

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

1. Technology Description

The technology uses In Situ Radio Frequency Heating (ISRFH) to excite polar molecules present within the soil profile, thus generating heat in a manner similar to that of a microwave oven. ISRFH uses a frequency (13.56 MHz) with a wavelength of 22m; therefore it has the capacity to penetrate the soil to a much greater extent than microwaves. ISRFH is effective in dealing with volatile contamination in tight, unsaturated soils which cannot be efficiently heated 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. The technology is also far less susceptible to soil moisture than resistive heating (either three-phase or six-phase); therefore the system performance is unlikely to collapse in the event of soil drying, an inevitable effect during heating. Due to the good penetration of the radiowaves into the soil, ISRFH produces a much smoother soil temperature gradient than the extreme gradient generally associated with conductive soil heating based on simple heating coils/rods.

Ecologia teamed up with UFZ (a German research institute) in 2006 to develop and commercialise the technology and carried out over 2 years of R&D work at its headquarters in Kent prior to trialling the technology in a real contaminated environment. Ecologia successfully completed the first commercial ISRFH application in 2007. The process is protected by a European Patent (No.1596998) jointly owned by Ecologia and UFZ.

Previous ISRFH applications are mostly restricted to the US as part of the Superfund Technology development programme carried out in the mid- to late 90s. 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.

The ISRFH energy is delivered into the surrounding soils by an array of electrodes, installed approximately 3-4m apart at predetermined, discrete depths. 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 contaminants 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 simultaneously heat both unsaturated and saturated soils with reduced energy consumption using the same piece of equipment. An image of one of Ecologia's commercial applications of ISRFH is presented in Figure 1.



Figure 1. Aerial photo of the ISRFH remediation layout during a remediation project.

2. Site Description

Total UK Ltd appointed Ecologia to carry out a remediation assessment of an in-situ soil heating technology at a decommissioned petrol station in Manston, Kent. The site was selected as it was impacted by VOCs such as benzene, ethylbenzene, toluene and xylenes (BTEX) and total petroleum hydrocarbons (TPH), mostly with C<21. The contamination was confined within the unsaturated Chalk strata to a depth of 10m below ground level (bgl). The project has also been selected by CL:AIRE as technology demonstration

project (TDP 28). For this site ISRFH electrodes were deployed in a triangular array between 3m and 6 m bgl together with eight multilevel SVE extraction wells (screened depth 2.5-5 m bgl and 5.5 and 7.5 m bgl). The site is typical of a decommissioned medium sized service station in an area with high groundwater vulnerability. Due to the presence of hydrocarbon contamination at depth additional remediation was required in order to reduce potential future environmental liabilities if the site is divested or redeveloped.

3. 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 radiowaves** – 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 produced near the electrodes or at the boundary of the treatment area.
- **Monitoring of the electromagnetic field** - The electromagnetic level outside the cage is lower than that generated by a mobile telephone and below the most recent guidance for time varying electromagnetic field for the general public published in the ICNIRP guidelines, 1998. This is the most restrictive guidance currently available.
- **Environmental permit** – 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 would not cause vertical migration of the contaminants into the underlying aquifer.
- **Stakeholder acceptance** – The process raised significant regional interest with the BBC featuring two short clips on the regional news at two different stages of the technology development (http://www.ecologia-environmental.com/?page_id=99).

4. Remediation Performance Parameters

In order to validate the potential benefits of the ISRFH system performance parameters such as soil temperature, strength of electromagnetic field, rate of extraction of VOCs by the SVE system were monitored manually and/or automatically with data loggers. An automatic Total Volatile Organic Carbon (TVOC) sensor, used to monitor the VOCs extracted by the SVE system, was calibrated using TENAX absorption tubes in order to provide both qualitative and quantitative specific information regarding the type of VOCs extracted. Soil validation samples were collected at T=0 and approximately 3 weeks after completion of the site operation to assess the performance of ISRFH.

5. 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, the SVE system was run alone in order to obtain baseline data. The ISRFH unit was then turned on during Stage 2 and run on its own until it heated the soil near the electrodes to a temperature of approximately 45°C. In Stage 3, the ISRFH and SVE systems were operated in tandem. In Stage 4 the ISRFH system was shutdown and the SVE system was left to run on its own. In Stage 5, 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. In Stage 6 the SVE was operated alone until the completion of the extended programme.

6. Process Performance

The ISRFH system achieved a maximum soil temperature of 96.4°C during Stage 5 of the trial, with an average of 49.1°C across an area of 57m². A 3-D graph of the soil temperature profile is presented in Figure 2.

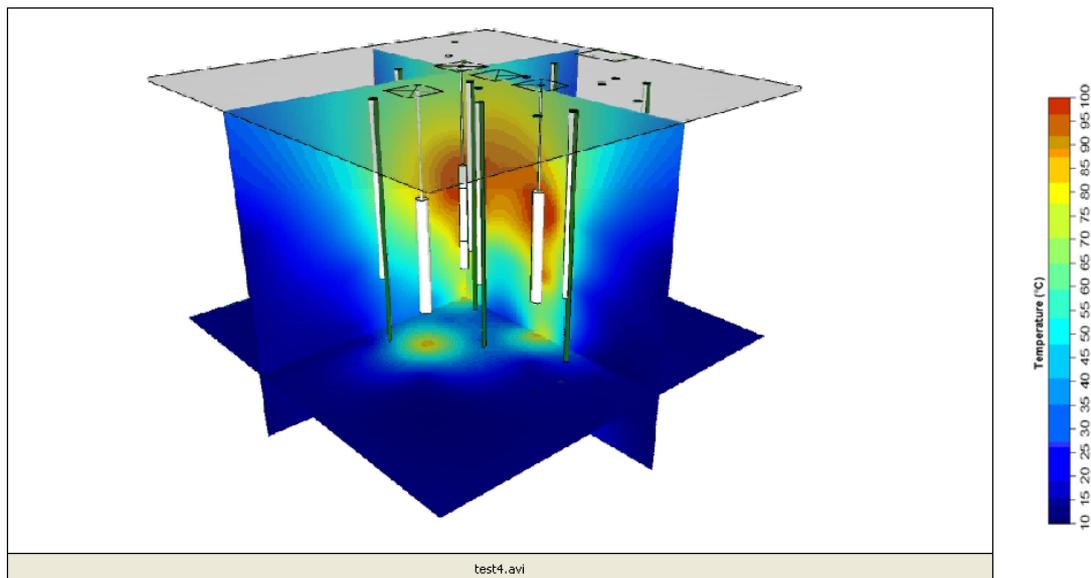


Figure 2. Temperature profile in the treatment area at the end of stage 5

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 Stage1 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 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°C/day), therefore extraction rates of VOCs remained significantly higher (on average approximately 5 fold) than 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.

The cumulative mass of VOC extracted vs. soil temperature in the soil during the various stages of the remediation is presented in Figure 3.

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 3.5m (°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	208.80	1421.58	226.2	66.12
	Avg	1,475.72	N/A	17,252.1	7,107.9	12,413.16	7,083.54
	Max	5,453.16	N/A	76,391.22	14,384.58	29,696.58	25,242.18
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

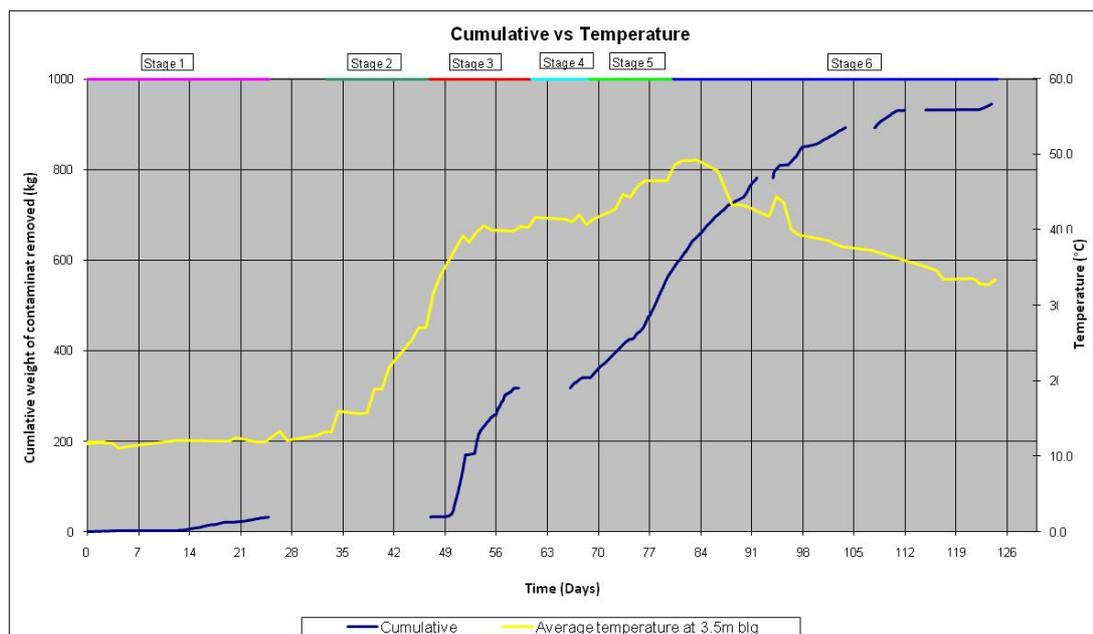


Figure 3. Comparison between cumulative total VOC removal and average soil temperature throughout the trial period.

6. Final Soil Validation

The validation sampling undertaken at the end of the trial confirmed that volatile compounds (BTEX and TPH >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 instance, the peak concentration of toluene (20,400 mg/kg) and xylenes (38,900 mg/kg) recorded at T=0 were reduced over 99.99% to 0.56 mg/kg and 0.72mg/kg respectively at the end of the remediation.

A similar behaviour was also observed for TPH long chain fractions (>C₁₆-C₃₅), despite the fact that the initial contamination recorded was much lower than the volatile Contaminants of Concern (CoC). The extent of the reduction observed (approx 80%) cannot be solely attributed to analytical error and must therefore be the result of the in-situ soil heating. Biodegradation and in-situ hydrolysis were considered as two potential explanations for such reduction. Occurrence of accelerated biodegradation at temperatures not exceeding 50°C has been demonstrated by our German partner UFZ in several scientific papers; however the Chalk geology present at the site prevented us from obtaining reliable measurements of oxygen depletion and CO₂ that would be indicative of microbial activity. In areas where the soil temperatures reached 70-80°C steam was produced in-situ, 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. Several scientific papers and specialised contractors have reported possible in-situ hydrous pyrolysis occurring during in-situ heating processes; at this stage the only firm supporting evidence that can be presented is significant non volatile contaminant reduction having occurred at the end of the remediation process.

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 1291kg 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 on line 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 using ISRFH carried out in the US.

Soil validation sampling confirmed that, with the exclusion of a 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 GAC tier 1 criteria for commercial/industrial use derived using the probabilistic CLEA software V1.0 carried out during the initial site appraisal.

7. 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 increase (°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

A comparison of using SVE alone, ISRFH+SVE operated continuously or ISRFH + SVE operated intermittently to remove approx 1 tonne of VOC contamination was also performed.

The comparison revealed that the application of the ISRFH+SVE operated intermittently would reduce the time required for remediation by 86% (46 days vs. 325 days) and decrease the energy input by 42% when compared to a traditional SVE with no heating.

The cost 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 £97/tonne with a programme of approximately 10 weeks, disposal to landfill of hazardous soil including sheet piling and backfilling operations was £172/tonne with a programme of approximately 5 weeks, whilst SVE alone was £87/tonne with a predicted programme of one year. These calculations based on the volume of soil treated during the remediation process (480m³ 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)

8. 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
- Significantly reduce treatment times without entailing excessive energy costs.

Application of the technology requires specific knowledge and expertise. H&S 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; soil requires energy to be heated, but also the capacity to retain heat as it is a good insulator. In soils such as Chalk this heat can be retained for days/weeks. Effective removal of volatile and water soluble CoC can generally be achieved at soil temperatures of 50-60°C therefore 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 large reduction in programme timescales is the principal reason for the overall *reduction* in energy requirements.

The cost assessment presented in Section 7 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 indicates 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 and in the light of the recent abolition of the landfill tax exemption and future landfill tax increases.