PARAMETERS

In order to validate the potential benefits of the ISRFH system, performance parameters such as soil temperature, strength of electromagnetic field and rate of extraction of VOCs by the SVE system were monitored manually and/or automatically with data loggers. Soil validation samples were collected at T=0 and approximately three weeks after completion of the remedial operation to assess the performance of ISRFH.

6.1 Automatic Monitoring

6.1.1 Volatile Organic Compounds (VOCs)

The concentration of VOCs extracted using the SVE system was continuously monitored throughout the trial using the TVOC coupled with a data logger.

The TVOC had a calibration range from 0 to 1000 parts per million (ppm). VOC concentrations during the trial fluctuated considerably and in many instances exceeded 10,000 ppm, with a maximum of 43,000 ppm; therefore the extracted vapour had to be diluted with fresh air in order to keep the VOC concentrations within the calibration range of the TVOC sensor. Dilution with fresh air was checked daily.

6.1.2 Airflow & Pressure

The mass of air extracted was calculated by an electronic airflow and vacuum pressure sensor installed within the SVE unit. These devices were also connected to the data logger in order to allow continuous monitoring. Flow rates were also corrected to account for vacuum, temperature and moisture.

6.1.3 Temperature

A total of eight fibre optic temperature sensors were installed in six of the monitoring wells at discrete depths of 3.5 m and 5.5 m bgl. The sensors were connected to the PLC of the ISRFH system in order to allow continuous monitoring of soil temperatures in the treatment area whilst the system was in operation. The temperature readings of the fibre optics were also included in the trial assessment as additional temperature backup data.

6.2 Manual Monitoring

6.2.1 Thermocouples

Thermocouple sensors were installed to monitor soil temperature at 3.5, 5.5 and 7.5 m bgl in all the monitoring wells. Manual soil temperature readings were taken daily (Monday to Friday) from each thermocouple during the remediation programme. The ISRFH system had to be temporarily shut down whilst these readings were taken as the electromagnetic field would have interfered with the output signal of the thermocouple.

6.2.2 Photo-Ionisation Detector (PID) Data

At the start of the trial PID readings were taken on a weekly basis from the soil vapour probes installed within the monitoring wells. The PID provides an indication of total VOC concentration. However, after reviewing the data against those collected from the TVOC and the TENAX tubes (see below), PID readings on the monitoring wells were stopped due to the excessive moisture build up interfering with the instrument. Subsequent PID readings were taken from the extraction wells.

6.2.3 TENAX Tubes

Semi-quantitative analyses were undertaken using TENAX thermal desorption tubes to validate the PID and TVOC data. Samples were collected onto TENAX tubes at various intervals throughout the trial. Sampling was initially restricted to monitoring wells MW1 and MW2, but this was subsequently extended to include the extraction wells until the end of the trial. Analysis of air samples from the monitoring wells was subsequently suspended due to the excessive build up of moisture caused by soil heating, which interfered with the sampling process.

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6.2.4 Calibration of TVOC Data with TENAX Tube Analysis

During the trial an attempt was made to determine whether VOC concentrations recorded using the TVOC could be correlated to the semi-quantitative analysis performed using the TENAX tubes. The calibration curve showed a good fit ($r^2 = 0.70$); consequently a dimensionless factor was calculated for converting the TVOC concentrations expressed in ppm to the concentration in mg/m^3 as reported in the TENAX tubes analysis. The calculated conversion factor was 1.74 with a standard deviation of 0.59.

7. REMEDIATION OPERATION

The remediation was performed in six stages in order to demonstrate the added benefits of coupling ISRFH to a traditional SVE system. In Stage 1 (25 days) the SVE system was run alone in order to obtain baseline data. The ISRFH unit was then turned on during Stage 2 (14 days) and operated without SVE until it heated the soil near the electrodes to a temperature of approximately 45°C . In Stage 3 (15 days), the ISRFH and SVE systems were operated in tandem. In Stage 4 (7 days) the ISRFH system was shutdown and SVE was continued. In Stage 5 (12 days), the ISRFH system was turned back on to operate in tandem with the SVE after an extension to the trial was granted by Total UK Ltd. In Stage 6 (44 days) the SVE was operated alone until the completion of the extended programme.

8. PROCESS PERFORMANCE

The ISRFH system achieved a maximum soil temperature of 96.4°C during Stage 5 of the trial, with an average temperature of 49.1°C across an area of 57 m^2 . A 3-D graph of the soil temperature profile is presented in Figure 4.

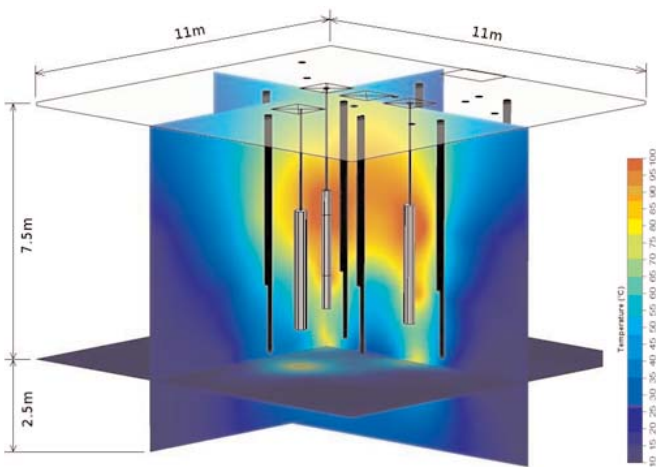


Figure 4. Temperature profile in the treatment area at the end of Stage 5.

Increased soil temperatures produced by the ISRFH technology resulted in a significant improvement of the extraction rate of VOCs when compared to SVE alone. The rate of extraction increased approximately 1200% (i.e. 12 fold) in Stage 3 when the average soil temperature reached 36.1°C . An 800% (i.e. 8 fold) increase in the rate of extraction compared to Stage 1 was observed in Stage 5, when the average soil temperature reached 45.4°C . Experimental data recorded during the remediation are presented in Table 1.

The average VOC extraction rate recorded when the soil was actively heated was approximately 10 fold higher than with SVE alone. Extraction rates of VOCs initially showed an exponential increase as average soil temperature increased, but generally levelled out at approximately half of the maximum peak recorded in Stage 3 and 5 when ISRFH was in operation. Soil cooling as a result of the SVE operation was very gradual ($0.374^\circ\text{C}/\text{day}$), and extraction rates of VOCs remained significantly higher (on average approximately 5 fold) than using SVE with no heating. This indicates that significantly improved extraction rates can be achieved when the soil has reached a threshold temperature, without incurring significant additional energy costs associated with continued operation of the heating equipment.

Table 1. Summary of data collected throughout various stages of the trial.

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Temperature at 3.5 m ($^\circ\text{C}$)	Min	10.5	11.1	12.1	20.8	20.8	18.0
	Avg	11.8	15.6	36.1	41.2	45.4	39.7
	Max	12.8	35.0	88.9	84.1	96.4	94.7
TVOC Concentration (mg/m^3)	Min	6.96	N/A	209	1422	226	66.1
	Avg	1,476	N/A	17,252	7,108	12,413	7,084
	Max	5,453	N/A	76,391	14,385	29,697	25,242
Extraction rate(kg/day)	Min	0.7	N/A	5.0	12.5	13.9	6.7
	Avg	2.9	N/A	37.4	16.5	24.8	17.5
	Max	4.8	N/A	86.3	19.4	37.8	30.2

The cumulative mass of VOC extracted vs. soil temperature in the soil during the various stages of the remediation is presented in Figure 5.

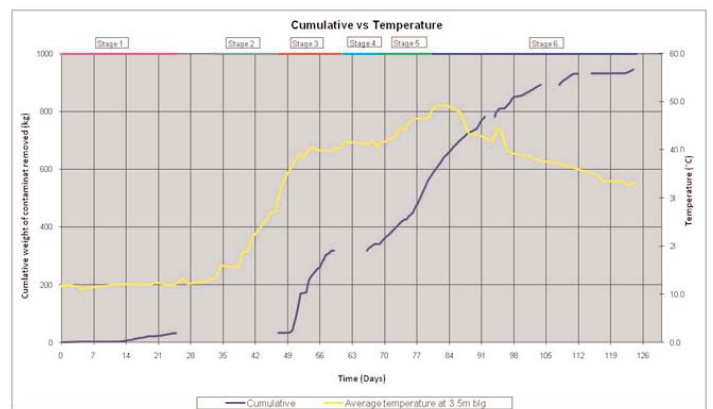


Figure 5. Comparison between cumulative total VOC removal and average soil temperature throughout the trial period.

An assessment of the measured extraction rates for each single volatile and semi-volatile contaminant of concern (CoC) against the estimated extraction rates based on their physicochemical characteristics (i.e. boiling point, vapour pressure and air moisture) revealed that:

- The average measured rates of benzene and toluene extraction were 85% and 36% lower than predicted. This may have been due to the fact that most of the benzene and toluene had been extracted prior to Stage 4 when TENAX tube monitoring of the extraction wells was implemented.
- The average extraction rates of ethylbenzene and xylenes were approximately 47.2% and 58.2% higher than predicted. The increased extraction rates were attributed to the fact that these molecules are slightly polar and therefore more likely to be directly heated by the electromagnetic field generated by the ISRFH.
- The average measured extraction rates for TPH aliphatic ($>\text{C}_8\text{-C}_{10}$) were generally 58.2% higher than the predicted extraction rates.
- The average measured extraction rates for TPH aromatic ($>\text{C}_8\text{-C}_{10}$) were generally 70.7% higher than the predicted extraction rates.
- The measured extraction rates for TPH aliphatic/aromatic ($>\text{C}_{10}\text{-C}_{12}$ and $>\text{C}_{12}\text{-C}_{16}$) were too low to be compared reliably with the predicted extraction rates.
- A total of 945 kg of VOCs was extracted during the trial mostly associated with BTEX and the light hydrocarbon fraction (i.e. $\text{C}<10$). In addition approximately 200 litres (172 kg) of free product (mostly BTEX and $\text{C}<10$) were recovered from the SVE system's air/water separator along with 1300 litres of aqueous condensate.

9. FINAL SOIL VALIDATION

The validation sampling undertaken at the end of the trial confirmed that volatile compounds (BTEX and TPH fraction >C₈-C₁₀) were almost completely removed from the soil (i.e. >95% reduction). Higher molecular weight hydrocarbons (TPH fraction >C₁₀-C₁₆) were also significantly reduced (approximately 80% on average) but showed some concentration build-up near the SVE wells where soil temperature is likely to be lower and therefore the mobility of the VOCs reduced. For example, the peak concentration of toluene (20,400 mg/kg) and xylenes (38,900 mg/kg) recorded at T=0 were reduced by over 99.99% to 0.56 mg/kg and 0.72 mg/kg respectively at the end of the remediation.

Similar behaviour was observed for the non-volatile TPH long chain fractions (>C₁₆-C₃₅), despite the fact that the initial contaminant concentration recorded was two orders of magnitude lower than the volatile CoC. The concentration observed across all the validation samples at the end of the trial was significantly lower (80%) than at T=0 suggesting that soil heating played a significant role in this reduction even though the C₁₆-C₃₅ TPH fraction would not have been volatilised. Two other removal mechanisms may have contributed to the observed reduction - biodegradation and *in situ* hydrolysis – although it was not possible to collect sufficient field data to support them.

Occurrence of accelerated biodegradation at temperatures not exceeding 50°C has been demonstrated by our German partner UFZ in several scientific papers (Roland et al., 2003; Roland et al., 2005). However, the dual porosity (through the matrix and fractures) and low permeability of the Chalk at the site prevented reliable measurements of oxygen depletion and CO₂ production being obtained that would have been indicative of microbial activity.

In areas where the soil temperatures reached 70-80°C steam was produced *in situ*, and this resulted in the production of an aqueous condensate (1300 litres) and free product distillate (approximately 200 litres) following the cooling of the extracted vapours. The US Department of Energy Technical Report 0504 (2000) suggested the possibility of *in situ* hydrous pyrolysis occurring during *in situ* heating processes, however the only supporting field evidence that can be presented is significant non-volatile contaminant reduction having occurred at the end of the remediation process.

Soil validation sampling confirmed that, with the exclusion of a single data point collected in proximity of extraction well SVE 2, the residual values recorded in the soil at the end of the process were below the stringent Generic Assessment Criteria (GAC) for commercial/industrial use derived using the probabilistic CLEA software V1.0 during the initial site appraisal.

10. MASS BALANCE

Mass balances are notoriously difficult to calculate due to the heterogeneous contamination likely to be present *in situ*. The mass of hydrocarbons extracted, calculated from extracted soil vapour measurements and volume of free phase condensate was 1291 kg of CoC. This compares against an estimate of mass of CoC removed from soil calculated from soil sampling data (T=0 minus T=final soil concentrations) of 2825 kg. Considering the potential for systematic analytical error during the continuous online process, known errors associated with the analysis of TPH fractions in soil and the heterogeneous contamination normally present in soil, an overall mass balance with a 40% recovery was deemed to be satisfactory and similar to previous technology demonstration trials reported by Lowe *et al.*, (2000) in a field trial using ISRFH technology coupled SVE at the Kirland Airforce Base (AFB) as part of the US Department of Defense (DOD) Advance Applied Technology Demonstration Facility programme.

11. COST EFFECTIVENESS AND DURABILITY OF THE ISRFH TECHNOLOGY

A summary of energy cost to heat up soil to predetermined temperature using mains electricity at typical 2009 rates (£0.12/kWh) is presented in Table 2. The field data demonstrated that the required energy input to heat soil is linear in the range 20-70°C, but increases by over two-fold for soil temperatures above 70°C as it gets near to the boiling point of water.

Table 2. Calculation of energy input in order to achieve set pre-determined average soil temperatures.

Soil average temperature (°C)	Energy input coefficient (kWh/m ³ /°C)	Cumulative energy requirement (kWh/m ³)	Energy cost (£/m ³) ¹
20-30	3.238	32.38	3.89
30-40	3.238	64.76	7.77
40-50	3.238	97.14	11.66
50-60	3.753	134.67	16.16
60-70	3.753	172.2	20.66
70-80	8.022	252.42	30.29
80-90	8.022	332.64	39.92
90-100	8.022	412.86	49.54

¹Cost calculated using a price of £0.12 / kWh, typical of electricity prices in 2009.

An average cooling rate of 0.098 °C/day was derived from the field data. This would require 102 days of SVE operation to achieve a reduction in soil temperature of 10°C. This value appeared to be extremely low and appears to be skewed by data obtained at increased depth, where soil temperature differentials are less extreme; this will need to be verified further. If the average cooling ratio of 0.374°C/day measured at 3.5 m bgl is used, this equates to 26.7 days of continuous SVE operation before a 10°C drop in soil temperature would occur. This fits well with the observed data and it is similar to observations recorded in previous trials at Ecologia's headquarters.

A comparison was made of using SVE alone, ISRFH+SVE operated continuously or ISRFH + SVE operated intermittently to remove 945 kg of VOC contamination from the Chalk. The results of this comparative assessment are presented in Table 3.

Table 3. Calculation of time and energy requirements to extract 945 kg of volatile CoC using SVE alone, SVE +ISRFH and SVE alone after soil heating with ISRFH.

Operating Mode	Description	VOC removal rate (kg/day)	Days to extract 945 kg ³	Daily power consumption (kWh/day)	Total power consumption (kWh)
1	SVE alone average	2.9	325	144	46,924
2	ISRFH+SVE average ¹	31	30	1539	46,749
3	SVE post ISRFH average ²	17	55	264	14,675
4	Combination of ISRFH with SVE + SVE post ISRFH	N/A ⁴	60	N/A ⁴	46,254

¹ Average RF value is calculated assuming that RF is operated both at full power (24 kW) and half power (10 kW)

² Average post RF is calculated assuming that chiller may be required if off gases are >40°C.

³ This does not include recovery of free product in the knock out tank.

⁴ N/A = Not applicable as VOC removal rate and/or daily power consumption is the sum of operating mode 2 (12 days) + mode 3 (34 days) multiplied by their respective removal and consumption rates.

The comparison revealed that the application of the ISRFH+SVE operated intermittently would reduce the time required for remediation by 81% (60 days vs 325 days) with comparable energy input to traditional SVE with no heating.

The costs of combining ISRFH with SVE and operating the system intermittently were compared to SVE alone (with no heating) and excavation and disposal to landfill. The calculated treatment cost for ISRFH + SVE was £194 per m³

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(£97/tonne) with a programme of approximately 10 weeks, disposal to landfill of hazardous soil including sheet piling and backfilling operations was £398/m³ (£197/tonne) with a programme of approximately 5 weeks, whilst SVE alone was (£174/m³ (£87/tonne) with a predicted programme of one year. These calculations based on the volume of soil treated during the remediation process (480 m³ with a density of 2g/cm³) and are inclusive of energy costs, maintenance and monitoring costs. SVE process performances are predicted on the basis of the extraction rates observed at the commencement of the remedial operations, but it is unlikely that the process will achieve the same performance of the ISRFH at normal soil temperature (i.e. approx 10°C).

Lowe *et al.* (2000) reported cost per m³ ranging from \$182 (i.e. approx £113 based on an exchange rate £/US\$ = 1.6) to \$288 (£180) on the basis of two different case scenarios treating 24,500 and 4900 m³ of soil respectively. These cost calculations were based on the assumption that the ISRFH unit was leased over the duration of the project and the achievement of an average soil temperature within the treatment area of 100°C. Energy costs per kWh were not published; therefore no attempt was made to compare the cost of the trials in the US with those carried out in Kent.

Khun *et al.* (2008) reported energy costs for resistive heating carried out in the US in 2003 to be around \$0.0475/kWh which is equivalent to approximately £0.03/kWh (based on an exchange rate £/US\$ = 1.6). This cost estimate is unlikely to be representative of current (2010) utility prices in the UK.

12. CONCLUSIONS AND POTENTIAL APPLICATIONS OF THE REMEDIATION PROCESS

The data from the remediation process demonstrated that combining ISRFH *in situ* heating with SVE would:

- significantly increase the removal rate of volatile and semi-volatile contaminants from the unsaturated Chalk;
- significantly improve the final soil contaminant concentrations that can be achieved; and
- significantly reduce treatment times without entailing excessive energy costs.

Application of the technology requires specific knowledge and expertise. Health, safety and operational issues associated with the application of the technology have been satisfactorily addressed and accepted by the regulator.

The perception that *in situ* heating is expensive and not sustainable is erroneous; heating of soil requires significant energy input, but soil also has the capacity to retain heat as it is a good insulator. Chalk in particular can retain this heat for days or weeks. Effective removal of volatile and water soluble CoC can generally be achieved at soil temperatures of 50-60°C thereby avoiding the need for excessive energy costs normally observed near the boiling point of water. Therefore once a predetermined soil temperature has been achieved, the operator can switch off the energy intensive ISRFH whilst continuing operation of the SVE at a much improved extraction rate thus significantly reducing the treatment time. The very significant reduction in programme timescales is the principal reason for the overall reduction in energy requirements.

The cost assessment presented in Section 11 demonstrates the feasibility of this approach in soils with poor permeability where mass transfer of pore water and/or contaminants is minimal and where traditional SVE or high vacuum multiphase extraction have been proven to be less effective for removal of VOC contamination. The field data indicate that if the ISRFH achieves soil temperatures approaching the boiling point of the CoC, significant removal/destruction of the contaminant is guaranteed.

A key advantage of ISRFH is that heat delivery into the ground can be pinpointed by installing the electrodes at predefined depths. This allows efficient and targeted heating of source areas, often at depth, without the need to heat the entire soil profile.

The preliminary cost assessment also suggests that ISRFH is likely to be competitive when compared to traditional excavation and disposal to landfill when material is disposed of as hazardous waste. This is even more relevant in the light of the recent abolition of the landfill tax exemption and future landfill tax increases in the UK.

ACKNOWLEDGEMENTS

We would like to thank Total UK Ltd for funding this remediation trial.

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