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Electrochimica Acta 52 (2007) 3449–3453
ELECTROCHIMICA Acta
www.elsevier.com/locate/electacta

Electro-bioreclamation
A combination of in situ remediation techniques proves successful at a site in Zeist, the Netherlands

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Received 5 December 2005; received in revised form 21 December 2005; accepted 18 January 2006
Available online 7 November 2006

Abstract

The site of a former silver factory that has been severely polluted with chlorinated solvents was treated by excavating the polluted soil and installing a pump and treat system. After an initial fall in contaminant concentrations, no further progress was observed over a number of years. The Province of Utrecht tried to solve the problem by requesting remediation contractors to propose a solution at a fixed price. The winning solution was electro-bioreclamation, a combination of in situ techniques: heating soil and groundwater in the source areas, combined with soil vapour extraction and low-yield groundwater pumping, and enhancing biodegradation in the groundwater plume area. Two years of heating and 2.5 years of biodegradation has been resulted in near-complete removal of the contaminants.

Keywords: Electro-bioreclamation; Bioremediation; VOC; Alternating current; Soil; Groundwater; In situ; Heating

1. Introduction

The site of a former silver factory has been severely polluted with chlorinated solvents such as perchloroethylene (PCE) and trichloroethylene (TCE) and their degradation products are *cis*-1,2-dichloroethene (C-DCE) and vinyl chloride (VC). The site was treated in 1991 and 1992 by excavating the polluted soil down to a depth of about 3 m below ground surface (bgs) with the purpose of redeveloping the site as a residential area. In 1993, a pump and treat system was installed to remediate the groundwater. After an initial reduction in the concentrations, no further progress was observed in the following years and in 1998 an additional investigation at the site showed that there was considerable residual contamination. Since the soil consists of alternating layers of sand and clay, it was no surprise that pump and treat was not a great success, as this technique is not suitable for clay layers. The authorities of the Province of Utrecht tried to solve the problem by requesting remediation contractors to propose a solution at a fixed price. On the basis of several proposals, the authorities opted for an innovative but proven technology which was offered at a very competitive price. The winning solution was *electro-bioreclamation*, a combination of techniques [1]: heating soil and groundwater in the source areas combined with soil vapour extraction and low-yield groundwater pumping, and enhancing biodegradation in the groundwater plume.

1.1. The influence of heating

When the volume of a volatile organic compound (VOC), mass of PCE and TCE that enters the soil is large enough, it will percolate down, leaving behind VOC droplets in the sandy layers and forming pools on less permeable clay layers. Because VOCs do not dissolve easily in groundwater, pump and treat will not have much effect when free product or high concentrations are present. Excavation underneath the houses was no option, so the efficient solution was to find a suitable in situ technique.

In this case Holland Milieutechniek BV proposed to solve the problem using electro-bioreclamation. This technique is based on the induction of alternating current (AC) in the soil. It has both physico-chemical and biological effects [2]. One of the physico-chemical effects is the Joule effect which results in an increase in soil temperature. A striking effect of temperature

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0013-4686/$ – see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.electacta.2006.01.089

increase in soil and groundwater is a reduction in the viscosity of the groundwater. The hydraulic permeability of the soil increases, allowing groundwater decontamination to be carried out much faster. Experience with other projects had shown that for every 20–25 °C increase in temperature, hydraulic conductivity is almost doubled. An additional advantage of this process is the increased breakdown of colloidal suspensions, opening up pores in the soil and increasing dissolution rates. The vapour pressure of the organic components also increases when the temperature is raised, in contrast to the solubility of these components in water when they are in the gaseous phase. Thus, heating of the soil is combined with groundwater extraction and soil vapour extraction. In order to maintain the heat economy in the subsoil, a low pumping rate is used. Pumping is done via a dense network of extraction wells in between the electrodes. The wells are not pumped at the same time, but in succession and only for a short period. So only small volumes of groundwater with relatively high concentrations of contaminants are pumped up.

1.2. Biodegradation

Alongside the physico-chemical effects of electric heating, elevated temperatures also enhance biodegradation [3]. During remediation, biodegradation is also accelerated by periodic injections of nutrients (N, P), electron donors and carbon sources [4,6]. The results of completed and ongoing electro-bioreclamation projects at VOC-contaminated sites have shown that first-order degradation constants, which were initially used to estimate the total remediation time, increased by one to two orders of magnitude.

Fig. 1. Installating the electro-bioreclamation system.

1.3. Temperature levels

Looking at some physical parameters of VOCs and their azeotropes, such as boiling point, vapour pressure, and dis-

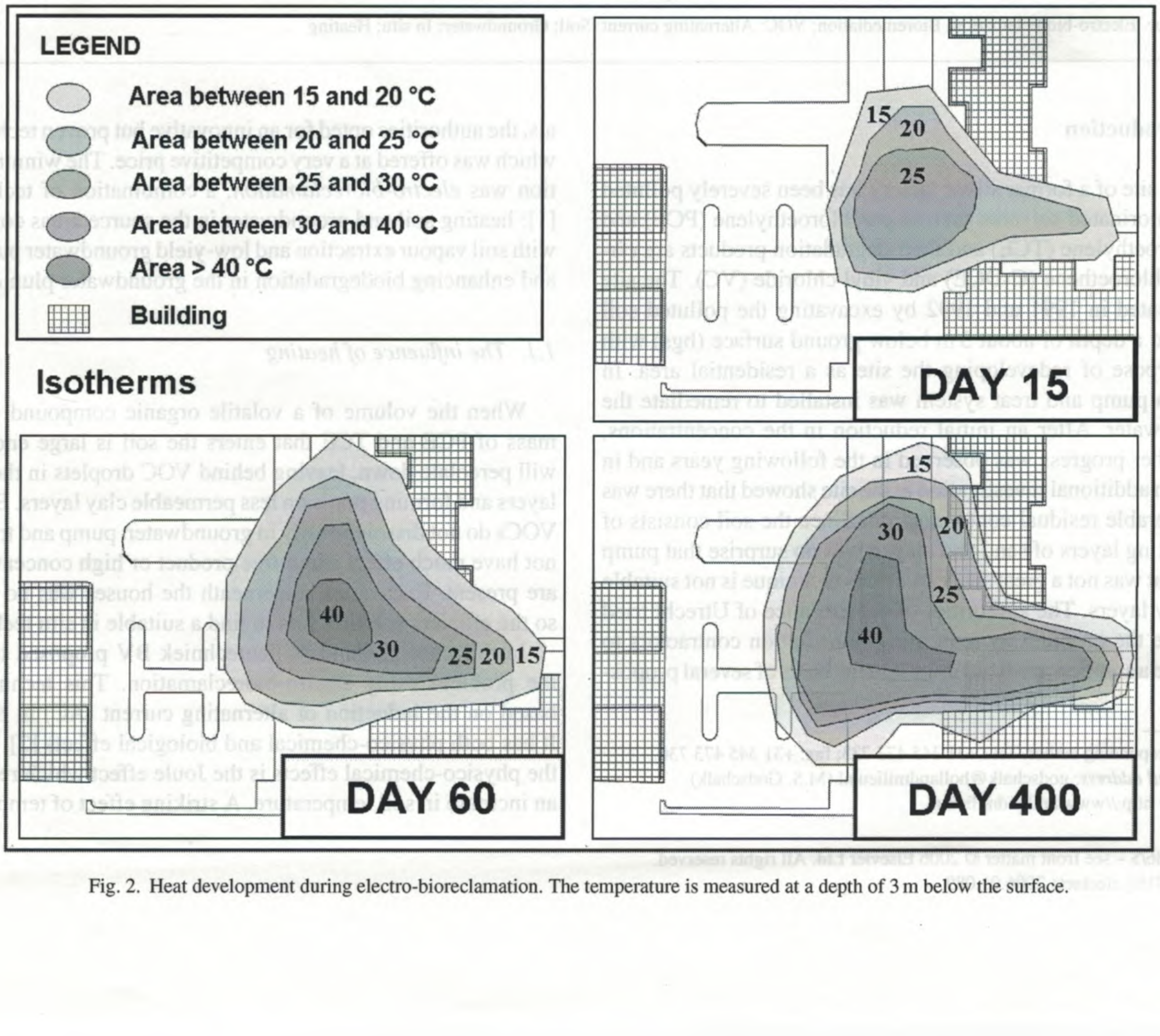

Fig. 2. Heat development during electro-bioreclamation. The temperature is measured at a depth of 3 m below the surface.

solution product, it would seem desirable to increase the temperature by as much as possible so as to "boil" the VOCs out of the soil. There are several reasons why we did not adopt this approach. First, temperatures above 100 °C in the unsaturated zone can only be reached with high radio frequency heating—a very costly technology that is very highly regulated. Second, such temperatures destroy beneficial micro-organisms (see why they are beneficial below). Although the energy requirements for heating just up to 100 °C using low (50 or 60 Hz) frequency are much lower, experience has taught us that most equipment and materials used such as pumps, extraction and electrode filters cannot stand aqueous solutions and gasses with free or dissolved VOCs compounds at this relatively high temperature. This means that special and therefore expensive equipment and materials need to be installed. For all these reasons, we have chosen maximum temperatures in the order of 70–80 °C.

These temperature levels, however, can only be applied when there are no buildings nearby. Otherwise, temperatures need to be in the order of a maximum of 40–50 °C, for the following reasons:

- Experience with electro-bioreclamation projects in residential areas and underneath manufacturing facilities has shown that ground temperatures above 50 °C may affect the mechanical properties of clay and argillaceous sand, resulting in compaction and subsequently in subsidence.
- Relatively high temperatures of the ground underneath the floor of houses will ultimately result in high temperatures of the floor itself, which is unacceptable for residents and/or personnel and underground cables and ducts and machines (computers and other domestic devices).

1.4. Phased approach

In view of the above, *electro-bioreclamation* is particularly suitable for treating both source areas and plumes. Nutrient injection starts already at the very beginning of the heating phase. Once concentrations in the source areas have decreased sufficiently, it is more efficient to stop heating and switch to an enhanced attenuation phase. By using the residual heat in the soil and continuing to inject nutrients for several months, bio-polishing can eliminate the remaining pollution.

In plume areas, heating is not an option because their size is usually in many cases prohibitive. The number of electrodes which would need to be installed would lead to unacceptable costs. However, concentrations of VOCs are relatively low and not toxic to bacteria, so biodegradation can be enhanced by injecting nutrients in relatively narrow bio-injection zones.

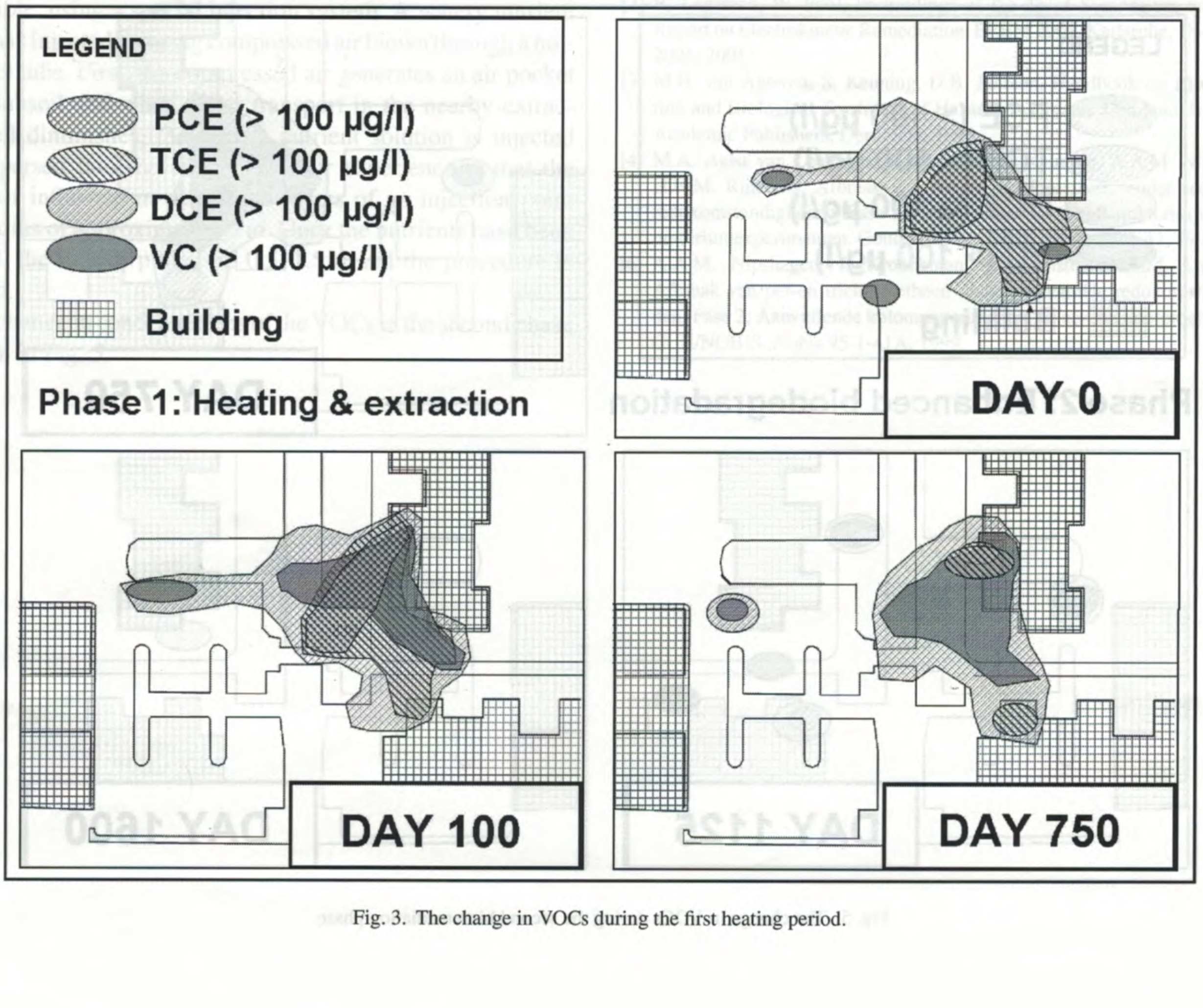

Fig. 3. The change in VOCs during the first heating period.

1.5. Realization

Installing a remediation system in an existing residential area requires special measures. Communication with the inhabitants is of the utmost importance; they need to be told exactly what is going to happen and how long the disturbance will last. In this case, the disturbance lasted 6 weeks. During this period, the pavement and the plants and bushes in the gardens were taken out, and a soil layer approximately 80 cm deep was removed (Fig. 1). In the excavated area 95 electrodes were installed in a hexagonal configuration. In the middle of each hexagon, a dual phase extraction well was installed. The floors of the houses were made gas-tight and an air extraction system with a gas detector was installed underneath the floors.

The equipment is normally placed in one or more containers. But in this particular area that was not much appreciated by residents. It was therefore decided to hide all of the equipment from view in an attractive wooden shed.

The equipment consisted of an electrical power supply unit, a groundwater and soil vapour extraction unit, and groundwater and soil vapour treatment units. The extraction unit is a so-called Divisio®-unit. This is a computerized system consisting of a multitude of electrical valves through which each extraction filter can be activated separately. So as not to disturb the underground heat management and in order not to pump large volumes

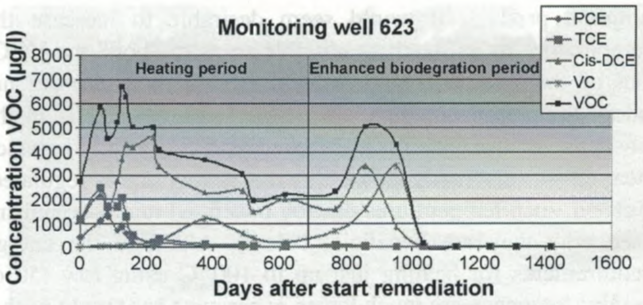

Fig. 4. The change in the VOCs in monitoring well 623.

of groundwater with only low contaminant concentrations, the pumping rate was limited to a maximum of 1.0 m^3/h.

1.6. Removal of the source: first phase

After the installation of the in situ system in the source area, the electrodes were activated and the temperature in the soil reached around 40 °C in 60 days (Fig. 2). After approximately 2 years, the electrodes were deactivated and the temperature level slowly decreased during the following period. The change in concentrations of the VOCs in the groundwater is shown in Fig. 3.

During the heating phase, 80 kg of VOCs were removed. PCE and TCE have disappeared from the soil and the groundwa-

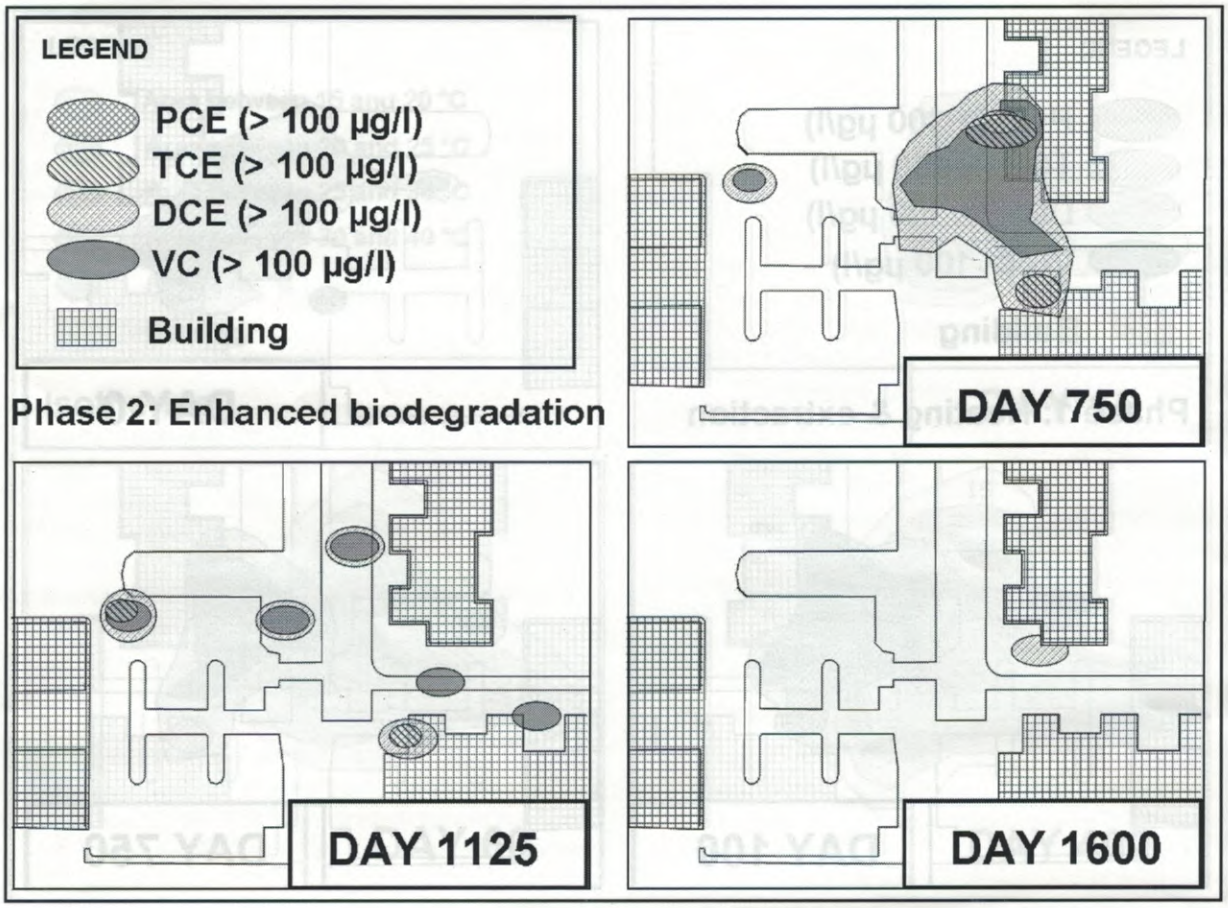

Fig. 5. The change in VOCs during the second bioremediation phase.

ter in most of the monitoring wells now complies with target values for VOCs. C-DCE and VC concentrations are still too high, because the biological degradation is not yet complete. The remaining contamination will be removed during the next phase of enhanced natural attenuation. The first or intensive phase is ended by shutting off the electrical current.

Changes in the concentration of VOCs are shown in Fig. 4.

Monitoring well 623 is situated in the heart of the source area, which contained the highest PCE concentrations at the start of the remediation. The figure shows the presence of PCE and TCE during the first 2 years, and it also shows their steady decline. As soon as the highest concentrations had disappeared, we stopped the heating and allowed to the micro-organisms in the soil to reduce the concentrations to the required levels. Today, the VOCs concentrations in this monitoring well are smaller than 0.5 μg/l.

1.7. Second phase: enhanced natural attenuation

Before the remediation started, field and laboratory investigations revealed that the boundary conditions for biological degradation were not optimal. During the first phase, these conditions were improved by periodically injecting suitable nutrients. During the second phase, this method was repeated several times. The injection of nutrients results in the biological reduction of sulphate and it starts biological dechlorinization. The nutrients are dispersed into the soil and groundwater as homogeneously as possible, using a special injection system. A watery nutrient solution is injected in, using compressed air blown through a hollow steel tube. First, the compressed air generates an air pocket in the subsoil and when water transport in the nearby extraction well diminishes, the watery nutrient solution is injected and dispersed into the air pocket. Our experience is that the sphere of influence in permeable layers of an injection point has a radius of approximately 5 m. Once the nutrients have been injected, the tube is pulled up 0.5–1.5 m and the procedure is repeated.

The change in concentrations of the VOCs in the second phase is shown in Fig. 5.

Based on the final monitoring samples, we can conclude that all PCE and TCE were removed and that concentrations of C-DCE and VC now comply with target levels. The concentration of VC exceeds the target level by 30% inside only one monitoring well. Based on the standard biodegradation curve, it can be expected that the VC concentration will fall below the target level within months.

2. Conclusions

A sandy soil with alternating clay layers poses serious limitations to classical in situ methods such as pump and treat. However, by deploying electro-bioreclamation, these limitations are overcome. During the heating phase, contaminants are desorbed and removed either by groundwater or soil vapour extraction. The remaining lower VOC concentrations in the source area are removed by enhanced natural attenuation during the second phase. Enhanced biodegradation is also used to clean-up the contaminants in the plume area. The Zeist project proves once again that a combination of heating, groundwater pumping and soil vapour extraction, followed by enhanced natural attenuation is an ideal method for the in situ removal of VOCs from soil and groundwater.

References

[1] R. Lageman, W. Pool, Eng. Geol. 77 (2005) 191.

[2] R. Lageman, W. Pool, Proceedings of the Third Symposium and Status Report on Electrokinetic Remediation, EREM 2001, Karlsruhe, 18–20 April 2001, 2001.

[3] M.H. van Agteren, S. Keuning, D.B. Janssen, Handbook on Biodegradation and Biological Treatment of Hazardous Organic Compounds, Kluwer Academic Publishers, Dordrecht, 1998.

[4] M.A. Aalst van Leeuwen, J. Brinkman, S. Keuning, A.A.M. Nipshagen, H.H.M. Rijnaarts, Afbraak van per-en trichlooretheen onder sequentiële redoxomstandigheden; Fase 1: Deelresultaat 2-6: Veldkarakterisatie en laboratoriumexperimenten. Gouda, CUR/NOBIS. Nobis 95-1-41, 1997.

[6] A.A.M. Nipshagen, J. Krooneman, A. Tuinstra, A.A.M. Langehoff, Afbraak van per-en trichlooretheen onder sequentiële redoxomstandigheden; Fase 2: Aanvullende kolomexperimenten en aërobe pilotproef. Gouda, CUR/NOBIS. Nobis 95-1-41A, 1999.