

Electrokinetic Remediation in Practice

Experiences with Field Applications

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1. Introduction

Electro-reclamation (ER) is a soil remediation technology that uses electrokinetic effects to remove inorganic contamination. It can, for example, be used to remove heavy metals, all types of cyanides, arsenic and other ionic or polar compounds. The basic principle involves applying a difference in potential, thus causing charged particles to migrate to the cathode or the anode. A special electrolyte system is used to both condition physical parameters around the electrodes and in the soil, and to remove the contaminants that have collected around the electrodes.

Applying this soil remediation technology requires special expertise; this chapter describes the technology and its applications, indicating the materials and decontamination methods that can be used and how the system should be initiated and controlled. It also specifies the samples that need to be taken in order to monitor the decontamination process. Before remediation can commence, however, it is first necessary to clarify where contamination is present in the area of soil concerned and in what form. It is furthermore necessary to perform electrokinetic laboratory tests with one or preferably more representative soil samples. Finally it is explained how the data are analyzed and used for carrying out the design of the remediation system.

2. Electro-reclamation

2.1. Principle and Fundamentals

Electro-reclamation belongs to the group of so-called physicochemical remediation technologies. Under the influence of an electric field, a number of electrokinetic phenomena occur:

1. Electromigration or the movement of ionic species in pore water or groundwater.
2. Electroosmosis or movement of water from anode to cathode.
3. Electrophoresis or movement of charged particles.

In the following sections, these phenomena will be described in more detail. 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 equation 1.



At the anode or positive electrode, electrons are being stripped from water molecules oxygen is evolved and protons, H^+ are formed and 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).



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, however, 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.

2.1.1. Soil as an electrolyte

Most soils are conductive due to the presence of dissolved ions, such as calcium, magnesium, sodium, potassium, (bi) 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 (table 1).

Clay Mineral	CEC (m.eq/100 g)
Kaolinite	3 - 15
Illite	10 - 40
Chlorite	10 - 40
Montmorillonite	60 - 120
Vermiculite	100 - 160

Table 1. Cation Exchange Capacity (CEC) of some clay minerals. Kaolinite is widely used for electrokinetic laboratory experiments, but because of the low CEC or buffering capacity, the results are of no great practical value as Kaolinite occurs in abundance only in soils that have been formed in hot moist climates, e.g. tropical rainforest areas. Note: there are no data available in literature for Anion 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. These materials have a very high ion exchange capacity and are usually closely bound to clay particles. Clays have ion exchange capacity in their own right, they derive their ion exchange capacity from the basic silicate structure, which acts like a Lewis acid. 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.

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.

2.1.2. The interaction of electrochemical and electrokinetic phenomena

When anodes are placed in soil and a direct current is passed between them, 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. 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

holds. For ion the average mobility amount to $5 \cdot 10^{-8} \text{ m}^2/\text{U.s}$, where U = drop in potential in Volts (table 2).

Cations	Mobility ($10^{-8} \text{ m}^2/\text{V.s}$)	Anions	Mobility ($10^{-8} \text{ m}^2/\text{V.s}$)
H ⁺	32.7	OH ⁻	18
Li ⁺	3.4	F ⁻	4.9
Na ⁺	4.5	Cl ⁻	6.8
K ⁺	6.6	Br ⁻	7.0
Cs ⁺	7.0		6.9
NH ⁺	6.6	I ⁻	6.4
Ag ⁺	5.6	NO ₃ ⁻	3.6
½ Mg ²⁺	4.6	CH ₃ COO ⁻	2.9
½ Ca ²⁺	5.3	C ₃ H ₇ COO ⁻	7.0
½ Ba ²⁺	5.7	½ SO ₄ ²⁻	6.2
½ Pb ²⁺	6.4	½ CO ₃ ²⁻	3.6
		1/3 Fe(CN) ₆ ³⁻	10.5
		¼ Fe(CN) ₆ ⁴⁻	9.8

Table 2. Average ion mobilities in aqueous environment, found in literature

Along the gradient in potential between the electrode pairs a hydrogen ion moves almost twice as fast ($33 \cdot 10^{-8} \text{ m}^2/\text{U.s}$) as hydroxyl ion ($18 \cdot 10^{-8} \text{ m}^2/\text{U.s}$) and 5 to 6 times faster than metal ions. In soil however, the hydrogen ion is quickly mopped up by the ion exchange sites on the soil particles; as a result, the metal ions are displaced 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 fill up 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. The effective ion mobility in soils is therefore much lower than in liquid solutions (table 38. 3).

Cations	Average Mobility ($10^{-8} \text{ m}^2/\text{V.s}$)	Range ($10^{-8} \text{ m}^2/\text{V.s}$)	Anions	Average mobility ($10^{-8} \text{ m}^2/\text{V.s}$)	Range ($10^{-8} \text{ m}^2/\text{V.s}$)
½ Cd ²⁺	0.28	0.16 – 0.41	1/3 As ³⁻	0.14	0.05 – 0.5
½ Cr ²⁺	0.25	0.07 – 0.55			
½ Cu ²⁺	0.26	0.05 – 0.54			
½ Pb ²⁺	0.30	0.15 – 0.56			
½ Ni ²⁺	0.16	0.09 – 0.18			
½ Zn ²⁺	0.27	0.04 – 0.55			

Table 3. Effective ion mobilities in the soil during electro-reclamation

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 compete with OH^- created at the cathode and so there will be a net drift of displaced anions to the anode due to electromigration.

As a result, the soil acidifies from the anode into the direction of the cathode and if no measures are taken, practically all the energy will be used for the transport of H^+ ions. Likewise there is increased alkalinity into the direction of the anode, ultimately leading to precipitation of metal hydroxides in the soil (figure 1).

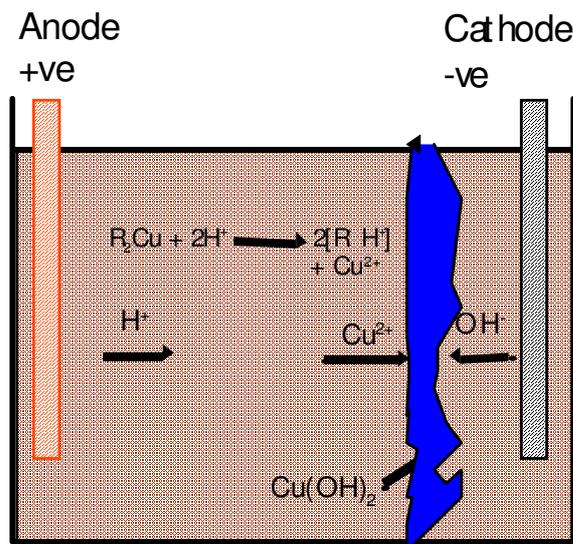


Figure 1. Precipitation of $\text{Cu}(\text{OH})_2$ due to pH increase near the cathode

Electromigration will occur with any species that will form ions in aqueous environments. The process can therefore be applied to contaminants such as:

- Inorganic anions and cations.
- Organic carboxylic acids, phenols.
- Sulfonated aliphatic and aromatic compounds like some dyestuffs.
- Detergents and some pesticides like paraquat and diquat.

2.1.3. Electroosmosis

Electroosmosis is the movement of pore water or groundwater under the influence of a DC field. With electroosmosis the direction of flow is from anode to cathode. In some cases one can also observe a flow direction from cathode to anode. This phenomenon is known as electro-endosmosis. Electroosmosis is determined by the following factors:

- The mobility of the ions and charged particles present in the pore fluid, including those ions and particles entering into the pore fluid via ion exchange.
- The hydration of ions and charged particles present in the pore fluid.
- The electrical charge and direction of movement of ions and particles, resulting in a net water transport.

- The ionic strength or ion concentration.
- The viscosity of the pore fluid.
- The temperature.
- The soil porosity.

Note that the volume of water removed per unit of time is directly proportional to the electrical power used per unit of volume of removed water. Thus, the faster the water transport, the more power is necessary to remove the same volume of water.

2.1.4. Electrophoresis

Electrophoresis, or cataphoresis, is to do with the movement of particles under the influence of a DC field. The term "particles" includes all charged particles like colloidal, clay and organic matter particles suspended in the pore fluid. The movement of these particles is similar to the movement of ions. In the pore fluid of clay soils, the particles participate in the transfer of electrical charges and influence the electrical conductivity and the electroosmotic flow.

Clay minerals can polarize in two ways. The first is the permanent dipole moment, which results from the structure and depends on the atomic masses. Its is oriented parallel to the long axis of the clay particles. The second polarity is perpendicular to the first one and is a result of the external electrical field. It depends on the polarization capacity of the electrical double layer. Thus, the mobility of clay particles depends on the combined action of these two moments and is therefore low, varying between $1 \cdot 10^{-10}$ and $3 \cdot 10^{-9}$ m²/U.s.

2.2. Practical realization

2.2.1. Electrodes and electrolyte management system

The key elements of an electrokinetic installation are as follows (figure 2):

- Ion-permeable electrolyte wells are placed in the contaminated medium and connected to a centralised electrolyte management system (EMS). Each well has an electrode inside. The result is alternating rows of anodes and cathodes. Electrolytes are circulated in a closed loop between the electrode wells and the EMS. Via these electrolytes, pH is maintained at a predetermined value. The electrodes are then energised. The water in the electrolytes is electrolysed, forming H⁺ ions and O₂↑ at the anodes, and OH⁻ ions and H₂↑ at the cathodes. These ions are then made to migrate through the casing into soil to generate a temporary and localised pH shift, which desorbs the contaminating ions. No acids are pumped directly into the soil.
- Once desorbed, the contaminating ions migrate to their respective electrodes, under the influence of the potential applied (electromigration). The anions migrate to the anodes, the cations to the cathodes. Here they pass through the electrode well screen and are taken up by the circulating electrolytes.
- Critical for the control of system performance is the careful management of the pH and other electrolyte conditions within the electrode casings.
- Contaminants are recovered from the circulating electrolytes by both precipitation and filtration, by electrochemical ion exchange (EIX), or by other ion-collecting systems.

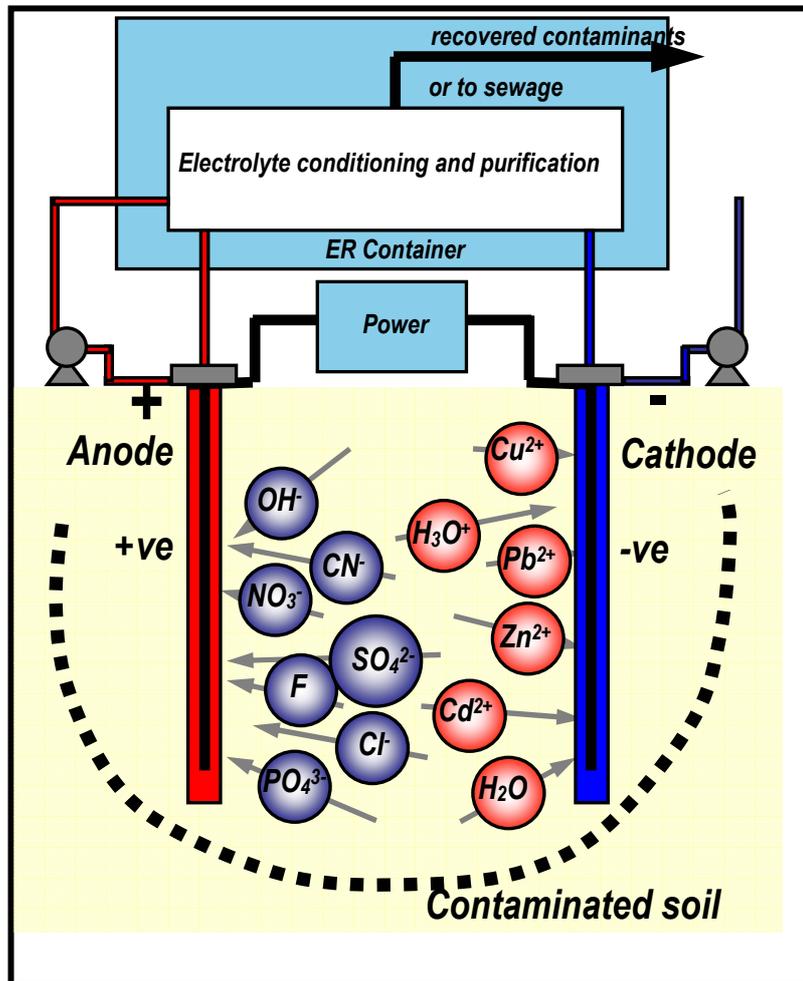


Figure 2. Schematic in-situ field set-up of Electro-reclamation

2.2.2. Electrolyte purification

When the electrical conductivity of the electrolytes has reached approximately 20 S/m, the electrolytes are pumped into a connected treatment installation. Depending on the type of contaminants, they are treated:

- With lye (NaOH), to precipitate metal hydroxides, which are then removed by filter press. The amount of filter cake produced depends not only on the concentrations of the heavy metals but also on concentrations of iron, alkaline earth and alkaline ions, carbonate, bicarbonate, magnesium etc. As a rule of thumb, 0.05 to 0.1% of the total volume of treated soil is ultimately collected as waste.
- By ion exchange through resins or electrochemical ion exchange (EIX[®]), a process developed by AEA Technology (Harwell) that uses electrochemically driven adsorption and desorption to remove ions from dilute electrolytes
- By using a so-called EnViroCell[®] for specific heavy metals and cyanide.
- The electrolyte management and purification systems are housed in containers, together with the electrical power supply. If necessary, electricity cables and circulation ducts and pipes can be installed underground.

2.3. Application area

Electrokinetic remediation can be deployed in four separate ways:

1. In-situ (figure 2). A network of electrode casings is placed directly in the ground, covering part - if the total area is too large to be remediated in one go - or the whole of the contaminated area. The distance between electrodes of both equal and opposite charge depends on site-specific conditions but, in general, amounts to 1.5 or 2 m. Contamination is recovered with minimal disturbance to the site. Electrodes can also be placed inside or underneath buildings, either vertically or horizontally.
2. Batch. In this configuration contaminated soil is transported to a mobile batch facility or a temporary lagoon and treated ex-situ (figure 3). This process has been operated at 2 m³ and 7400 m³ in size.
3. 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.
4. 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.

The technology is applicable for diffusely dispersed pollutants both in the non saturated and saturated zone and in clay, sand, and peat soils. Contaminants which can be recovered by electro-reclamation can be heavy metals, arsenic, nitrates, phosphates, halogenides, and polar and/or water soluble organic compounds such as cyanides, phenols, and nitro aromatics (such as TNT). Minimal moisture content should be 15% to 20%. Not economically applicable to heavy metals in metallic form, such as metal grindings, slag and cinder, concretions, and paint particles (putty).



Figure 3. *Electro-reclamation of cadmium polluted soil in a temporary lagoon*

2.4. Combination with other Technologies

The technology can be combined with electro-bioreclamation for removing cocktail of inorganic and organic compounds.

2.5. Supplementary provisions

Availability of an electric power supply is a prerequisite. If no connection via the grid is possible, a generator can be used. Because of the high noise levels, a generator can only be deployed outside residential areas. Temperatures > 40 °C can have an adverse effect on some coatings of subsurface cables. The presence and location of these cables must be known so that they may be insulated. Cathodic protection of subsurface metal cables, pipes, and objects such as tanks may be necessary, when they are directly in the electric current zone.

2.6. Remediation time

The remediation time is dependent on the nature, concentration, and extent of the pollution and the capacity of the remediation equipment. More extensive polluted sites are cleaned up in sections. Cleanup duration varies from a few months to several years.

3. Investigation and design of Electro-reclamation

3.1. Laboratory and field tests

The design and dimensions of the electro-reclamation system to be deployed at a site are based on and derived from the data collected during the preceding investigations and one or more electrokinetic laboratory tests. If possible, some electrical resistivity soundings should be performed on the site in order to measure the electrical resistance of the ground.

3.1.1. Laboratory tests

Electrokinetic laboratory tests are done on soil samples from the site, preferably taken at the contamination hotspots, i.e. the locations with the highest concentrations of contaminants. The client can choose between two separate or combined test configurations:

1. Turbo test, which requires a soil sample of 4 - 6 kg or
2. Standard test, which requires a soil sample of 10 - 15 kg soil.

For both tests, the soil samples are homogenised and analysed for their heavy metal content, pH, iron, Ca, Mg, Na, Cl, and clay and organic matter contents. Before the tests start, the cation exchange capacity (CEC) of the soil is determined, using a buffer test.

3.1.2. C.E.C. and A.E.C. test

The method used to find the CEC (Cation Exchange Capacity) or AEC (Anion Exchange Capacity) indicates the total amount of exchangeable cations or anions. Cations could be alkaline earth and alkaline, metals, and organic complexes. Anions comprise e.g. cyanides, arsenic etc. The purpose of the CEC test is:

- To get information of the buffer capacity of the contaminated soil
- To get information of the amount of energy or acid needed to lower pH to an optimum value to mobilize the contaminants. The pH change is effectuated by protons which

are generated at the anodes and which are needed to lower pH to an optimum level. It can be calculated in Faraday (A.s).

- The purpose of the AEC test is:
- To get information of the buffer capacity of the contaminated soil
- To get information of the amount of energy or lye needed to increase pH to an optimum value to mobilize the contaminants. The pH change is effectuated by hydroxyl ions which are generated at the cathodes and which are needed to increase pH to an optimum level. It can be calculated in Faraday (A.s).

The method is as follows: several 50 ml volumes of demineralised water are acidified with hydrochloric acid or another acid, depending on the contamination, to different pH levels, and then mixed with 10 g (dry matter) of the sample. After thorough mixing for 24 hours, the mixture is left for a time, to settle out, and then the pH of the solution on top of the sample material is determined. The results are generally presented in a diagram, where pH of the solution is plotted as a function of the mill equivalent H^+ added per kg dry matter (Figure 4).

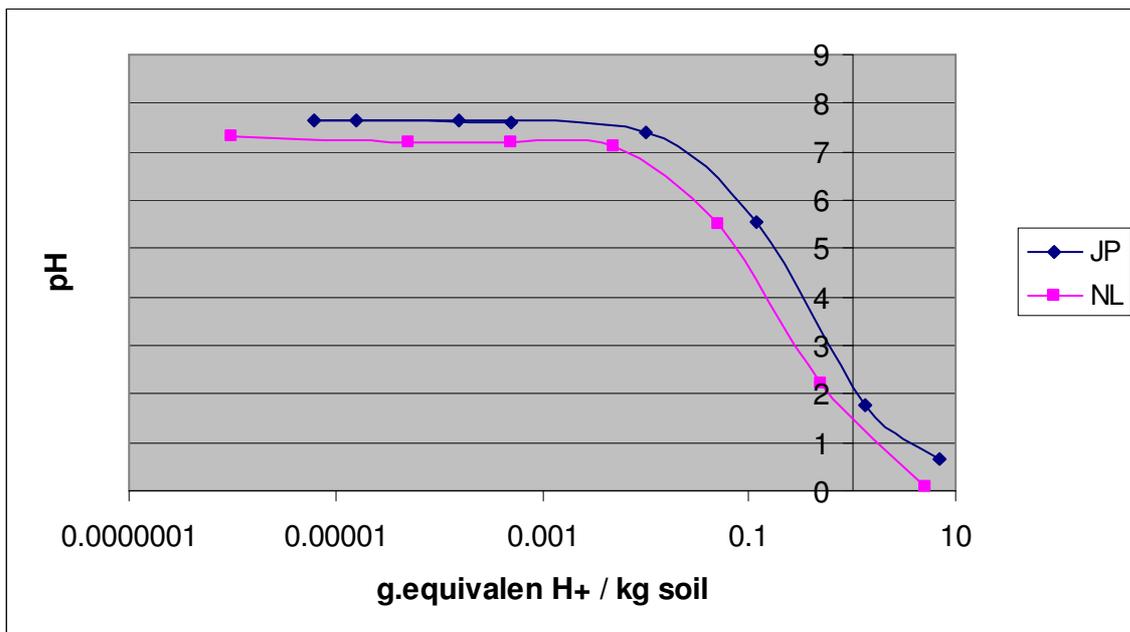


Figure 4. Graphic representation of CEC test in Japan (JP) and in Netherlands (NL)

3.1.3. Turbo test.

In the turbo test (figure 5) the soil material is divided equally between several small containers, each of which is given a different energy supply and/or electrolyte solution (different inorganic or organic acids). This kind of test is used if data about the origin and type of contaminants is scanty or not available, or the client wants to have a quick scan of the possibilities of deploying electro-reclamation. It gives less accurate data on energy requirements and remediation time, but indicates whether the contaminants can be mobilised at all, using a specific kind of electrolyte solution.

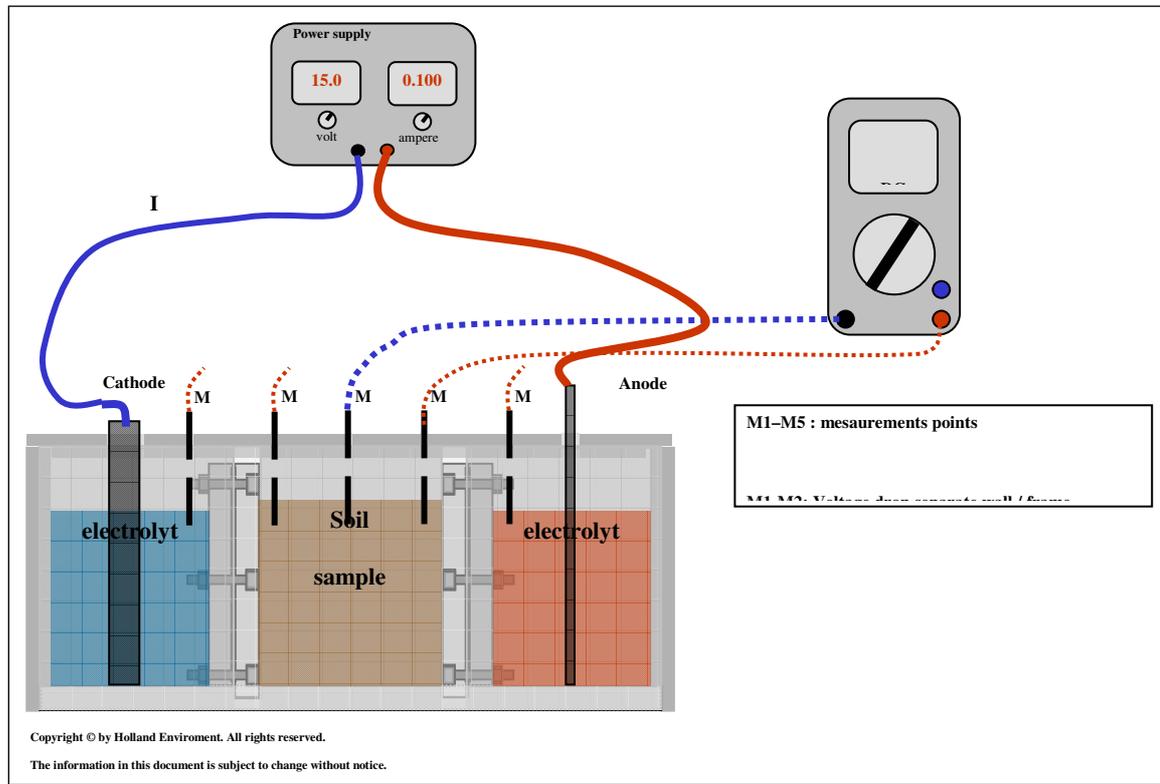


Figure 5. Set-up of Turbo Test

A turbo test lasts 2 to 4 weeks. The time can be shortened to one week if high current densities are used. Each container is sampled once at the end of the test. Five samples for analysis are taken from each soil compartment: anode side, anode middle, middle, cathode middle and cathode side. Precipitates are prepared from both the cathode and anode compartments and are analysed.

3.1.4. Standard test

In the standard test, all soil material is treated in one laboratory set-up. This set-up is used when the client has supplied ample data on the origin of the sample and its contaminants. This kind of test gives accurate data on energy requirements and remediation time. The most reliable results are obtained when the two tests are combined: a turbo test followed by a standard test run using the electrolyte solutions that came out best during the turbo test.

A standard test lasts about 8 to 10 weeks. Sampling frequency is 1 week. At the time of analysis, five samples are taken and analysed: anode side, middle, and cathode side, and precipitates in the cathode and anode compartments.

3.1.5 Test Results

The electrokinetic laboratory tests are finalised with a report. This presents relevant data, such as sample preparation, analysis results, concentration decrease, type of electrolyte solutions, electrolyte conditioning, and electrical and electrokinetic parameters.

The electrical parameters are:

- Voltage (V),
- Drop in potential (V/m),

- Current (A),
- Current density (A/m^2),
- Electrical power (kW/m^3) and
- Resistivity ($Ohm.m$).

Conditioning parameters comprise:

- Type of acid or lye and
- Amount of Faraday (A.s) necessary to reach and maintain an optimum pH level.

Electrokinetic parameters pertain to:

- Electrokinetic mobility (EKM in $m^2/V.s$),
- Electrokinetic velocity (EKV in $m/s = m^2/V.s * V/m$),
- Effective electrokinetic mobility (EEKM in $m^2/V.s = A/m^2/kWh/m^3 * distance (m)$).
- Energy (kWh/m^3),
- Electroosmotic mobility (EOM in $m^2/V.s$),
- Electroosmotic velocity (EOV in $m/s = m^2/V.s * V/m$), and
- Electroosmotic transport (EOT in m^3/s).

Particular detail is given on the decrease in concentration of the contaminants in relation to the amount of energy used (kWh/ton of per m^3) and the time involved.

Examples of standard laboratory tests with soil contaminated with copper, zinc and arsenic are given in figures 6, 7 and 8 respectively.

ER Laboratory Test Removal of Copper from sandy clay

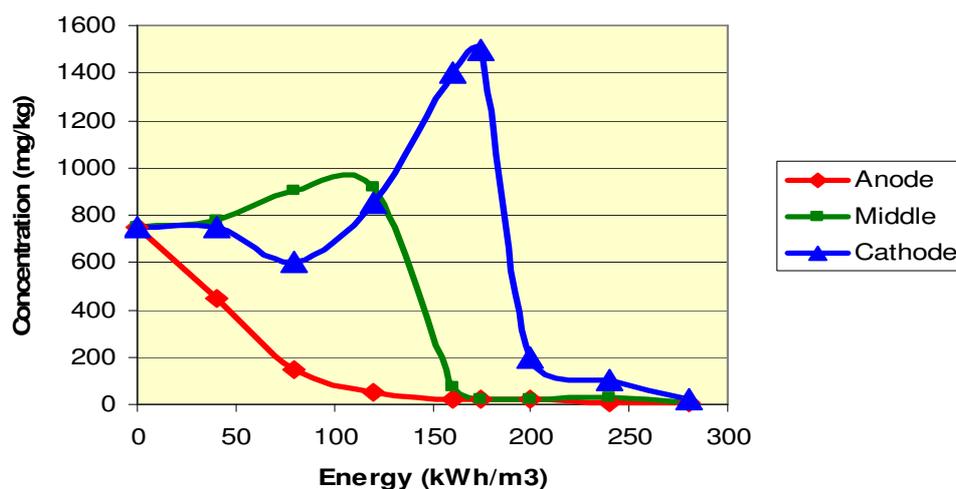


Figure 6. Decrease of copper concentration at the anode, in the middle and at the cathode side of the test sample

Figure 6 is a good example of the movement of metal ions (copper in this case) under the influence of an electric field. Copper ions are first disappearing at the anode side and moving into the direction of the cathode. After an energy inducement of ca $180 kWh/m^3$, the bulk of

the copper ions have reached the cathode side and are then collected in the catholyte. After ca 270 kWh/m³ of energy inducement all copper has disappeared from the sample.

ER Laboratory Test Removal of Zinc from heavy clay

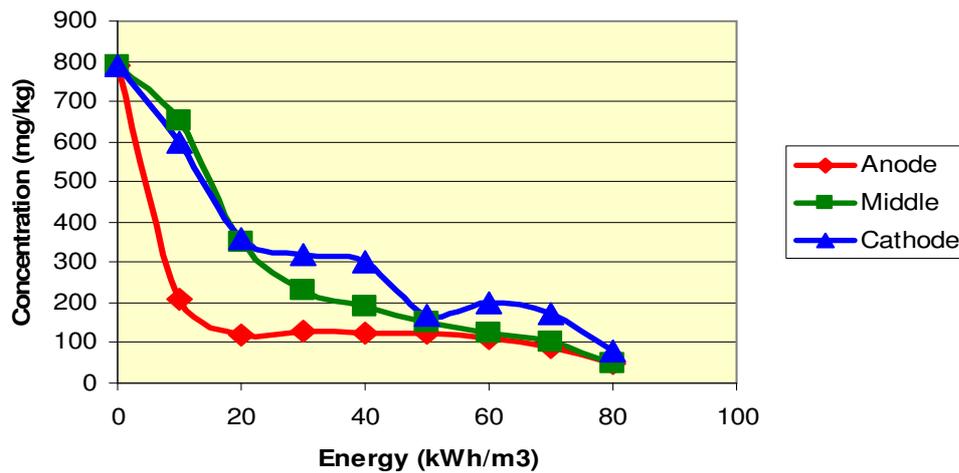


Figure 7. Decrease of zinc concentration at the anode, in the middle and at the cathode side of the test sample

The diagram of figure 7 shows that zinc ions are removed quickly and with low energy input. This is caused by low buffering capacity of the soil and the initially low pH of the sample (pH=4). The zinc ions are desorbed easily and move into the direction of the cathode. No built-up of Zn-concentration in the middle and at the cathode side.

ER Laboratory Test Removal of Arsenic from sandy soil

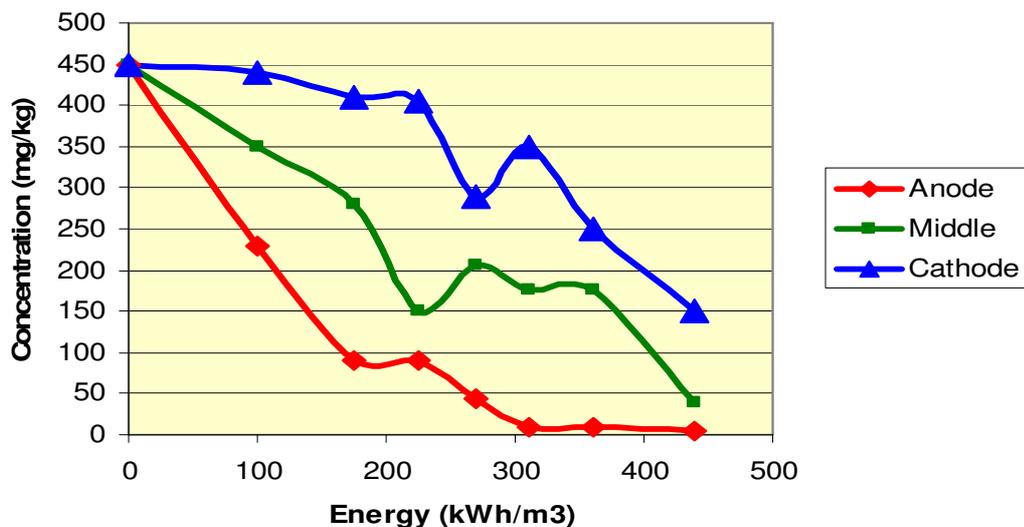


Figure 8. Decrease of arsenic concentration at the anode, in the middle and at the cathode side of the test sample

In figure 8 results are shown from a standard test with soil with a high buffering capacity, contaminated with arsenic. After ca 300 kWh/m³ the arsenic concentration at the anode side has reached the target level, but in the middle and at the cathode side concentrations are still too high. Even after an energy inducement of 450 kWh/m³, target level has not been reached. In this case the laboratory test indicated that it would take too much energy to clean this soil by electro-reclamation

3.2. Field test

A geo-electrical survey enables the measurement of formation resistivities of the subsoil. These are necessary so that the distance between electrodes can be calculated and also the amount of energy necessary to migrate ions or polar constituents through the soil in the most efficient way.

The electrical resistivity method is a non-intrusive exploration method for determining the electrical resistance. It does so by applying an electric current (I) to metal stakes (outer electrodes) driven into the ground. The apparent potential difference (ΔV) is then measured between two inner electrodes (non-polarising DC type, i.e. porous pots filled with CuSO₄ solution, or metal stakes in AC type) buried or driven into the ground. Figure 9 gives an indication of the field set-up of the resistivity method.

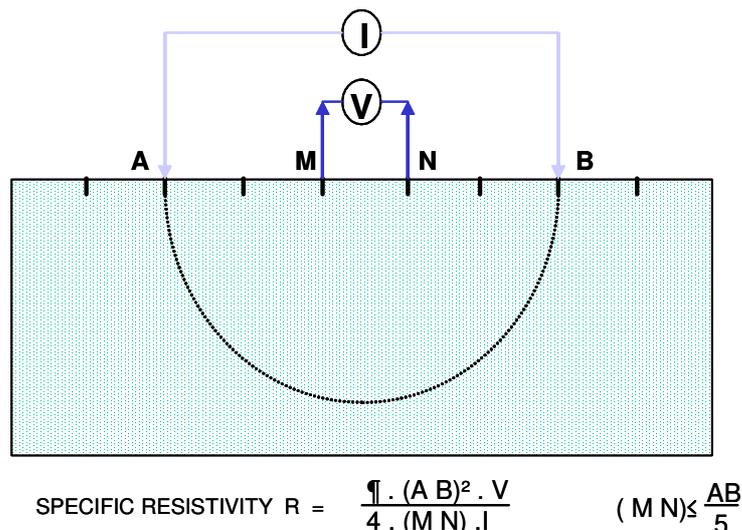


Figure 9. Geo-electrical field set-up. A and B: current electrodes. M and N: measuring electrodes

Increasing the spacing of electrodes A and B increases the depth of penetration of the current. The apparent electrical resistivity ρ_a , obtained at different spacing (m) by measuring the resistance $R (= \Delta V / I)$, is plotted on a log-log paper against the spacing between the outer electrodes. The depth at which current enters a formation of higher or lower resistivity is signalled by a change in the resistivities recorded at the ground surface. The field curves are interpreted using indirect or direct interpretation computer programs. This makes it possible to identify clay and sand layers, and also changes in water quality (e.g. fresh, saline or contaminated).

3.3. Remediation data and parameters

In order to successfully electro-remediate a site contaminated with inorganic species like heavy metals, cyanide, arsenic or other ionic or polar species, an inventory of the site has to be made by collecting basic data. These data include:

- General data: Present owner, type of company and production processes, type of chemicals used, type of waste products, possible causes of pollution
- Historical data: date on which the site came into use, date on which production processes started, location of production processes, calamities, earlier investigations or remediation actions.
- Site-specific data: location, topography, underground tanks, ducts and cables, neighbouring facilities, electricity supplies and their availability, sewage and mains water connections.
- Hydrogeological and lithological data: Groundwater levels, thickness of aquifers and aquitards, hydraulic conductivity, groundwater flow velocity, recharge and/or discharge areas, soil types, silt content, organic matter content, porosity.
- Chemical and physicochemical data and parameters: Type and concentration of chemical constituents, pH, groundwater conductivity, soil resistivity.

3.2. Sampling strategy

Site investigations are relatively expensive, because they consist of many borings, samples and analyses. It is therefore essential to base them on a practical and well designed sampling plan. Sampling strategy is of prime importance and it should be based on expert assessment of soil type, soil stratification, hydrogeological situation, type of contamination and company data. It is also advisable to investigate the site in phases. This means choosing the location of every new sampling point or monitoring well on the basis of the contaminant situation established during the foregoing investigations.

Some of the data mentioned above may have already been collected during earlier investigations. It is not always possible to collect all the relevant basic data, but the essential data are the lithological and hydrogeological data and chemical and physicochemical parameters. Additional soil investigations should focus on:

- Demarcating the contaminants, both vertically and laterally, by drilling boreholes and installing groundwater monitoring wells, and taking soil and groundwater samples. The density of the network of boreholes and monitoring wells depends on the size of the site and the number of potentially hazardous locations within the site (hotspots). At these hotspots, sampling density is higher than in the surrounding less contaminated areas.
- Taking soil and groundwater samples for laboratory analyses. Soil samples should be taken from different depths.
- Soil samples for laboratory tests should be representative of the contaminant situation. They should preferably be taken from the known hotspots, where the highest concentrations of contaminants are found.

Note: *Often, groundwater flow has carried the contaminants beyond the site boundaries. If this is the case, it may be necessary to consult with the competent authorities and the 'neighbours'.*

3.3. Remediation strategy

The aim of any soil and groundwater remediation is to clean up a contaminated site or area within a certain period of time and for a certain price. These basic principles also apply when deploying electro-reclamation. That is why basic data are important. Only if there is abundant and reliable data can realistic estimates be made of the cost and duration of the remediation.

As soon as it has been decided to remediate a site, a remediation plan has to be drawn up. The first step is to work out possible remediation options in relation to the basic assumptions. This phase is called the remediation investigation. When assessing the remediation options it is necessary to consider the technical as well as environmental and financial aspects. Sometimes, electro-reclamation is not the sole remediation option; in certain cases, it should be combined with other methods in order to maximize the remediation efficiency.

Briefly, a remediation plan includes:

- A description of basic environmental assumptions.*
- The reason(s) for choosing the particular remediation method or methods.
- A detailed description of the chosen remediation technique or techniques.
- The design and dimensions of the remediation method(s).
- A timetable and the phases envisaged.
- A description of remediation target and of the procedures to establish that this target has been reached.*
- A monitoring plan and sampling procedures.
- The proposed treatment of excavated soil, if applicable, or of soil from borings.
- The proposed treatment of groundwater, if applicable.
- The proposed treatment of electrolytes and filter cake.
- The environmental supervision and reporting.
- A schedule for applying for the necessary permits
- The electricity, mains water and sewage connections required.
- A safety plan.
- A calculation of the costs.
- The payment schedule.

Depending on the size and complexity of the contaminant situation, the remediation plan may vary from a short description to an extensive report.

* Note: The most important aspect of any soil or groundwater remediation is that the competent authorities, the client and the remediation contractor have agreed about the remediation target. The target values laid down by the Government are generally very low and in certain cases are unrealistic or hard to achieve. From the outset it should therefore be completely clear what the remediation target will be and how it will be verified.

3.4. Design and dimensions

The design and dimensions of the electro-reclamation system to be deployed at a site are based on and derived from the data collected during the foregoing investigations and one or more electro-reclamation laboratory tests.

3.4.1. Field set-up

Anodes and cathodes are installed in separate rows parallel to each other. The design of the field set-up is based on the following data and parameters:

- Size (area and depth) and shape of the area or areas to be remediated.
- Length of the anode and cathode rows of electrodes.
- Distance between the electrodes of equal charge, i.e. anode–anode and cathode–cathode.
- Distance between the electrodes of opposite charge, i.e. anode–cathode.
- Number of anodes connected up to one anode electrical cable. *
- Depth to water table.
- Distance between the remediation area(s) and the remediation equipment installed in containers.
- Distance to the grid connection.
- Length of electrode cables.
- Length of pipes for circulating anode and cathode electrolytes.

* **Note:** *In certain cases, the number of anodes needed in the field exceeds the number of anode connections available on the rectifying units (see following section). In such cases, up to a maximum of 3 anodes can be connected to 1 connection point, provided the total current per connection does not exceed 20 Amperes.*

In the following figure 10 an example of a field layout is presented.

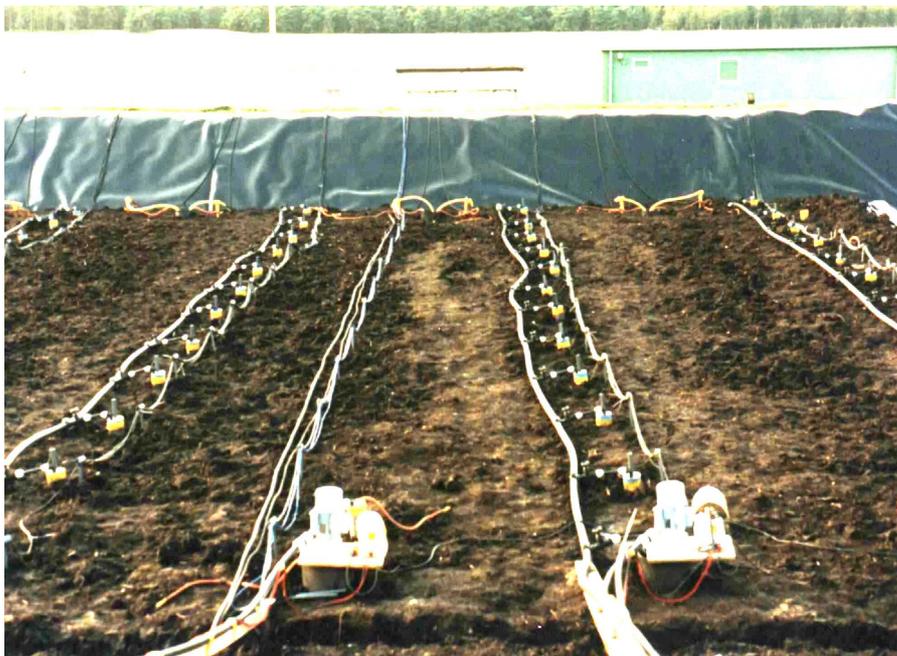


Figure 10. *Field layout of anodes and cathodes*

3.4.2. Remediation equipment

An installation for electro-reclamation consists of an electrical power unit, an electrolyte management unit and, optionally, an electrolyte treatment unit and in certain cases an EnViroCell[®]. All the equipment is built into separate containers that are each 20 ft long.

The electrolyte management unit consists of several buffer tanks for anode and cathode electrolytes, plus acid and base dosing units. The number of buffer tanks corresponds to the size of the electrical power units.

The electrolyte treatment unit consists of a mixing tank, buffer tanks, and a filter press.

The EnViroCell[®] is a special device for treating certain heavy metal solutions and electrolytes containing cyanides.

Which power and electrolyte management units are deployed depends on the size of the remediation area, the number of electrodes, how much electricity is needed and the regulations concerning the use of electricity. For practical and safety purposes the current should not exceed 6,000 Amps. The electrolyte treatment and the EnViroCell[®] units are not needed if existing on-site water purification facilities can be used.

3.4.3. Electrode materials

A variety of electrolytic processes take place at the electrodes. At the anode, a wide range of peroxides occur, in addition to hydrogen ions and oxygen, meaning that the anode has to be made of a precious metal. A relatively inexpensive alternative is to construct the electrodes of titanium with a precious-metal coating. Titanium has the advantage of being light; it can also be welded electrically. It has the disadvantage of a relatively high specific resistance for a metal. Various models of titanium electrode are available, for example as wires, mesh, sheets, etc. If ions such as fluoride are present in the anode electrolyte, the coated titanium electrode will dissolve. In the case of such contaminants, the anode can be made of Ebonex, a ceramic titanium oxide material. The latter is also available in a wide variety of forms but the delivery time is longer and the price higher than that of titanium electrodes.

At the cathode, electrolysis produces hydroxyl ions and hydrogen and various reduction processes take place. The cathode material can basically consist of such materials as iron gas pipes, concrete-reinforcement steel, cables etc. When the ER process is running well, the hydroxyl ions are compensated for by supplying acid to the cathode electrolyte. The average acidity of the cathode electrolyte is decided depending on the contaminants, the current strength, and the flow of electrolyte. Although the cathode is "cathode protected", corrosion of iron will occur around the water level in the cathode well if the pH of the cathode electrolyte is < 1.7. Suitable cathode materials under such conditions are graphite pipes and a special type of steel also used as the anode material when cathodic protection is applied. The use of coated titanium as the cathode material cannot be recommended because the development of hydrogen will cause the coating of precious metal to come away from the surface of the titanium. As a result, the titanium surface will corrode and consequently cease to conduct electricity effectively.

The ER system makes use of one-sided rectified current. This has the advantage that the neutral point of the transformer can be used as the cathode. In the case of two-sided rectified current, there are problems if the minuses of the diode bridges are connected to one another.

3.5. Risks and uncertainties

3.5.1. Risks

The general definition of risk is the danger of injury, harm or loss. With respect to soil and groundwater remediation this definition can be extended to the danger of failure or the

likelihood of an unwanted situation occurring. The probability that one or more of these calamities will actually happen is the risk factor.

During remediation operations one can furthermore distinguish between direct and indirect risks, which in turn can be divided into foreseeable and unforeseeable risks:

- Direct risks pertain to calamities occurring immediately during the execution of an activity e.g. as a consequence of neglect or inattentive behaviour and/or actions.
- Indirect risks pertain to calamities occurring at a later time because of negligent actions.
- Foreseeable risks are the unwanted situations that may be expected but can be averted by taking the right countermeasures beforehand.
- Unforeseeable risks are those calamities or unwanted situations that occur completely unexpectedly.

When establishing the risk factor for remediation projects the following classification and definitions are used:

Risk factor	Indication	Risk profile
0	No risk	Little or no chance that remediation will be delayed or unsuccessful.
1	Low risk	Potential problems can be anticipated and/or prevented, or fixed with little effort.
2	Medium risk	There is a fair chance that remediation will be slowed down, but problems can be dealt with and there are alternatives
3	High risk	A high chance that remediation will be slowed down or targets will be met only partly, if at all. Alternative options are expensive and entail much effort.
4	Extreme risk	A very high chance of failure to meet remediation targets. No remediation alternatives are available. Project acceptance and execution only under very stringent conditions.

Table 4. *Definition of risk factors*

Situations which might influence the risk factor are:

- Contaminant situation differs from start-up situation.
- Influence of other contaminants.
- Power failure.
- Malfunctioning of electrolyte management system.
- Insufficient remediation progress.
- Excessive rainfall.
- High outdoor temperature (in summer).
- Low outdoor temperature (in winter).

3.5.2. Uncertainties

No matter how thorough the preparations preceding an electro-reclamation project, some uncertainty will always remain, especially with respect to the calculated, estimated or predicted decrease in contaminant concentrations during a certain period of time. It should always be kept in mind, that:

Field investigations never give a total picture of the contaminant situation. Usually, the number of samples in relation to the size of the contaminated site will merely indicate the existing situation. Only by using an experienced team of remediation specialists (hydrogeologists, chemists, soil specialists, etc.) will it be possible to minimise the uncertainties and thus the risks.

The laboratory experiments generally consist of one standard test or turbo test. Again, the amount of soil subjected to the laboratory tests is but a tiny fraction of the total volume of soil which has to be remediated. When taking one or more soil samples for the laboratory experiments, those site locations should be chosen, where the highest concentrations are found (hotspots). At least the results of the laboratory experiments will then indicate the required energy and period of time necessary to clean up those hot spots.

4. Some project results

In the following table results of a number of electro-reclamation projects and large scale field tests are shown.

Project	Volume (m ³)	Start (mg/kg)	End (mg/kg)	Notes
Former paint factory, Groningen	300 peat/clay soil	Cu >5,000 Pb >500-1000	Cu <200 Pb <280	First electro-reclamation pilot project. In 1987.
Galvanizing plant, Delft	250 clay soil	Zn >1,400	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	2,500 argillaceous sand	Cd >180 (Also Pb, Zn, CN)	Cd avg 11	Ex-situ electro-reclamation in 2 batches. Goal was to reduce Cd to <10 ppm. Total remediation time 2 years (1990-1992).
Military airbase, Woensdrecht	3.500 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

Project	Volume (m ³)	Start (mg/kg)	End (mg/kg)	Notes
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	4,300 sandy loam and silty sand	Ni 1350 Zn 1300 <i>Groundwater</i> Ni 3500 µg/l	Ni 15 Zn 75 <i>Groundwater</i> Ni 15 µg/l	In-situ electro-reclamation project, inside production plant, started at the beginning of May 2003. Depth up to 6 m bgs.
The Hague, former galvanizing plant	5,800 medium fine sand and silty clay layer	<i>Groundwater</i> Zn 2,000 µg/l	<i>Groundwater</i> Zn avg. <600 µg/l after 2 years	In-situ remediation of groundwater contaminated with zinc using Electro Stimulated Groundwater extraction (ESGE). Running project. Target value Zn <400 µg/l. Project ends in 2009

Table 5. Results of some electro-reclamation projects and large field tests