Electro-reclamation, a versatile soil remediation solution

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Abstract

Work on electrokinetic technology started in the Netherlands around 1985 with Geokinetics. In 1994 the company teamed up with Hak Milieutechniek (HMT), which became full owner of the company in 1999.

This paper briefly compares and contrasts Geokinetics' and HMT's commercially driven approach with that of the more traditional and academic approach adopted by many other workers in the field. It outlines our primary attention and focus on electrokinetic technology to solubilize and recover ionic contamination from ground and groundwater. The simple fact that most of the contaminated sites all over the world contain more often than not a mixture of both inorganic and organic components forced us to extend the use of electricity to cope with all sorts of pollution. The knowledge we gained and the challenges of this opportunity lead us to the development of electro-remediation, a combination of techniques having electricity as the common denominator:

- electrokinetic recovery of inorganic contamination and electroheated recovery of organic contamination in combination with soil vapour extraction and low flow groundwater extraction;
- electroheated and electrokinetically enhanced biodegradation in combination with addition of nutrients and electron donors or acceptors;
- electrokinetic containment and remediation of polluted sites and groundwater plumes.

The paper gives an overview and description of a number of benchmark projects in the aforementioned areas.
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1. Some historical background

At the end of the 1970s, beginning of the 1980s, the deteriorating environment and especially the contamination of ground and groundwater were put high on the political agendas in a number of European and North American countries. It marked the beginning of the development of all kinds of remediation technologies to cope with these contamination problems. As there was neither much knowledge about nor any experience with decontamination of soil, people were rather optimistic at that time. In the Netherlands, for example, first estimates in 1981 to clean-up all contaminated sites arrived at a period of 5 years for a mere 1 billion guilders (0.5 billion Euros). Six years later, cost estimates had already risen to 10 billion Euros, while in 1996 a number of 50 billion Euros was used. As for the period that the clean-up should be accomplished, it changed from 5 to 10 years, to 20 years, and at the beginning of the new millennium, into many decades. But one thing is clear, one estimate is as good as the other and in our opinion, another 50 years will be more realistic than another 20 years.

The numbers given above are only for the Netherlands, but when, on a worldwide scale, the effects of mining, the metallurgical industries, chemical manufacturing, power generation, refining, use of pesticides and intensive agriculture are added, the problem takes on immense proportions. It will run into thousands of billions of dollars and probably most of the coming century to resolve the most severe problems.

Apart from costs and clean-up time, over the years there has also been quite some development in clean-up levels. The Netherlands was one of the first countries that came with a list of concentrations of inorganic and organic compounds in ground and groundwater (soil), the so-called $A-B-C$ list or Dutch List, indicative for clean soil (A value), contaminated soil which needed further investigation (B value) and soil which had to be remediated (C value). Especially the rigid use of the A values as target levels for clean soil frustrated the deployment of in situ techniques. It took the regulators more than a decade to realize that a more differentiated and pragmatic policy was needed in order to eliminate the existing backlog in soil remediation. In 1996, the policy of multifunctional soil remediation was to a large extent changed into functional soil remediation, which can be related to the concept of 'Brownfields' and 'Greenfields'. It is based on the future use of the site and incorporates assessment of contact risks and any possible future mobility of remaining contaminants. The A, B and C values were replaced by target, intermediate and intervention values.

2. Technology development

As for the methods to deal with contaminated soil, 'dig and dump' was the original approach followed by 'dig and incinerate' or 'dig and wash', and for the remediation of groundwater 'pump and treat' was the common treatment method. Gradually, however, focus shifted from ex situ remediation to in situ remediation and several techniques were developed, tested and either successful, or less so. For volatile organic contaminants like, e.g. aromates, the most efficient technique was soil vapour extraction, and for inorganic contaminants like heavy metals electrokinetic remediation turned out to be a viable method. Unfortunately, through common use, the term "electrokinetic remediation" embodies many different approaches. Broadly, these approaches have followed two separate paths each based on a different electrokinetic phenomenon.

The first approach is the removal of ionic (and polar) species using classical electromigration techniques where ions move under an applied direct current (DC) field (Collopy, 1958; Slater et al., 1976; Hamnet, 1980; Agard, 1981). This approach was pioneered commercially by Reinout Lageman, Wiebe Pool and Geert Seffinga of Geokinetics during the middle and late 1980s (Lageman et al., 1988; 1989). They focused on electromigration and patented the use of circulating electrolytes and the use of ion permeable wells to hold the anolyte and catholyte in 1987 (Pool, 1989; 1995). A second approach relies on the movement of water through the electrical double layer created on porous media (Prausnitz and Reitstotter, 1931, Casagrande, 1947; 1949; 1953; Londiche and Lancelot, 1984; Honig et al., 1987). Pollutants are carried along in this moving layer of water towards an implanted cathode or adsorption media placed in the way of this moving front. This approach was initiated, apparently simultaneously at MIT (Shapiro et al.,

1989) and at Louisiana State (Acar and Gale, 1992; Acar, 1994). A review of later papers by these workers show that their attention moved away from electro-osmosis to encompass electromigration. In particular, Acar and Gale et al. at Louisiana State have written many papers describing both electro-osmosis and electromigration, as it has evolved over the last 10 years.

During the first half of the 1990s, the Lasagna group from Monsanto, General Electric and Dupont pursued the use of electro-osmosis as the driving and collecting mechanism for removing organic materials from contaminated land (Ho et al., 1994), but it has not developed into a commercially viable technique. It now appears that electro-osmosis has been largely abandoned for recovering ionic contamination. In Germany, 'Geo-oxidation' was promoted during the middle 1990s as an in situ technique to 'mineralise' organic contaminants (Doering, 1994; Doering and Doering, 2001). It is based on the idea that as a result of the induced electrical field, individual soil particles are acting as electrochemical electrodes, giving rise to anodic oxidation and cathodic reduction processes at each individual soil particle. The claims of success, however, seemed hard to sustain (Grünzig et al., 1995; Rahner et al., 2001). In Japan and South Korea, interest in electrokinetic techniques started in the middle 1990s.

The 1990s, furthermore, marked the growing interest in the use of bacteria to solve contamination problems of organic compounds (Brodsky et al., 1995). Natural attenuation became fashionable. Conditions for microbial activity in the soil, however, are mostly unfavourable because of low temperature and lack of nutrients and high contaminant concentrations create a toxic environment for micro-organisms. The use of electricity to heat up soil well over 100° C in the vadose zone to vapourize and extract hydrocarbons using soil vapour extraction had already been taken up by some vendors, but these high temperatures are not very benign for micro-organisms, to say the least. Instead, we focused on low temperature heating below 90 °C, which results in accelerated desorption and mobility of the organic contaminants and which has a pronounced stimulating effect on microbial activity, even at temperatures of 70–80 °C. In combination with other in situ techniques like soil vapour extraction and selective and low yield ground-water extraction, the desorbed and mobilized contaminants are subsequently removed as vapours and/or liquids, while biodegradation is furthermore enhanced by supplying additional nutrients and carbon sources, which are injected into the ground by a special injection technique or by electrokinetic transport. It seemed obvious to name this technology electro-bioreclamation.

From the very beginning, our technology development has been driven by commercial pressures and practical clean-up operations. We needed models of our operations to allow for costing the projects and understanding the best deployment methods. As we were in the learning curve mode while committing to full-scale operations, we used a strong support laboratory to advance our techniques and support field operations, we fed our models with data on real polluted soils from the legion of samples we tested. This was expensive but prudent. It also led to rapid development of our techniques. This is in strong contrast to academic workers at Universities and Research Laboratories, who have written much about modeling on ideal systems. It cannot be overly stressed that electrokinetic remediation can only be learned in the field.

3. Fundamentals of electro-reclamation of inorganics

When inert electrodes are placed in water and a direct current is passed, changes occur at the anode and cathode according to the scheme presented in Eq. (1).

$$2H_2O - 4e^- \rightarrow O_2 + 4H^+ \tag{1}$$

At the anode or positive electrode, electrons are being stripped from water molecules, oxygen is evolved and protons H^+ are formed, which travel through the electrolyte towards the cathode.

Meanwhile, the cathode is donating electrons to water molecules creating hydroxyl ions and liberating hydrogen gas (Eq. (2)).

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \tag{2}$$

Note that the two reactions, generation of protons at the anode and hydroxyl ions at the

cathode, are in balance and no net change in pH of the electrolyte occurs. In a liquid electrolyte, sufficient mixing occurs such that the local pH changes around the anode and cathode are difficult to detect unless the electrodes are well separated. In soil, sludge, concrete and gels, mixing is reduced or eliminated so that the area around the anode becomes acidic and the area around the cathode becomes alkaline due to inhibition of the remixing of the electrolyte. This has a significant impact on the process in soil.

4. Soil as an electrolyte

Most soils are conductive due to the presence of dissolved ions, such as calcium, sodium, potassium, carbonate, some soluble fatty acids, nitrate, phosphate, sulfate and chloride ions. Most seemingly dry soils have more than 5% moisture, sufficient to provide a continuous path for these ions to move. This is essential for plants as the roots need access to these nutrients and ion transport across membranes are the means with which they extract them. The most significant feature of natural soils, with respect to their contamination and subsequent remediation, is the high ion exchange capacity. Heavy metals such as cadmium, lead, iron, zinc, in their metallic state, corrode and form salts and bases which take up cationic sites on soil particles. In some cases, land is often contaminated from the spillage of heavy metal ions directly from aqueous plating shop wastes or airborne pollution from metal smelters. Soil has the capacity to immobilize significant quantities of heavy metal ions, to the 2–3% level in some cases, such as the top soil around lead smelters.

Soil is made up of several components derived from the weathering of rocks and the addition of organic materials from growth and decay of plants and organisms. The more permanent background of organic materials in soil is supplied by humus (Aiken et al., 1985), a complex mixture of humic and fulvic acids which are characterized by their highly functionalized aromatic structure. These materials have a very high ion exchange capacity and are usually closely bound to clay particles. Clays have an ion exchange capacity of their own, they derive their ion exchange capacity from the basic silicate structure

which acts like a Lewis acid (Durrant and Durrant, 1962). Note that the basic unit contains excess oxygen atoms which are able to form chains, sheets or three-dimensional networks. End groups in such networks provide cation vacancies. Such complex silicates behave as ionic exchangers for metal cations. Multivalent cations attached to silicates can also provide sites for attachment of anions such as arsenites, sulfates, cyanide, and carbonates and hydroxide ions.

Organic polyacids such as humic and fulvic acids, formed from the decay of plants, are highly functionalized and act as ion exchangers in soil, their ion exchange capacity is even greater than vermiculite, the most effective of the clays. Stevenson and Ardakani (1972) have described the attachment of humic acid molecules to clay particles by hydrogen bonding and metal–humate–clay site interactions.

The ion exchange capacity of the combined clay–humate is lower than the sum of the contributions of clay and humates in soil due to these interactions. The metal–humate and metal–clay interactions are sensitive to H^+ ion. At pH 7 the concentration of H^+ is too low to significantly affect interactions between ion sites on the soil and protons in the water. This explains why washing soil with water as a remediation technique for contaminated soil and clay is ineffective.

5. The interaction of electrochemical and electrokinetic phenomena

When anodes are placed in soil and a direct current applied between the electrodes, the amount of available H^+ is raised significantly. The ion travels much faster than other ions and carries a disproportionate share of the total current. The understanding of ion transport and ion mobilities (that is, classical electrochemical phenomena) applies to the movement of ions in soil as it does in liquid electrolytes, except for one major difference: ions interact with ion exchange sites on the soil and their progress is modified by this (Ho et al., 1994).

Although the presence of particles and the difference in path length due to the tortuous route taken by ions will affect the values of ion mobilities in water, the differences in mobilities between the various ions still hold. Hydrogen ion moves under the potential gradient between the electrodes pairs almost twice as
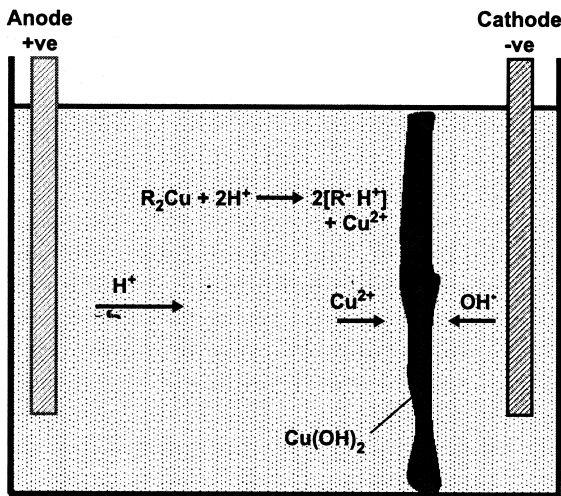
Anode
+ve

Cathode
-ve

Fig. 1. Unmanaged electromigration of copper ions in a typical top soil, resulting in precipitate of $Cu(OH)_2$.

fast as hydroxyl ion and significantly faster than metal ions. In soil, however, the hydrogen ion is quickly mopped up by the ion exchange sites on the soil, leading to displacement of the metal ions into the electrolyte. Even if the soil picks up the metal ion on a new ion exchange site, there is a net drift towards the cathode as the ion exchange sites are filled by protons emanating from the anode. Metal ions will be in equilibrium with other available sites on the soil in front of the proton sweep.

In unmanaged electrolysis, a similar but slower drift of hydroxyl ions moves from the cathode displacing anions adsorbed onto the soil particles. Free anions in the water electrolyte will be in equilibrium with available sites on the soil. Note however that these sites are in competition with OH^- created at the cathode and so there will be a net drift of displaced anions to the anode due to electromigration.

In a demonstration of this phenomena referred to above, a sample of top soil was doped with cupric sulfate at about 1000 mg/kg dry soil. This was then placed in a soil container with Ebonex™ anodes and cathodes placed in wells either side of a 10-cm-wide compartment. A DC current was passed for 24 h with no attempt to modify the electrolyte pH in either anolyte or catholyte chambers. The copper front precipitated about 2/3 of the way across the soil towards the cathode. Fig. 1 shows this graphically.

When the experiment was repeated with the catholyte made slightly acidic to counter the production of hydroxyl ions, the copper front passed into the catholyte (Fig. 2).

The first part of this experiment, where the electrolyte was not modified to prevent the hydroxyl front advancing from the cathode (Fig. 1), although more sophisticated, repeats the observations made by Ryss and Goldberg (1973). The second part of the experiment (Fig. 2), where the electrodes are placed in special filters and the pH and speciation is controlled, is a demonstration of the electrolyte management
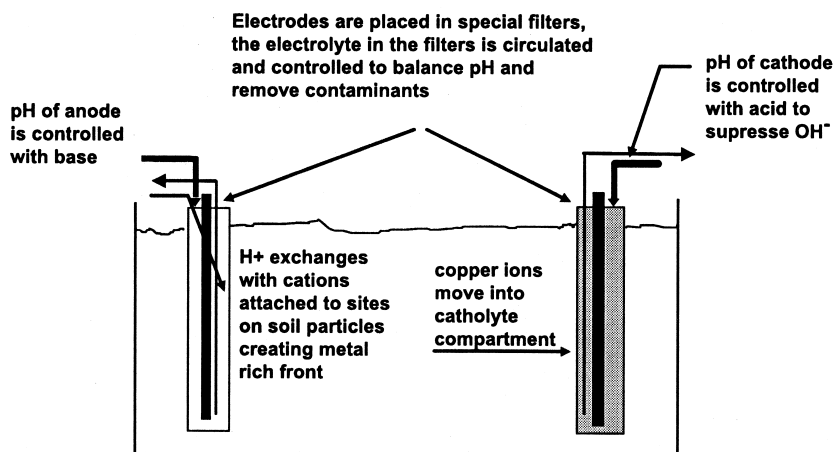

Fig. 2. Electromigration of copper ions in a typical top soil using patented electrolyte management and control, which does not result in precipitation of $Cu(OH)_2$.

technique, patented in 1987. The complete experimental sequence shows that:

(i) hydrogen ions will readily displace heavy metals from soil (confirming the work of Stevenson).
(ii) putting electrodes directly into soil will fail, as found by earlier workers.
(iii) managing the electrolyte is essential, in fact it is a "conditio sine qua non".

Electromigration will occur with any species which will form ions in aqueous environments, thus the process can be applied to contaminants such as:

(i) inorganic anions and cations;
(ii) organic carboxylic acids, phenols;
(iii) sulfonated aliphatic and aromatic compounds like some dyestuffs;
(iv) detergents and some pesticides like paraquat and diquat.

Large, moderately polar molecules will also transport, but very slowly under electrophoretic mechanisms.

6. Electrokinetic technology in practice

Recovery of ionic contamination from ground and groundwater is limited by the fact that soil is a powerful ion exchange media. Ionic contamination becomes adsorbed on soil particles following contact. Flushing alone will not recover it. A pH shift must be applied to desorb and mobilize it. However, flushing with strong acids usually destroys the basic soil structure.

Our technology was developed to address these issues in an elegant and practical manner. Moreover, it avoids denuding or destroying the soil structure. The key elements are as follows:

(i) Ion-permeable electrolyte casings are placed in the contaminated media and connected to a centralized electrolyte management system (EMS). Each casing has an electrode inside. Together, these form alternating rows of anodes and cathodes. Electrolyte is circulated in a closed loop between the electrode casings and the EMS.
(ii) The electrodes are then energized. Electrolysis of water in the electrolyte results in the formation of H^+ ions at the anodes and OH^- at the cathodes. These ions are then made to migrate through the casing into soil to generate a temporary and localized pH shift which desorbs contaminating ions.
(iii) Once desorbed, the contaminating ions migrate under the influence of the applied potential (electromigration) to their respective electrodes (anodes for anions, cathodes for cations). Here they pass through the electrode casing walls and are taken up by the circulating electrolytes.
(iv) Careful management of the pH and other electrolyte conditions within the electrode casings is the critical element in controlling system performance.
(v) Contamination is recovered from the circulating electrolytes, either by precipitation and filtration, by electrochemical ion exchange (EIX), or other ion collecting systems.

6.1. Deployment options

Electrokinetic remediation can be deployed in four separate ways:

(i) *In situ*. Electrodes are placed directly in the ground and contamination is recovered with minimal disturbance to the site. Electrodes can also be placed inside or underneath buildings. One example of this deployment is an ongoing electro-reclamation project at a galvanizing facility at 's Heerenberg in the eastern part of the Netherlands (Lageman and Pool, 2001). Here four rows of electrodes have been installed inside the plant, in between the production lines. Only during installation the production had to be temporarily halted. All electrodes, electrical cables and ducts and pipes of the electrolyte management system have been installed underneath or flush with the plant floor to avoid any hindrance in plant operations.
(ii) *Batch*. In this configuration, contaminated media is transported to a mobile batch facility

or a temporary lagoon and treated ex situ. This process has been operated at 2 and 7400 m³ in size (Lageman, 1993).

(iii) *Electrokinetic fence (EKF)*. This uses a chain of electrode pairs deployed in the ground to halt the migration of contaminated groundwater from a point source.

(iv) *Electrokinetic biofence (EBF)*. Besides the chain of electrodes, a row of filters with nutrients is placed upstream of the electrodes. Groundwater transports the dissolved nutrients towards the electrodes. Under the influence of the electrical field, the electrically charged nutrients are dispersed homogeneously between the electrodes, enhancing biodegradation.

6.2. Cost and maturity

The cost of each remediation project depends upon the concentration, surface area, depth, type of pollutant and type of soil. These are factors we cannot control. Controllable factors are the cost of the electrodes, well structures, hole drilling, installation and process operation and control. Here we have developed reusable systems and minimized the size of and number of holes required for a given site size. We have developed power control systems for alternating current (AC) and DC operation and the plcs to monitor drive and control them. The integration of these technologies allows our process to be fully automated. In turn, this gives us low operating costs and the capability of remote operation in hazardous environments.

6.3. Some project results of inorganic contaminants

See Table 1 for a list of results.

7. Electro-bioreclamation

Since 1994, we have developed and fully commercialized electro-bioreclamation. With more than 15 commercial projects completed, we have shown that we have a very cost-effective and rapid treatment system for volatile organics, semi-volatile organics, dense non-aqueous phase liquids (DNAPLs), heavy fuel oils, creosote and polycyclic

aromatic hydrocarbons (PAH). This technique uses Joule heating of the soil with AC or DC currents. Note that the soil is evenly heated as the soil itself is the resistor. Soil is an excellent heat insulator and retains more than 95% of the heat. Unlike steam-heated soil vapour extraction, it does not sterilize the natural bacteria or over-saturate the soil locally. Electrical heating is combined with soil vapour and groundwater extraction technology and nutrient injection. We have deployed our process outside, inside and beneath buildings and structures up to 12 m below ground surface (bgs), and have completed remediation work during extensive building projects (Lageman and Pool, 2001).

7.1. Technology description

Soil which is contaminated with heavy organics, such as weathered fuel oil, mixtures of petroleum-based fluids and diesel oil and many solvents can be treated by this technique. The composition of the contamination, together with the adsorption of compounds within the soil, the presence of colloidal suspensions and oil in water and water in oil phases means that current solitary decontamination methods, such as vacuum extraction and/or pump and treat methods do not achieve the desired results. We have therefore developed a method which deals with the problems of volatility and desorption. This may not seem like electrochemistry but the management of the electrodes requires that electrochemical techniques are deployed at the electrode electrolyte interfaces otherwise the process rapidly closes down. Calculations undertaken using the "HyperVentilate" computer program (Johnson et al., 1990; Johnson and Stabenau, 1991) clearly indicate that increased soil and soil air temperature speeds up the decontamination process appreciably. To heat the soil, electrodes are inserted into the ground in a fixed pattern. In general, the electrodes are placed so that they coincide with the lowest point at which groundwater decontamination is to take place.

The extraction well is located centrally between the electrodes. This well is used both for extracting groundwater and soil air. The electrodes are connected to a generator or electrical source and the extraction well is connected to a vacuum blower and a groundwater pump.

Table 1
Some completed and running projects of inorganic contaminants

Project	Volume (m³)	Start (mg/kg)	End (mg/kg)	Notes
Former paint factory, Groningen	300 peat/clay soil	Cu>5000, Pb>500–1000	Cu<200, Pb<280	First electro-reclamation pilot project. In 1987.
Galvanizing plant, Delft	250 clay soil	Zn>1400	Zn 600	In situ electro-reclamation of area outside of operational plant.
Former timber impregnation plant, Loppersum	300 heavy clay soil	As>250	As<30	In situ electro-reclamation at the site of a former timber impregnation plant. After remediation site became residential area.
Temporary landfill, Stadskanaal	2500 agrillaceous sand	Cd>180 (also Pb, Zn, CN)	Cd avg. 11	Ex situ electro-reclamation in two batches. Goal was to reduce Cd to <10 ppm. Total remediation time 2 years (1990–1992).
Military airbase, Woensdrecht	3500 clay soil	Cr 7300, Ni 860, Cu 770, Zn 2600, Pb 730, Cd 660	Cr 755, Ni 80, Cu 98, Zn 289, Pb 108, Cd 47	Ex situ electro-reclamation in temporary landfill. Goal was to reduce Cd to <50 mg/kg. Total remediation time 2 years (1992–1994).
Batch test Hallschlag	40 loamy soil	TNT 49, DNT 188, DNB 553, PAH 40, Org. As 11	TNT 10, DNT 3.3, DNB 6.8, PAH nd, Org. As 0.1	Ex situ electro-reclamation test with soil from an old World War I munitions factory in Germany (which exploded in 1918). During the test nutrients were added to enhance biodegradation
Kapelle	130 clay soil	CN 120, PAH 45	CN 18, PAH 2	Pilot project ex situ batch electro-reclamation during 12 weeks.
Former gaswork at Oostburg	120 clay and sandy clay soil	CN 930	28	Pilot project in situ electro-reclamation, partly underneath building. Depth up to 4 m bgs. Duration 3 months. Removal percentages varied from 83% to 97%.
Operational galvanizing plant at 's -Heerenberg	4300 sandy loam and silty sand	Ni 1350, Zn 1300, groundwater, Ni 3500 µg/l	Ni 19[a], Zn 82[a], groundwater, Ni 15[a]	In situ electro-reclamation project, inside production plant, started at the beginning of May 2003. Depth up to 6 m bgs. Project is scheduled for 2–2.5 years (2003–2005).

[a] Target values.

The air which is extracted is cooled and then passed through scrubbers to prohibit any leakage of vapour to atmosphere. The groundwater which is extracted is also purified and in some cases returned to the soil via a return system.

Apart from these physical/chemical effects of electrical heating, temperature increase has a pronounced and positive effect on biodegradation. Earlier expectations, predicting adverse effects when increasing temperature above 30–40 °C, have not been observed. On the contrary, investigations during gradual heating of the soil up to 80 °C over a period of 6–8 weeks showed abundant biological activity, even at these relatively high temperatures. At temperatures of 70–80 °C, thermophylic bacteria populations are observed at significantly higher levels than are active at temperatures of 20–30 °C. After closing down the electrical system, these populations can be observed adapting again to the changing (cooling) temperature conditions. Biodegradation is once more accelerated by periodic injection of nutrients (nitrogen, phosphorus), and, depending on the type of contamination, carbon sources, oxygen and/or electron donors or acceptors. Results of finished and ongoing electro (bio)reclamation projects at sites contaminated with

Table 2
First order biodegradation constants without (1) and with (2) Electro-Bioremediation

	k_1	k_2	k_3	k_4
PCE	➡ TCE	➡ Cis-DCE	➡ VC	➡ Ethene

'Normal' conditions(1)	Enhanced conditions(2)
k1 = 0.0023	k1 = 0.221 – 0.361
k2 = 0.0033	k2 = 0.193 – 0.317
k3= 0.0038	k3 = 0.051 – 0.09
kK4 = 0.0015	k4 = 0.0062 – 0.051

volatile organic compounds (VOCs) have shown that first-order biodegradation constants which were initially used for estimation of total remediation time increased one to two orders of magnitude (Table 2).

In practice, electro-bioreclamation of organic contaminants has led to the following phased remediation approach (Table 3).

Table 3
Remediation phases during Electro-Bioreclamation

| (1) Intensive phase	AC-heating of soil and groundwater in areas with high concentrations (free product zones and hotspots). Direct heating of the saturated zone and indirect heating of the unsaturated zone (capillary fringe and smear zone) by rising heat from the saturated zone. Heating is combined with groundwater and soil vapour extraction and periodical injection of nutrients, carbon sources, oxygen and/or electron donors/acceptors, depending on the nature of the pollutants.
(2) Extenuate phase	During this phase attention is focused on biodegradation in the remaining source areas and adjoining groundwater plumes. Electrical heating is stopped. Groundwater and soil vapour extraction continue as well as periodical injection of nutrients oxygen and/or electron donors/acceptors and carbon sources.
(3) Monitoring phase	Monitoring and control on the basis of periodic sampling and analyses, if clean-up criteria have not yet been met completely or there is risk of possible recontamination.

Efficiency Electro-Bioreclamation
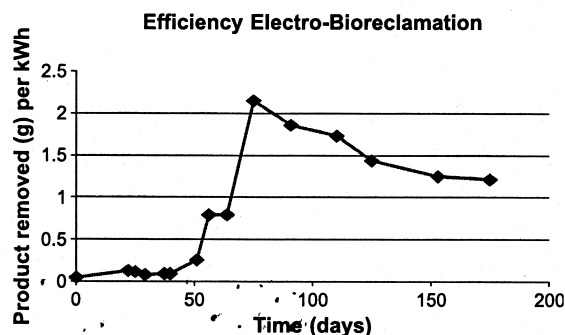
Fig. 3. Efficiency curve during intensive phase of electro(bio)-reclamation of PCE contamination. During first 50 days, remediation efficiency is low. After 50 days efficiency increases dramatically as a result of desorption and mobilization of PCE. After 80 days, no free product is left and the amount of dissolved PCE removed against the costs of electricity result in a downward slope of the efficiency curve. That is the moment to shift to the extenuate phase.

The execution of the different phases depends on the results of the foregoing ones. Changing from one phase to the other also depends on the so-called efficiency profile(s) of the remediation, as pictured in Fig. 3. Electro-bioreclamation is particularly suited to clean-up "hotspots" during the intensive remediation phase, creating optimal conditions for a subsequent second phase of extenuate remediation or stimulated natural attenuation.

7.2. Some project results of inorganic contaminants

See Table 4 for a list of results.

8. Conclusions

In this paper, we have tried to show the method and scope of electro-remediation as it stands today, a combination of techniques having electricity as the common denominator. For electro-reclamation of inorganic contaminants, the essential steps are control and management of the circulating electrolytes and selecting the appropriate method for each contaminant type. For electro-bioremediation of organic contaminants, the essential steps are management and control of electrical heating, management and control of the rate of groundwater pumping and soil vapour extraction and a thorough

Table 4
Some completed and ongoing projects of organic contaminants

Project	Contaminants/Lithology	Notes
Former industrial site at Vorden	Diesel fuel and aromates, fine sand	First electro-bioreclamation pilot project. In 1993. Clean-up of 5000 m^3 ground and groundwater up to 6 m bgs. Initial load 25,500 kg. Product removed 23,500 kg.
Waterlooplein in Amsterdam	Heavy fuel oil, clay and sand	In situ electro-bioremediation underneath "Saskiahuis" in the center of town
Pipe coating company at Maassluis	Mineral oil, sandy loam and clay	In situ electro-bioremediation of 1500 m^2 ground and groundwater inside production plant within 1.5 years
Commune for physically and mentally handicapped people at Woudenberg	Fuel oil, fine sand and clay layers	In-situ electro-bioremediation of 950 m^3 ground and groundwater. Initial load of 9000 kg reduced to 1200 kg during Intensive phase of 378 days. Another 1000 kg 1000 kg removed during extenuate phase of approximately 1 year.
Former silver factory at Nieuwpoort	VOCs, peat, sand and clay	In situ electro-bioremediation of 12,500 m^3 ground and groundwater contaminated with VOCs. Intensive phase size 4800 m^3, duration 2 years. Extenuate phase 7700 m^3 during 2–2.5 years. Remediation depth 12 m bgs. Target values reached after 4.5 years. >100 kg of free product has been removed.
Network office building at Hilversum	Fuel oil, sand	In situ electro-bioremediation in between and partly underneath office buildings up to 9 m bgs. Product removed 450 kg. Target values reached after 7 months.
Former gas station and fuel storage facility at Horst	Diesel oil, gasoline, fine sand and clay layers	In situ electro-bioremediation up to 8 m bgs. Intensive phase: size 4600 m^3, heating up to maximum of 94 °C. After 1.5 years 21 m^3 of free product removed. After cooling down, removal during extenuate phase of another 2 m^3 by enhanced biodegradation during the following 2–3 years.
Farmland near Maasdam	Aromates, silty, loam, clat	In situ electro-bioremediation of 11,500 m^3 of ground and groundwater on farmland contaminated with gasoline. Calamity whereby 50,000 l were sprayed over the land, covering an area of 3000 m^2. Intensive phase: Within 80 weeks target values for soil and groundwater were reached.
Former silver factory at Zeist	VOCs, sand and clay	In situ electro-bioremediation up to 5 m bgs, at the site of a former silver factory at Zeist, presently a residential area. Site had already been remediated (excavation) by 3rd party, but ongoing pump and treat was not successful. Intensive phase: size 1080 m^3, duration 2–3 years (2000–2003). Extenuate phase: size 7200 m^3, duration 2.5 years (2003–2005). All field equipment has been installed underground. No hindrance for the residents.
Petroleum harbour at the Hague	Mineral oil and aromates, sand, peat clay	Removal of 76 underground tanks, excavation of 30,000 m^3 of soil. Off site transport of 10,000 m^3 of soil contaminated with mineral oil and aromates >10,000 mg/kg. Relocation of 20,000 m^3 soil at the site and in situ bioremediation of 10,000 m^3 contaminated <10,000 mg/kg.
Former industrial site at the Hague	VOCs, heavy clay and peat	Excavation, off site transport and biological clean-up of 4000 ton soil, contaminated with VOCs
Existing galvanizing plant at Temse (Belgium)	Chromium and VOCs, fine sand, loam and clay	Combined in situ electro-reclamation of chromium contamination and electro-bioremediation of VOC-contamination underneath galvanizing plant

insight into the biological boundary conditions for each contaminant type. Electrokinetics is not a "be all and end all" for soil remediation, but it is a set of very powerful tools that can remediate land and groundwater completely for any subsequent use. The development of the technology is still work in progress, e.g. improvements on process control and process assessment, efficient use and reuse of surfactants, optimization of current control per electrode, treatment of electrolytes, and pressurized electrolyte circulations systems.

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