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Distribution of Ammonium Nitrate as Nitrogen Containing Nutrient for In-situ Biodegradation by Means of Electrokinetics

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ABSTRACT

Distribution of Ammonium Nitrate as Nitrogen Containing Nutrient for In-situ Biodegradation by Means of Electrokinetics

Valentina Boeva

In-situ bioremediation is a technology, which has recently gained the attention of specialists for the clean-up of hydrocarbons. Organic chemicals are persistent and hard to deal with, because they are usually present in three forms: dissolved into groundwater, as free product over the groundwater surface, and adsorbed onto soil particles. The requirements for the bioremediation process to occur are the availability of microorganisms, a biodegradable pollutant, an electron acceptor, and nutrients. The shortage of nutrients in an available form for the microorganisms is very often a limiting factor for successful bioremediation in-situ. The main difficulties for the supply of nutrients usually come from the low permeability of soils. The feasibility of the application of electrokinetic processes, and, more specifically, the induced electroosmotic flow, for achievement of uniform distribution of nutrients for in-situ bioremediation in a natural clayey silt was investigated. Three different concentrations of ammonium nitrate solution were used. The experiment showed the efficiency of the electrokinetic method for supplying nutrients in a low permeability soil, especially for distribution of solutions with intermediate (1 000 mg/L) concentrations. An advantage of the method is the prevention of the leaching of nitrates through the controlled electroosmotic flow.

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CHAPTER 1

INTRODUCTION

1.1 Statement of the problem

Contamination of soils is a problem of growing concern all over the world. A wide variety of natural and synthetic chemicals are being introduced into the soil each year, of which many are toxic and persistent in the environment. In Quebec alone, the number of contaminated sites registered with the data bank GERSOL by June 1992 was 589. Among them, 177 are in Montreal and Lanaudiere. Up to 73% of the sites are contaminated with organics, including petroleum products (482 sites - 82%), polyaromatic hydrocarbons - PAH (44 sites - 7%), monoaromatic hydrocarbons - MAH (103 sites - 17%), chlorinated hydrocarbons - CHC (89 sites - 15%), etc. (Ministère de l'Environnement, 1993).

These statistics indicate that organics, and petroleum products in particular, pose the most risk to the environment. Pollution with oils and fuels generally occurs as result of leaking storage tanks and associated pipelines (above- and underground), or of accidental spills. The leaks are caused not so often by the corrosion and aging of tanks and pipes, as by the shifting of pipes and installations due to changes in the surrounding soil as a result of freezing and rain. In addition, a large number of leaking tanks and pipes remain unreported or undetected (Riser-Roberts,1992).

Complexity of the subsurface contamination makes it difficult to treat. Migration of contaminants via groundwater leads to spreading and intensification of the problem, as well as to inaccessibility for treatment in some cases. The tendency of pollutants to bond and sorb to the soil particles greatly complicates sites remediation.

Organic chemicals are extremely persistent and difficult to deal with, since they are usually present in three forms: dissolved in groundwater, as free product over the groundwater surface, and adsorbed onto the soil particles. In order to reduce the damages from contamination, measures for containment and treatment should be applied to all three. Otherwise, the free mobile product will continue to contaminate through sorption and to dissolve into the groundwater. The saturated soil will be a continuing source of contamination for the groundwater, which will transport the chemicals, thus increasing the negative impact on the environment.

1.2 Solution alternatives

The best solution to the problem is obviously protection of soils and aquifers from contamination. Unfortunately there are a great number of sites already contaminated, and with accidental spills anticipated, the development of new remediation technologies is essential.

Traditional techniques currently in use include control of the flow or physical containment of the pollutants in the groundwater, removal and transportation of the contaminated soil to an approved facility, pumping and treatment of the groundwater, physical, chemical, or biological treatment of the soil in-situ, or excavation and treatment on-site.

Of these, the process most often used involves excavation of the contaminated soil and its removal to a secure place, then pumping and a follow-up treatment of the groundwater by physical, chemical, or biological processes. These methods, though, have limited effectiveness and often are very costly without offering permanent solutions for containment or remediation, but they are practical in certain cases. Excavation is the only possible technique when leaking underground tanks or pipe lines have to be repaired or replaced. It can also be effective for immediate action in cases of accidental spills, to deal with high concentrations posing health or environmental hazards, as well as to prevent contamination of the groundwater when only the surface of the soil is affected. However, excavation does not solve the problem, since it transfers the contamination from one site to another. In most cases not all of the contaminated soil is removed, and soil disturbance can lead to accelerated groundwater contamination.

A definition given by the US Environmental Protection Agency describes bioremediation as "...a process that uses microorganisms to transform harmful substances into nontoxic compounds...one of the most promising technologies for treating chemical spills and hazardous waste problems" (EPA, p. 1, 1991).

In-situ bioremediation is an attractive and propitious technology with numerous advantages for a permanent clean-up of hydrocarbons (e. g. the pollutant can be destroyed in all its forms - sorbed by the soil matrix, dissolved in the groundwater, or free gaseous or liquid phase; the excavation and introduction of other, possibly hazardous chemicals is avoided; disruption of traffic or infrastructure, or demolition of buildings is not necessary. Perhaps most importantly, in-situ bioremediation can be less expensive and more effective than other methods.

In general, the essential requirements for bioremediation are the availability of microorganisms, a biodegradable pollutant, and a bioreactor (location where biodegradation takes place). Microorganisms used to accomplish biodegradation are either the indigenous, selected and cultured site-specific (pre-packaged), or genetically engineered so-called "super bugs". The activity of soil microorganisms depends on certain environmental conditions including water potential, soil composition, a proton donor (for aerobic microorganisms) or acceptor (for anaerobic ones), nutrients (carbon, nitrogen, and phosphorus mainly, as well as potassium, sodium, sulfur, magnesium, and others - micronutrients), along with a favourable ambient temperature and pH.

Among the elements involved in the process of biodegradation nitrogen is ranked fourth after carbon, hydrogen, and oxygen. At a site contaminated with hydrocarbons carbon and hydrogen are abundant, but nitrogen and oxygen are not always in sufficient amounts. Nitrogen is a mineral nutrient required in large quantities because it constitutes approximately 10% of the dry weight of bacteria (Gottschalk, 1985). Therefore it should be supplemented to ensure that it does not limit bacterial activity. It is important that nitrogen is available to microorganisms in a usable form and in an appropriate concentration, as well as in a proper ratio to the degradable pollutant.

1.3 Need of new techniques.

The delivery of the nutrients and the electron acceptor to every point of the contaminated site constitutes a major problem in the case of fine grained soils. Their low permeability does not allow fast and uniform distribution and this is often the reason for failure or avoiding in-situ bioremediation as a solution.

This problem creates the necessity of the development of new techniques for delivering of the nutrients uniformly and in suitable form to the microorganisms.

1.4 Objectives.

The main objective of the present study is to examine feasibility of application of electrokinetic phenomena for uniform distribution of nutrients for in-situ bioremediation in fine soils and to improve the effectiveness of their delivery to the microorganisms.

Investigation of the behavior of the nutrient solution such as ammonium nitrate, due to electrokinetics and the influence of the nitrogen concentration on the process rate, are secondary objectives of this work.

CHAPTER 2

LITERATURE REVIEW

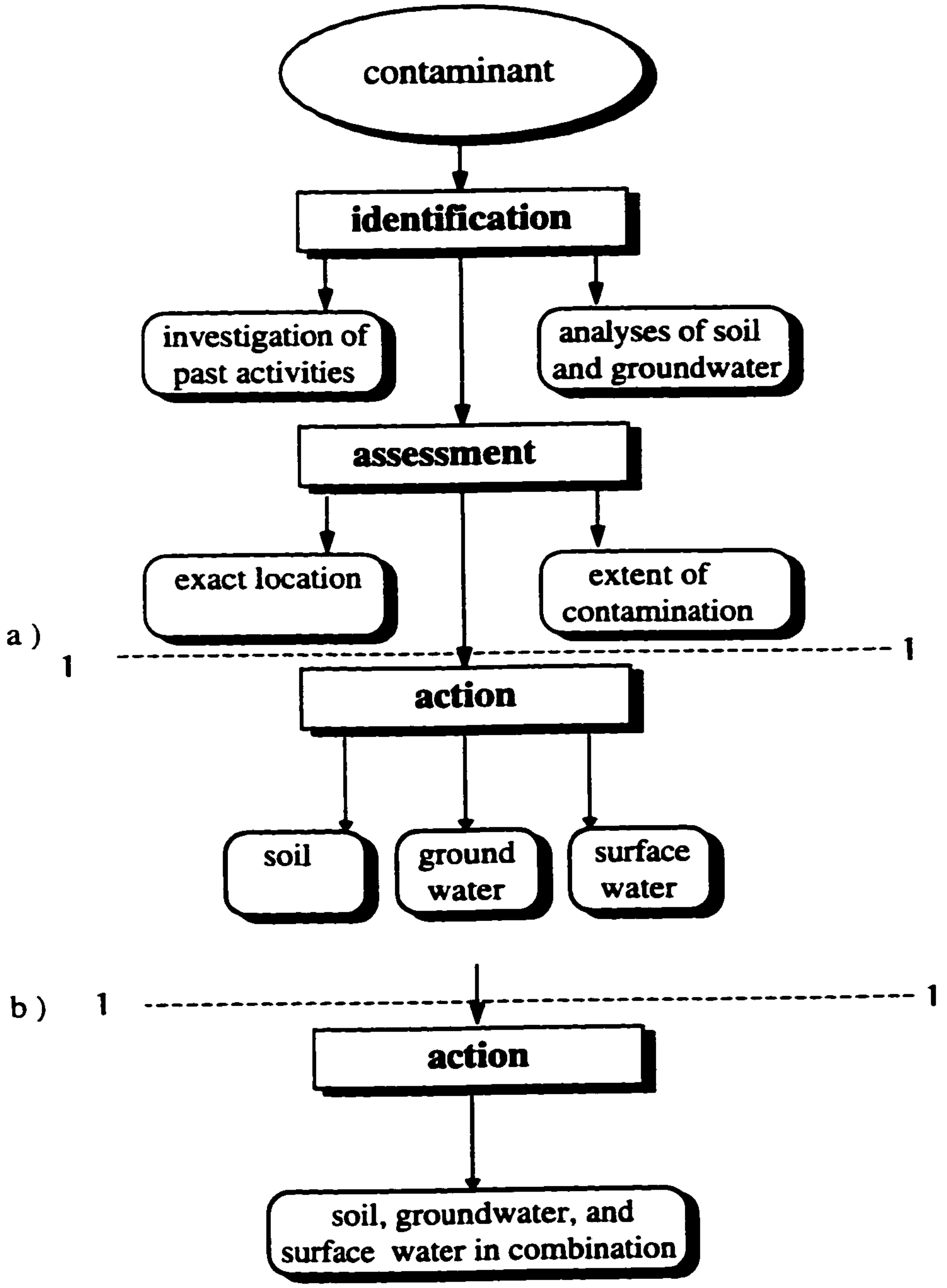
2.1 Remediation strategies

Solving the worrisome contamination problems requires development of new, more efficient remediating strategies. Their choice is determined by many factors, including the behavior of contaminants, climatological, geological, and hydrogeological conditions at the site. As discussed in *Soils and Environmental Quality* (Pierzinski, Sims, and Vance, 1994), a remediation program usually consists of three stages: identification, assessment, and action. During the first stage, the past activities that potentially caused the contamination of the site are investigated or analyses of water and soil are conducted. The assessment stage evaluates the exact location and determines the extent of the contamination. A remediation action plan is then developed depending on the specific problems of the site. It can include treatment of soils, surface-, and groundwater alone, or in conjunction (Fig 2.1, a and b).

The problems of contaminated groundwaters are solved mainly through three general strategies: containment, in-situ treatment, or pump-and-treat method. Various techniques are available for implementation of each strategy, such as use of different type of barriers, grouting, biotreatment, chemical oxidation, reduction, or precipitation, ion-exchange, etc. (Smith, 1985; EPA, 1984, 1985, 1992).

Figure 2.1

Principal scheme of a remediation program. (Adapted from Pierzinski et al., 1994)



Solution alternatives for contaminated soils are also containment or treatment. The latter can take place either in-situ, or ex-situ (when the soil is excavated). Two options are available for the latter: treatment in a prepared bed on the site or in treatment facilities after transportation (off-site).

The treatment techniques involve three types of processes: physical (adsorption, stripping with air or steam, washing with water or suitable solvent and surfactant, separation, flotation, solidification, and thermal treatment), chemical (ion exchange, chelation, and oxidation/reduction), and biological (landfarming, composting, biostimulation, bioventing, slurry reactors) (Cookson, Jr., 1995; Baker and Herson, 1994; EPA, 1984, 1985, 1992; Pierzinski et al., 1994; Smith, 1985). More details on the available in-situ and ex-situ techniques are presented in Tables 1 and 2 in the Appendix.

2.2 Biodegradation - basic definitions

Degradation is the transformation of the contaminants chemically, microbiologically, or under the influence of electric current or light (visible or UV).

The process of microbiological break down of contaminants is called ***biodegradation***. To be more precise, it is the transformation of chemical compounds through a complex series of coupled oxidation-reduction reactions, termed ***catabolism***, These reactions are catalyzed by enzymes - products of microbial activity (Cookson, Jr., 1995; Baker and Herson, 1994). Biodegradation includes different microbial processes, such as mineralization, detoxification, cometabolism, or activation (Alexander in Riser-Roberts, 1992).

Mineralization is the complete biodegradation of an organic contaminant to inorganic compounds (CO_2, H_2O, and mineral ions, such as nitrogen, sulfur, and phosphorus, or methane instead of CO_2 under anaerobic conditions).

When organic compounds are transformed by the action of microorganisms into innocuous or less toxic organic substances, the process is called ***detoxification***. However, the products of biodegradation can be of greater environmental concern than the parent compound, either in terms of increased toxicity, or of higher mobility and bioavailability. This type of degradation is referred as ***activation***.

Degradation of hazardous chemicals can be a result of ***cometabolism*** (termed ***cooxidation*** if an oxidation reaction is involved). It is a process when transformation of a non-growth substrate (organic contaminant) occurs coincidentally (fortuitous transformation) due to enzymes generated by microorganisms to metabolize the growth substrate (Cookson, Jr., 1995).

Biodegradation is a process that occurs naturally in soils. Since the natural process is very slow, the efforts of scientists and engineers are directed towards enhancement of the rate of degradation through alteration of the factors favoring it: quantity and type of microorganisms, soil moisture, soil oxygen, pH, nutrients.

2.3 Bioremediation

2.3.1 Definition

Bioremediation is "the use of microorganisms to control and destroy contaminants" (Macdonald, p. 1974, 1993), or, according to EPA it is "...a process that uses microorganisms to transform harmful substances into nontoxic compounds..."(EPA, p. 1, 1991).

2.3.2 Bioremediation strategies

There are two well-known strategies for biodegradation which have beween used in wastewater treatment for decades but are relatively new in terms of technology for treatment of contaminated soils. These strategies are based on aerobic and anaerobic processes.

In general, nutrients, aerobic (or anaerobic) microorganisms, and water (if necessary) are added to the contaminated soil which is placed in a reactor (fermentor, container, or a suitable bed), where the microbiological degradation takes place (ex-situ method). Alternatively, all these agents are delivered into the soil at the contaminated site. If an aerobic process is to be performed, the soil is aerated (in-situ method).

The limitations for application to biodegradation of contaminated soils stem from the following conditions:

- the environmental factors for the microbiological process (temperature, availability of the nutrients, moisture content) are difficult to control in the case of in-situ strategy.
- constituent losses and hazard from volatilization during excavation of the soil, and
- necessity of pre-treatment operations to enhance the microbiological conversion rate and reduce the long residence time (the volume of the reactor, respectively) for ex-situ strategy.

Based on the type of bacteria used for the biodegradation, two approaches are possible (Canter and Knox, 1986): a microbial ecology and a microbiological approach.

1) The microbial ecology approach

The growth of the microorganisms specific to the site and suitable for the degradation of the contaminants is stimulated through creation of favorable soil conditions.

Stimulation of the activity of the natural microorganisms can be achieved by alteration of moisture, oxygen, pH, and nutrients.

Soil water potential influences decomposition process by altering microbial activity in the soil. It has been determined that the degradation rates of certain contaminants are highest at a soil water potential between 0 and -1 bar (Riser-Roberts, 1992). Mineralization has been slower in dry soils. This fact can be used for acceleration of the degradation of some easily degradable contaminants by soil moisture optimization, but in general it is suitable only in combination with some other techniques.

Soil oxygen content may require alteration in two directions - an increase for aerobic degradation or a decrease for the anaerobic process.

Most organic contaminants are decomposed under aerobic conditions. Such an environment can be provided by tilling, bioventing (developed in Holland), injection of oxygen through tubes with fine screened holes (Oxygen Microbubble In Situ Bioremediation developed by OHM Remediation Services Corporation, Findlay, OH), extraction of air, or drainage of the soil to let the air from the atmosphere penetrate in depth.

Methanotrophic bacteria can be used for detoxification of soils contaminated with halogenated aliphatic hydrocarbons, including trichloroethylene, dichloroethylene isomers, vinyl chloride, dichloroethane isomers, chloroform, and others (Oleszkiewicz & Elektorowicz, 1993; Hinchee & Olfenbuttel, 1991). Methanotrophs use methane as a source of energy and oxidize chlorinated hydrocarbons through cometabolism. Based on this process, Bio Trol, Inc. has developed the Methanotrophic Bioreactor System (presently applied in a field scale only to contaminated wastewater and gaseous streams from air stripping or in-situ vacuum extraction) (EPA, 1992).

Anaerobic conditions for dehalogenation or complete degradation of some halogenated hydrocarbons can be provided by diking and flooding the contaminated soil. This technique, however, requires a complex combination of soil manipulations (moisture control, organic amendment, and compaction) and subsequent aerobic treatment. Therefore, the use of anaerobic degradation is still at the conceptual stage. Laboratory studies using this process are scant.

Alteration of soil pH may be necessary depending upon the nature of contaminants to be degraded. Some microorganisms require certain pH for their activity. In general, the optimum range of pH tolerated by most bacteria involved in biodegradation of wastes is between 6.5 and 8.5. High values of pH can be obtained through liming, and acidic pH - with acid-producing materials or sulfur. Liming is commonly used in agriculture.

2) The microbiological approach

This involves the addition of exogeniously grown microorganisms (selected and cultured site-specific, pre-packaged, or genetically engineered). In this case biodegradation depends upon microorganisms added to the soil system to degrade the pollutants. These microorganisms can be selected by enrichment culturing or genetic manipulation (EPA, 1984).

Enrichment culturing refers to the selection of microorganisms by repeated exposure to a certain pollutant. The type of microorganisms which are isolated depends on the source of the inoculum, the conditions used for the enrichment, and the substrate. A wide range of microbial inoculants is available commercially. They can be applied in liquid suspension or with a solid carrier. Pre-packed bacteria are used in most of the technologies developed in recent years (e.g. Augmented In Situ Subsurface Bioremediation Process by Bio-Rem, Inc., In Situ Biological Treatment by Ecova Corporation, Deep In Situ Bioremediation Process by In-Situ Fixation Company, etc.) (EPA, 1992).

A new technique of using ***genetically engineered microbes*** (super bugs) has recently been developed. Genetic alterations increase the growth rate and provide multiple degradative capabilities of the microorganisms. Genetic engineering should ensure, however, that newly created mutant microbes are safe both for the environment and human health.

The goal of bioremediation is degradation that results in detoxification of a parent compound to a product or products that are no longer hazardous to human health and/or the environment (Sims et al., 1990). In order to achieve this, a number of requirements have to be met.

2.3.3 Bioprocess requirements

Successful bioremediation, regardless of the treatment technology, depends in general "...on having the right microorganisms in the right place with the right environmental conditions..." (Baker & Herson, p. 3, 1994).

These requirements can be summarized as follows:

- biodegradable contaminants
- an available form and non-toxic concentrations of the contaminants to the microorganisms
- microorganisms capable of degrading the contaminants of concern
- a readily available source of energy and carbon
- an adequate electron acceptor/donor system
- nutrients in a usable form, appropriate concentrations, and proper ratios
- appropriate environmental conditions, including favorable temperature, pH, and moisture (Cookson, Jr., 1995).

2.3.3.1 Contaminants

One of the basic components of a biodegradation process is the contaminant which has to be degraded.

Despite the statement of E. F. Gale, quoted by Cookson, Jr. (1995) that probably "...somewhere or other some organism exists which can, under suitable conditions, oxidize any substance which is theoreticaly capable of being oxidized." (p. 10), today's engineering science is still far from utilizing bioremediation for *any* hazardous chemical. Heavy hydrocarbon compounds, polynuclear aromatics, and PCBs, for example, are non- or hardly biodegradable, even under optimal conditions (persistent contaminants). Their degradation can take several years, sometimes without significant success (Smith, 1985).

Contaminants susceptible to biodegradation under certain conditions are cyanides, aromatics (benzene, toluene, xylene, phenol), polyalkanes, cycloalkanes, chlorinated aliphatics with 1 or 2 C- atoms (as $C_2H_4Cl_2$), certain pesticides, some heavy metals (Fe, U) (Smith, 1985). A table with organic compounds suitable for bioremediation from a more recent source (EPA, 1991) is enclosed in the Appendix (Table 3).

Important factors for the biodegradation itself and/or its rate related to the contaminant are its physical and chemical properties and the matrix in which it is present. The concentration of the chemical of concern can be decisive in the outcome of the biological process. For example, phenol in concentration greater than 0.1 % is bactericidal and, in order to be degraded, should not exceed 0.05 %. Also, bacteria can metabolize 2,4-dichlorophenol only if its concentration is less than 0.005 % (Walker, 1975).

Other parameters of importance to the feasibility of biodegradation are solubility, partitioning, adsorption, volatility, and viscosity of hazardous chemicals. These properties affect the establishment of a contact between the contaminants, bacteria, nutrients, and the electron acceptor (Norris et al., 1994).

2.3.3.2 Microorganisms

Soil is the habitat of a great variety of microorganisms. They include bacteria, actinomycetes, fungi, algae, and protozoa. Among them only bacteria and fungi are of importance for biodegradation (Cookson, Jr., 1995).

Microorganisms destroy contaminants by using them for growth and reproduction. Organic contaminants provide a source of carbon, which is one of the basic building blocks of the microbial cell, as well as electrons, which serve the organisms to obtain energy.

Microbial transformation of contaminants involves enzimatically catalyzed, energy producing chemical (oxidation-reduction) reactions. Through these reactions the chemical bonds are broken and electrons are transferred from the contaminant-electron donor (oxidation) to the electron acceptor (reduction). The energy gained from this process along with some carbon from the contaminant is then used for cell reproduction. The electron donor and electron acceptor are called the primary substrates for biodegradation (Water Science and Technology Board, NRC, 1993).

The type of the redox reaction defines the metabolism mode. The metabolic pathways are broadly classified as aerobic and anaerobic depending on the electron acceptor. In all cases of aerobic reactions the electron acceptor is molecular oxygen. This form of metabolism is aerobic respiration. Anaerobic reactions occur only in the absence of molecular oxygen and are subdivided under anaerobic respiration, fermentation, and methane fermentation. In the case of anaerobic metabolism, the role of electron acceptors is served by various organic or inorganic compounds, other than molecular oxygen, including nitrates, sulfates, carbon dioxide, etc. (Cookson, Jr., 1995).

Depending on the type of metabolism, the nutritional requirements are different. Some microorganisms need only sunlight, carbon dioxide, water, and inorganic nitrogen for biosynthesis. Others cannot grow without supplementation of amino acids and vitamins.

2.3.3.3 Nutrients

As briefly mentioned in the previous section, an important factor for the microbial growth are the nutrients and their availability to the microorganisms in particular. The requirements of the microorganisms for nutrients are determined by the cell composition.

Carbon forms the skeleton of all living cells. The other three major elements are hydrogen, oxygen, and nitrogen. These four elements constitute about 95% of a cell's weight - 8% H, 20% O, and 14% N. Phosphorus and potassium represent another 4%, and the remainder consists of the so called micronutrients - trace concentrations of sulfur, sodium, calcium, magnesium, iron, chlorine, and others (Cookson, Jr., 1995).

It has been determined that the proportion of carbon, nitrogen, and phosphorus in bacterial cells -- C:N:P ratio, is approximately in the range between 100:15:3 and 120:10:1 (Electorowicz, 1994, Riser-Roberts, 1992[1]). If the available inorganic forms of nitrogen and phosphorus are not within these limits, they should be supplemented to provide sufficient quantity of nutrients for the growth of the microorganisms. This technique is conventional in agriculture and is an important part of all bioremediation technologies depending on the specific soil conditions. An optimum supplementation should be provided to ensure sufficient amount of nutrients without overloading the soil with elements that may cause additional toxicity and leaching problems.

The main difficulties for the supply of nutrients for bioremediation in-situ usually come from the low permeability of soils. This problem can be avoided by a pretreatment of the soil (changing its density and transmissibility) and remediation on site (Elektorowicz, 1994).

2.4 Nitrogen cycle

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[1] Sources: Zitrides, 1983

and Alexander, 1977

Among the 106 known elements 88 occur in nature. Of these eighteen exist in the earth's crust, oceans and atmosphere in amounts between 50 and 0.03 mass percent, totaling 99.51%, while the rest are present in trace amounts and constitute only 0.49% (Zumdahl, 1992).

The distribution of these eighteen elements in order of their abundance is presented in the following table:

Distribution of the most abundant elements in the lithosphere, hydrosphere, and atmosphere[1]

Element	Mass %	Element	Mass %	Element	Mass %
O	49.2	K	2.40	Mn	0.09
Si	25.7	Mg	1.93	C	0.08
Al	7.5	H	0.87	S	0.06
Fe	4.71	Ti	0.58	Ba	0.04
Ca	3.39	Cl	0.19	N	0.03
Na	2.63	P	0.11	F	0.03

The distribution of the elements in the biosphere is quite different. Carbon, oxygen, nitrogen, and hydrogen form the basis of the living portion of the Earth. These elements represent 50.0, 20.0, 14.0, and 8.0 %, respectively, of the elemental composition of the bacterial cell (Cookson, Jr., 1995[2]).

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[1] Zumdahl,1992

[2] Source: Stainer, R. Y., Ingraham, J. L., Wheelis, M. L., and Painter, P. R.,

Although not the most abundant element, nitrogen is one of the most important constituents of the four spheres of the Earth: the lithosphere, hydrosphere, atmosphere, and biosphere. More than 98 % of the nitrogen is found in the earth's crust and the remainder (less than 2 %) is distributed between the atmosphere, hydrosphere, and biosphere. Nitrogen gas comprises 78 % of atmospheric gases. In the hydrosphere, it appears as dissolved organic and inorganic nitrogen compounds.

The amount of nitrogen in the four spheresis presented below (Stevenson, 1986):

Inventory of N in the Four Spheres of the Earth[1]

Sphere	N content, $\times 10^{16}$ kg
Lithosphere	16,300
igneous rocks	
of the crust	100
of the mantle	16,200
core of the earth	13
sediments (fossil N)	35 - 55
coal	0.007
sea-bottom organic compounds	0.054

The Microbial World, 5th Edition, Prentice- Hall, Englewood Cliffs, N.J., 1986

[1] Most estimates are from Burns and Hardy and Söderlund and Svensson. The values for terrestrial soils are from Stevenson.

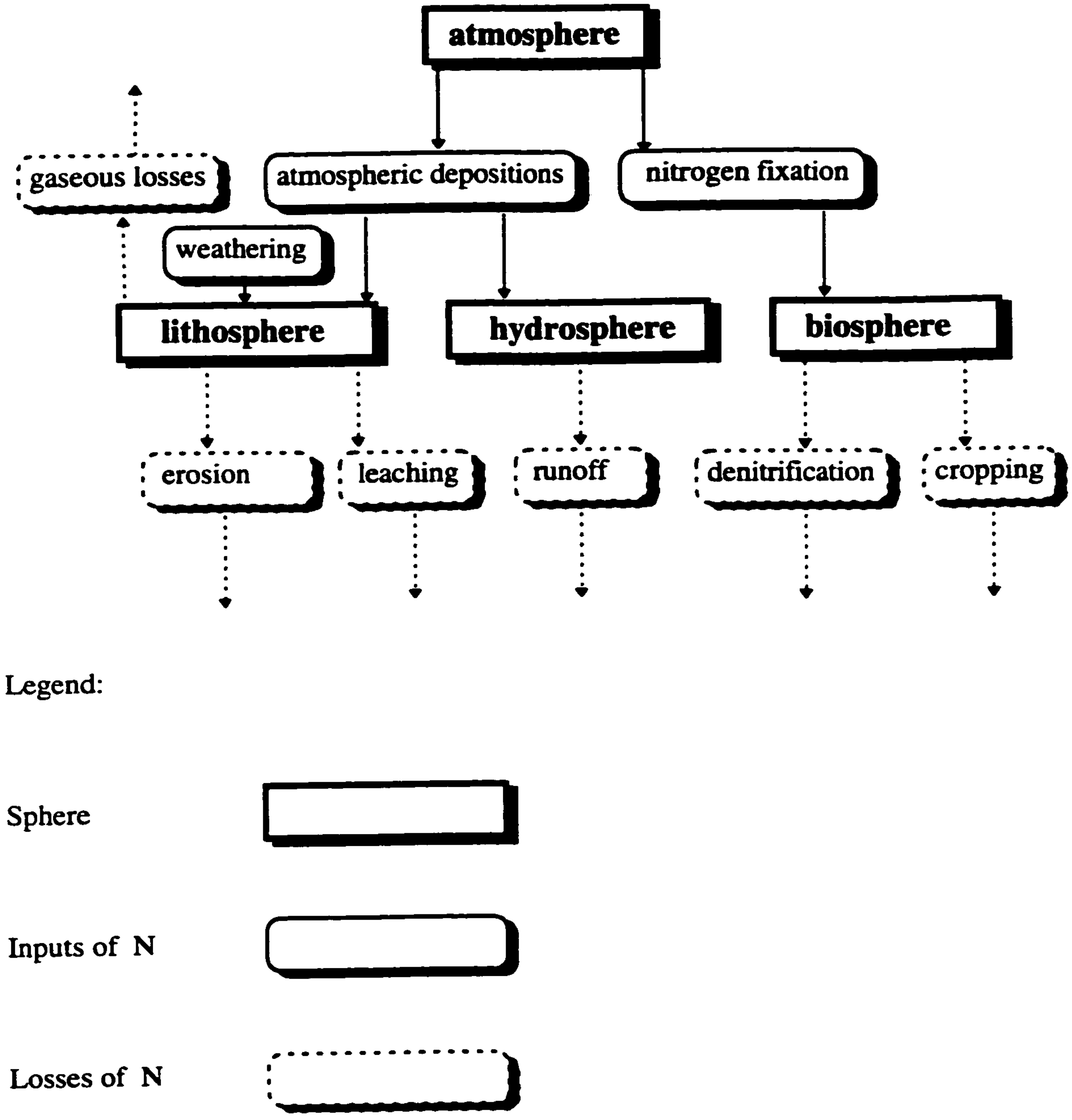
terrestrial soils	
organic matter	0.022
clay-fixed NH_4	0.002
Atmosphere	386
Hydrosphere	
dissolved N_2	2.19
combined N	0.11
Biosphere	0.028 - 0.065

Nitrogen is an extremely dynamic element and is constantly transformed chemically and biochemically from one sphere to another. The consequence of these processes is referred to as ***the global nitrogen cycle*** (Figure 2.2).

An important subset of the overall cycle is the soil nitrogen cycle.

The three major natural inputs to the soil nitrogen cycle are the atmospheric deposition, biological N-fixation, along with weathering and decomposition.

Figure 2. 2 Global nitrogen cycle



The nitrogen deposited from the atmosphere can be in organic or inorganic form in precipitation or as a dry particulate matter. Symbiotic and nonsymbiotic organisms biologically fix nitrogen by conversion of gaseous N_2 from the atmosphere to ammonia and then to organic N. The third important group of processes for the contribution to the soil nitrogen are the weathering and decomposition reactions in which N is transformed from stable inorganic or organic forms to more chemically or biologically active ones. Conversely, nitrogen is lost from the soil mainly by two natural pathways: in gaseous form through NH_3 volatilization and bacterial or chemical denitrification of nitrates, or in water and sediments through transport processes such as leaching, runoff, and erosion (Pierzinski et al., 1993) .

All these natural transformations along with the activities of humans lead to the redistribution of nitrogen in the global cycle and its accumulation in some sectors of the environment, while others are depleted. Typical examples for excessive concentration of N due to civilization are agricultural lands, as well as streams, soils, and air near cities as result of municipal, some industrial wastes, and transportation. This is not the case, though, with the sites contaminated with hydrocarbons where carbon occurs in excess compared to the quantities of nitrogen.

To employ the natural process of biodegradation for destruction of the contaminants, delivery of additional nitrogen in available form to the microorganisms may be necessary - C:N to be approximately 10:1 (Chapter 2.3.2.3). Its supplementation should be carefully assessed, so neither limitation of the biomass growth, nor overloading and additional pollution problems would be incurred.

Nitrogen and other nutrients should be applied as uniformly as possible to avoid shock loading (EPA, 1985).

2.5 Transport processes

The distribution of nutrients for enhancement of biodegradation in-situ is an important part of the remedial process. It is especially problematic when the contamination is deep under the surface and the soil is of low permeability. The flow of the nutrient solution towards the site can be induced by three energy phenomena: hydraulic, chemical, and electrical.

Each of the three flow types can be expressed by an equation with the following general form (Mitchell, 1976).

$$J_i = L_{ii} X_i$$

where J_i is the flux,

L_{ii} is the conductivity coefficient, and

X_i is the respective gradient

Written for specific flow, the equation becomes:

Water flow:

$q_h = k_h \, i_h$ Darcy's law

k_h = hydraulic conductivity (permeability), cm/sec

i_h = hydraulic gradient (head), cm/cm

Chemical flow:

$J_D = D \, i_c$ Fick's law

D = diffusion coefficient, cm^2/sec

i_c = concentration gradient, $moles/cm^4$

Electrical flow:

$I = \sigma \, i_e$ Ohm's law

σ = electrical conductivity, coulomb/sec/volt

i_e = electric gradient, volts/cm

In cases of environmental contamination, the flows can be coupled (i.e., contaminants flow driven by the hydraulic gradient coupled with the contribution of osmosis). In general, such coupled phenomenon is expressed by

$$J_i = L_{ij}X_j$$

where L_{ij} is the coupling coefficient, and

X_j is the gradient of one type causing a flow J_i of another type

If an electric field is applied, the soil solution will be conducted under the combined action of the hydraulic, concentration, and electric gradients. The equation for this coupled flow becomes:

$$q_h = -k_h \frac{\Delta H}{L} A + k_c \frac{\log(C_B/C_A)}{L} A - k_e \frac{\Delta E}{L} A,$$

where k_h , k_c , and k_e are the hydraulic, osmotic and electric gradients, ΔH is the hydraulic head, ΔE is the electric gradient, and C_B and C_A are the salt concentrations on opposite ends of a clay layer with thickness L and cross section A.

The contributions of the different gradients to the total fluid flow strongly depend on the type of soil, degree of saturation, and concentration of dissolved salts in the pore fluid. (Mitchell, 1976). The influence of electric and concentration gradients is almost negligible relative to that of the hydraulic head in cohesionless soils, but they can cause considerable flows in low permeable soils.

Olsen (1972) has made measurements of the coupled osmotic and electroosmotic flows in kaolinite. Mitchell (1976) refers to the summarized results in his discussion on the increase of osmotic and electroosmotic flows relative to the hydraulic flow with a decrease in the void ratio.

The diffusion coefficients for electrolytes in water at 25^0C are in the range of $1\text{x}10^{-5}$ to $2\text{x}10^{-5}$ cm^2/sec (Robinson and Stokes, 1959). However, they are much smaller in porous media because of the impact of adsorption and tortuosity. The apparent diffusion coefficient D* for nonadsorbed ions in soil can be expressed by the equation:

$$D^* = \omega D \qquad \text{(Freeze and Cherry, 1979)}$$

where ω is a coefficient taking into account the influence of the solid matrix on the diffusion; values of ω obtained in laboratory studies are between 0.5 and 0.01.

Mitchell (1976) reports diffusion coefficients as high as 10^{-5} cm^2/sec in saturated soils. As for the coefficient of electroosmotic permeability, he presents more complete data. Depending on the type of soil and its moisture content, this parameter varies between 1.5×10^{-5} and 12×10^{-5} cm^2/sec.

2.6 Electrochemical processes

An electrochemical cell is a system consisting of two electronic conductors (metals) separated by an ionic conductor (electrolyte) in which electrochemical processes accompanied with the passage of electric current may occur. If the cell transforms chemical energy to electrical energy it is called a ***galvanic cell***. If, instead, under the consumption of electric current from an external energy source it stores chemical energy, it is said to be an ***electrolytic cell***.

In an electrochemical cell, by definition, the anode is that electrode through which positive current passes into the electrolyte, i.e., in an electrolytic cell the positive electrode is the anode and the negative electrode is the cathode, while the opposite is true of a galvanic cell. The reaction that occurs at the anode is oxidation, while at the cathode it is called reduction. In this process, the metallic anode of an electrolytic cell dissolves, liberating the respective metal ions (cations). They migrate towards the cathode, accept electrons and are deposited over it as electroneutral metal atoms. At the same time anions from the solution migrate towards the anode conducting the negative charge through the electrolyte solution. The process described above is called ***electrolysis*** and, in general, can be divided into two parts (Wranglén, 1985):

a) The processes that occur at the electrode/electrolyte interface.

b) The charge transfer through ion migration and transport of electroneutral molecules through diffusion in the bulk solution.

As a result of the oxidation-reduction reactions, a potential difference develops on the electrode surface. It is expressed by the Nernst equation (Tan, 1982):

$$E = \frac{RT}{nF} \ln \frac{K,}{M^n}$$

where

E is the potential difference, R is the gas constant, n is the valence of the ion, F is the Faraday constant, T is the absolute temperature, K is the impulse of metal to dissolve, and M is the ion activity.

Since it is not possible to measure the potential of a single electrode, but only in relation to another, a standard hydrogen reference electrode is introduced. It consists of Pt sheet, covered with a Pt sponge and immersed in a solution with the hydrogen ion activity equal to 1 and a hydrogen pressure 0.1 MPa. Its potential is by convention 0.000 V (Rieger, 1994).

The potential of an electrode (potential of the half cell reaction) measured against the standard reference electrode is (Tan, 1982):

$$E_h = E^0 - \frac{RT}{nF} \ln \frac{\text{reduction}}{\text{oxidation}}$$

E^0 is the standard electrode potential (the standard potential of the cell in which the reactants and products have unit activity). It characterizes the oxidizing or reducing ability of the component of the oxidation-reduction system.

Standard electrode potentials of various oxidation-reduction reactions at 25°C are included in tables in different sources (e. g., Bard et al., 1985).

These data give a quantitative indication of the preferential oxidation-reduction reactions having a tendency to occur. Those with the lowest energy requirements are dominant. For example, the reaction at the cathode is the production of hydrogen gas from water, with $E^0 = -0.83$ V

$$2H_2O + 2e^- \rightarrow H_2\,(g) + 2OH^-$$

At the iron anode the half cell reaction is oxidation and dissolution:

$Fe \rightarrow Fe^{+2} + 2e^-$, $E^0 = -1.23$ V (Segall and Bruell, 1992)

Secondary electrolytic reactions may also occur depending upon the concentration and type of the species in the cell (Acar and Alshawabkeh, 1993):

$H^+ + e^- \rightarrow (1/2)H_2(g)$

$Me^{n+} + n\ e^- \rightarrow Me$

$Me(OH)_n + n\ e^- \rightarrow Me + n\ OH^-$

Soil with electrodes inserted in it and connected to a source of direct current can be considered as an electrolytic cell in which the ions in soil solution are the current carrier. However, since the medium is not pure electrolyte, the processes in such cell are more complex. In addition to electrolysis (which includes diffusion and electromigration), two other transport phenomena due to the application of an electric field are involved - electroosmosis and electrophoresis.

2.7 Electrokinetic phenomena

Electrokinetic phenomena include four processes: electroosmosis, streaming potential, electrophoresis, and migration of sedimentation potential (Mitchell, 1976).

Electroosmosis is the phenomenon when water flow is caused by the migration of ions towards the respective electrodes. Since there is an excess of cations in the system to neutralize the net negative charge on the surface of the soil particles, they drag the water in the direction of the cathode.

The streaming potential (occurrence of electric potential difference) results from displacement of the double layer charges due to a flow caused by a hydraulic head difference. It is proportional to the hydraulic flow rate and could be in the range of several tens of milivolts.

Electrophoretic phenomenon is observed when a direct current is applied across a soil suspension. Negatively charged colloid particles are attracted by the anode and repelled by the cathode.

Gravity settling can induce electric potential due to the viscous drag of the water which retards the movement of the diffuse layer relative to that of the clay particles.

From the above described processes, electroosmosis is the one of particular interest in geotechnics and, lately, in geoenvironmental engineering. Electroosmotic flow is a coupled flow (fluid flow caused by electric gradient) and, when there is no hydraulic or chemical gradient, can be characterized by the equation:

$$J_h = L_{he}X_e, \qquad \text{where}$$

J_h electroosmotic flow

L_{he} coupling conductivity coefficient

X_e electrical gradient

Usually the equation is given in the form:

$$q = vA = k_e i_e A, \qquad \text{where}$$

q flow rate

v flow velocity

A cross section normal to the direction of the flow

k_e coefficient of electroosmotic permeability (a soil property representing the hydraulic flow velocity under a unit electrical gradient)

i_e electrical potential gradient

The coefficient of electroosmotic permeability is not as dependent on the type of soil as on the pore solution concentration. It can be determined experimentally. Typical values for k_e and k_h (coefficient of hydraulic permeability) are shown below:

Coefficients of Electroosmotic and Hydraulic Permeability (Mitchell, 1976)

Type of soil	Water content (%)	k_e (cm^2/sec.V)	k_h (cm/sec.)
kaolin	67.7	$5.7x10^{-5}$	10^{-7}
clayey silt	31.7	$5x10^{-5}$	10^{-6}
Na-montmorillonite	170	$5x10^{-5}$	10^{-6}
mica powder	49.7	$6.9x10^{-5}$	10^{-5}
fine sand	26	$4.1x10^{-5}$	10^{-4}
quartz powder	23.5	$4.3x10^{-5}$	10^{-4}
silty clay	32	$(3 - 6)x10^{-5}$	$(1.2 - 6.5)10^{-8}$

Electrokinetic processes, and, more specifically, the induced electroosmotic flow, have been used in geotechnics and construction since the 1930s. Its application for removal of contaminants from soils with low permeability was studied by a number of scientists recently (Putnam 1988; Bruell et al. 1992; Hamed et al., 1991; Shapiro and Probstein, 1993; Hicks and Tondorf, 1994; etc.).

Segall and Bruell (1992) have evaluated the feasibility of nutrient-transport due to an electrical field. In their experiments, transport of nitrates through an electroosmotic column packed with simulated soil (pure kaolinite clay) was examined. The average concentration of ammonia-nitrogen in the effluents was between 10 and 25 mg/L, and of nitrate-nitrogen was about 1.5 mg/L. The results for the concentration of nitrogen in the soil were not reported in the publication.

CHAPTER 3

METHODOLOGY

This study is investigating the feasibility of nutrient supply for in-situ bioremediation in low permeability soils using electrokinetics. It is an attempt to achieve relatively uniform distribution of an ammonium nitrate solution in natural clayey silt through application of direct current. Conditions close to natural ones were simulated as much as possible in this experiment.

3.1 Characterization of the medium

3.1.1 Physical parameters of the soil

The soil material for the experiment was provided from the region of Montreal. It was natural clayey-silt soil with an initial mean water content of 57%, average bulk unit weight 1.76 g/cm^3 , dry unit weight 1.07 g/cm^3, plastic limit 26.7%, liquid limit 60%, and plasticity index 33.3%. After air drying and dispersing the soil, the fraction passing through a # 40 (0.425 mm) sieve was used for the experiment. Its mineralogical composition determined by X-ray diffraction was as follows: non-clay minerals - quartz - 31%, feldspar - 28%, calcite - 4%, dolomite - 3%, clay minerals - illite - 15%, chlorite - 5%, kaolinite - 4%, and 5% mica, attapulgite and amphibole.

3.1.2 Chemical characteristics of the soil

Chemical analyses were carried out to determine some important chemical parameters of the soil: pH = 7.55, CEC = 21 meq /100 g, carbonate content = 6 % as $CaCO_3$, Kjeldahl nitrogen content = 0.84 mg N/ g dry soil, ammonium-N - not detected, nitrate-N - not detected.

3.2 Choice and description of the nitrogen containing nutrient

The choice of ammonium nitrate as a source of nitrogen for in-situ bioremediation was determined by several factors:

1) The form of nitrogen most readily appropriated by all microorganisms is ammonia, although nitrate is also used by many microorganisms (Gottschalk, 1985).

2) Using this source, introduction of ions unnecessary for the growth of bacteria is avoided.

3) Nitrate introduced in the electrical field is reduced at the cathode to ammonia according to the following formulas:

$NO_3^- + 2H^+ + 2e^- \Leftrightarrow NO_2^- + H_2O$, $E^0 = +0.84$ volts

$NO_2^- + 8H^+ + 6e^- \Leftrightarrow NH_4^- + 2H_2O$, $E^0 = +0.89$ volts

$2NO_3^- + 12H^+ + 10e^- \Leftrightarrow N_2(g) + 6H_2O$, $E^0 = +1.24$ volts (Segall and Bruell, 1991).

So, as a result of electroosmosis, ammonia is the prevailing form of nitrogen.

4) The yield of microorganisms is favorable to the presence of nitrogen in the ammonia form (Droste, 1991).

5) The diffusion coefficient is relatively high in comparison with the other nitrogen compounds - in the range from 1.75×10^{-5} cm^2sec^{-1} to 1.9×10^{-5} cm^2sec^{-1} for concentrations between 0 and 0.2M, while the values for ammonium sulfate are from 0.87×10^{-5} cm^2sec^{-1} to 1.53×10^{-5} cm^2sec^{-1} (Robinson and Stokes, 1959).

6) Among the nitrogen containing compounds which are available on the market, ammonium nitrate has a considerably high nitrogen content - 33%.

7) Ammonium nitrate has a comparatively low price.

The choice of experimental concentrations for the nitrogen containing nutrients is based upon data reported in literature for the C:N:P ratio. In soil bacteria it is 31:5:1, while in soil it is up to 120:10:1 (Paul and Clark, 1989). Soil contaminated with oils (90% C) at a concentration of 50 000 mg/kg dry soil contains approximately 45 000 mg C. For its degradation at least 4 500 mg N are necessary, or in the case of NH_4NO_3 (33% N), 13 000 mg (an average ratio of 100:10:1 is assumed). Aggarwal et al. (Hinchee, 1991) give concentrations from 11 to 19 564 mg/L NH_4^+ as a component of nutrient solutions for bioreclamation. On this base 100, 1000, and 13 000 mg/L are assumed for the experiment.

3.3 Experimental installation

The installation design is a result of a long process of theoretical and experimental consideration and optimization of the systems features (materials, dimensions, hydraulic, chemical, and electrical parameters).

Four cells, each with the dimensions 17/5.0/4.5 cm were packed with soil wetted in advance (31% moisture content). Two plate electrodes made of stainless steel mesh at both ends of three of the cells were connected in parallel to a power supply. The applied potential between the electrodes was 8.5 V at a distance of 17 cm (0.5 V/cm). Partial potentials between the cathode and anode, as well as between the cathode and 16 silver probe electrodes inserted in the soil of cells 1, 2, and 3 were measured twice a day (once during the second half of the experiment when the current of the processes slowed down). The current in the system was recorded at the same time. The fourth cell was not connected to the power supply and served for control, with fluid transport due only to the hydraulic gradient. Each cell was supplied with a nutrient solution of ammonium nitrate with the following concentrations: 13 000 mg/L - cell 1, 100 mg/L - cell 2, 1 000 mg/L - cells 3, and 1 000 mg/L - cells 4. The solutions were delivered at a constant level from reservoirs separated by sand filter from the mesh of the anode. The purpose of the filter was to prevent undesirable clogging of the mesh and soil pores next to it, due to eventual precipitation. The solution level in each cell was five mm below the soil surface in order to avoid overflow of the liquid instead of conduction through the soil. The flow due to the electrokinetic transport phenomena was discharged through drains at the bottom of the cells next to the cathode and collected into vials for analyses. (Fig.3. 1). The experiment duration was 741 hours.

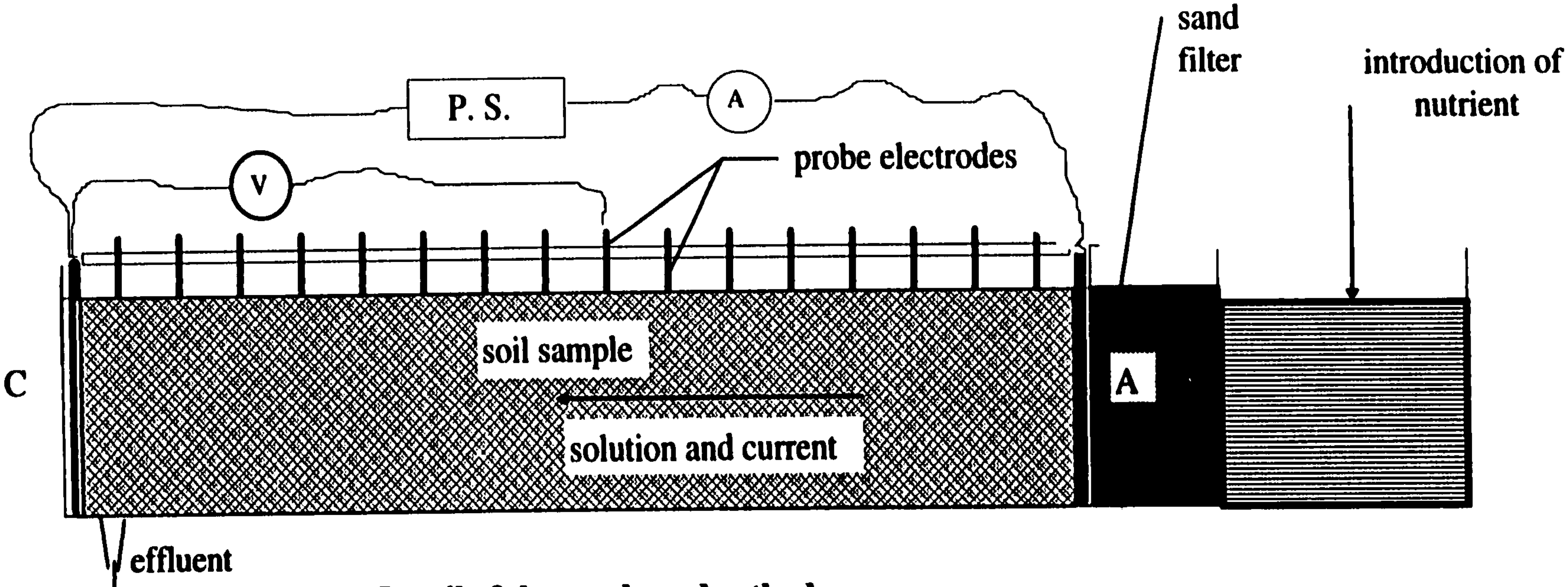
3.4 Measurement of the parameters involved in the processes

3.4.1 Electrical parameters

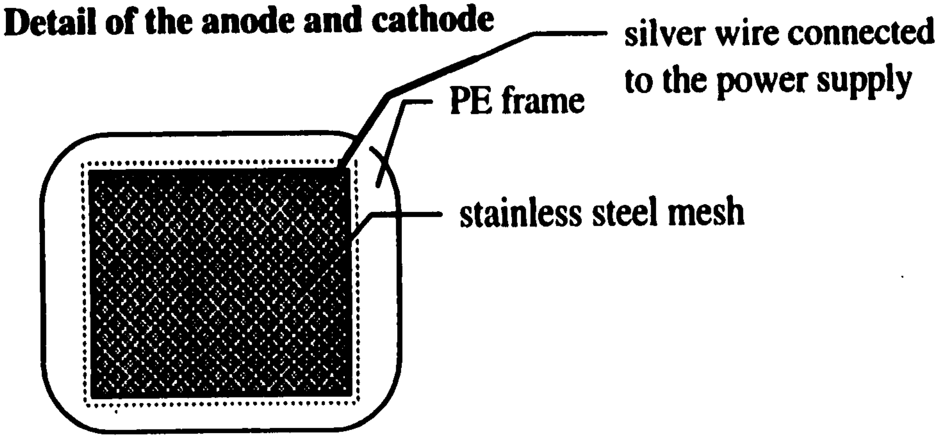
The potential differences between the anode and cathode, as well as between the cathode and every probe were measured in parallel by a voltmeter. An ammeter was constantly connected to measure the electric current in the system.

Figure 3.1

Experimental installation (lateral section)



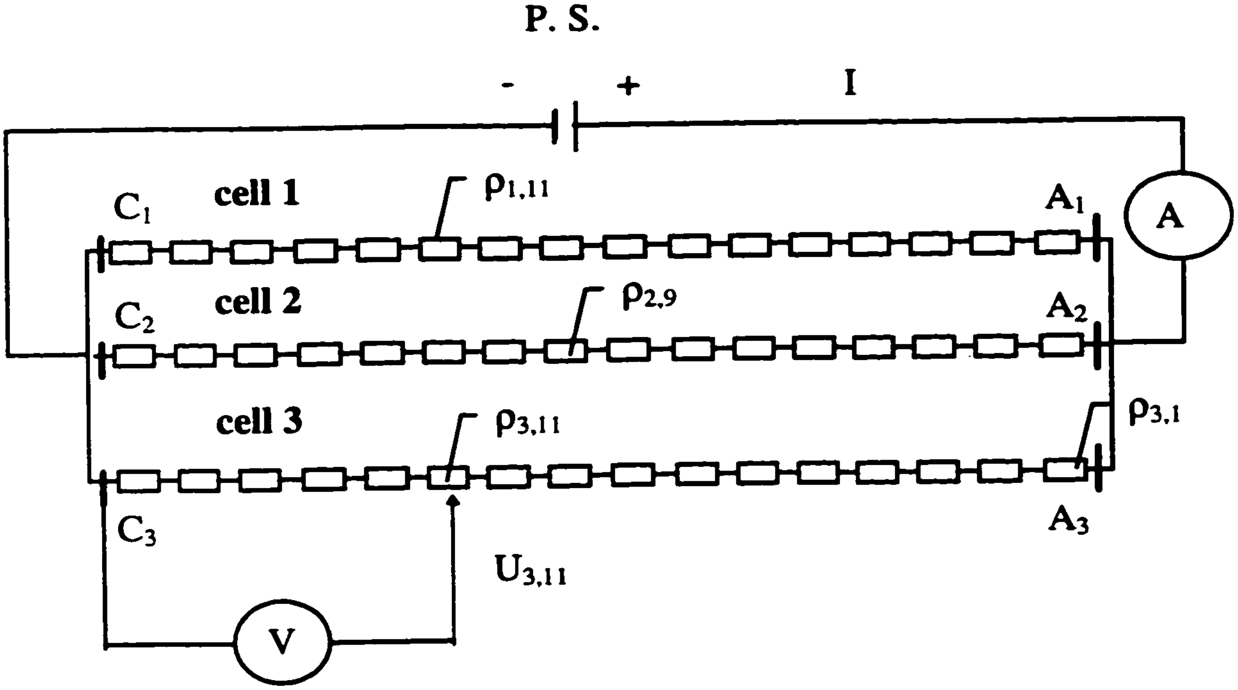
Detail of the anode and cathode



Measurement of the current in each cell would have been more precise but would have complicated the electric scheme unnecessarily, since the relative values and not the absolute ones are important for differentiation between the cells (Fig.3. 2).

Figure 3.2

Electrical scheme



Each ▭ represents a one cm long section of the soil sample in the respective cell with a probe in the middle.

Based on these data and applying Ohm's law, the overall and partial resistivities of the soil samples were calculated.

The change of resistivity with time for each cell was plotted in graphs, shown in Chapter 4. The tabulated data are enclosed in the Appendix.

$U_{C1,A1} = U_{C2,A2} = U_{C3,A3} = 8.5\ V$

$$\ldots \quad \rho_{1,4} = \frac{U_{1,4} * A}{I * l_4}, \ldots \quad \rho_{3,11} = \frac{U_{3,11} * A}{I * l_{11}}, \ldots$$

U - potential

ρ - resistivity

A - cross-sectional area

I - current

l - lenght

3.4.2 Physical parameters (water content)

The water content of the soil samples was measured using the standard procedure of ASTM. The water content of a sample is the difference between the weights of the wet and dried sample in an oven at 105°C, divided by its dry weight and expressed in %. The average water content of a representative sample was determined before the beginning of the experiment. After the disconnection of the experimental set-up, the changes in the water content regarding distance and depth were examined by destructive sampling. The results were processed and the tables are included in the Appendix.

3.5 Chemical analyses

3.5.1 Measurement of pH

The soil pH was measured electrometrically in a soil paste with a ratio of dry soil to water 1:2.5 by weight (Hesse, 1971).

Since the measurement of the pH is quite arbitrary and the values strongly depend on the adopted procedure, all of the samples were processed strictly adhering to the following procedure: three grams of air-dried soil were made into a homogeneous paste with 1.5 mL of distilled water. The paste was diluted with an additional 6 mL of water and the suspension was shaken for 1 hour at a speed of 150 rpm on an orbital shaker, then left to settle for 1/2 hour. The bulb of the pH electrode was immersed into the soil paste and when a constant reading was obtained (up to 5 min.), the value was then recorded.

The pH of the influents and effluents was measured directly in the solution without any prior treatment.

The tables with the pH values are included in the Appendix. The figures (pH vs. distance from cathode for the soil samples, or vs. time for the influent and effluent solutions) are presented in Chapter 4. 3.

3.5.2 Ammonium concentration

The concentration of exchangeable ammonium ions was measured electrometrically using an ion-selective electrode from Canadawide Scientific Inc. It is a gas sensing electrode and detects dissolved ammonia. In order to measure its concentration, the ammonium ion is first reduced to ammonia by alkalization of the solution. At pH above 11 more than 97% of the ammonium is converted to free ammonia (Rump, H. H., 1988).

Influent and effluent solutions were analyzed directly, without preliminary treatment.

Soil samples were processed by extraction of the exchangeable ammonium ions with 10 mL/g of dry soil of 2M potassium chloride solution. The suspensions were shaken for two hours, then left to settle for one hour. The supernatants were used for the analysis (Hesse, 1971).

Fifteen mL samples of the analyzed supernatants were placed into scintilation vials. Each sample was stirred thoroughly with 0.3 mL of 10M sodium hydroxide. The tip of the ammonia electrode was immersed into the liquid and the reading in mV was recorded when it became stable. The mV readings were converted to concentration units (mg/L) by using a standard curve prepared in advance. The procedure was in accordance with the electrode manufacturer's instructions and method 4500 - NH_3 - F (Standard Methods for the Examination of Water and Wastewater, 17th ed., 1989).

The ammonium concentrations for the soil samples were recalculated as mg NH_3-N/g of dry soil. The soil samples were not tested for ammonium in fixed form. Fixed ammonium is not available for the microorganisms, so it is not a subject of the present research.

All results are presented in tabular form in the Appendix.

3.5.3 Nitrate concentration

Nitrate-N in the solutions and in soil was measured in the same samples used for the determination of ammonium.

The samples were analyzed according to method 4500 - $N0_3$ - G (Standard Methods for the Examination of Water and Wastewater, 17th ed., 1989). This method makes use of a NH_3 gas-sensing electrode after reduction of the nitrate to ammonia with a titanous chloride reagent. The method is applicable in a narrow range of concentrations - between 0.1 and 20 mg NO_3^--N/L. When necessary, it can be extended by appropriate dilution of the samples. This method evaluates both ammonium- and nitrate-N, so, in order to obtain the NO_3^--N concentration alone, the NH_3-N determined in advance should be subtracted from the result.

The distribution of NO_3^--N in each cell is presented in tables included in the Appendix.

CHAPTER 4

EXPERIMENTAL RESULTS

The description of nitrogen compounds distribution and behavior in soil under an electrical field requires information about the distribution of electrical and physico-chemical parameters. Consequently, the following parameters were taken into consideration in the discussion of results: resistivity of soil, water content, pH of discharge liquids and soil, and concentration of ammonia and nitrates distribution.

4.1 Resistivity of soil

The resistivity of a one centimetre soil section of each of the three cells, was calculated based on the measurements of the electric current in the system and the potential gradients between 'cathode and probe electrodes', as well as between 'cathode and anode'. All three cells were connected in series to the power supply. The variation of resistivity versus time is plotted in Fig. 4.1.1 - 4.1.5. The resistivity as a function of distance from anode is presented in Fig. 4.1.6 - 4.1.8.

In all three cells, the changes in resistivity during the first ten days of the experiment were insignificant but did show a slight increase. After this period, dramatic peaks of higher values were observed. The resistivity sharply increased especially in the vicinity of the electrodes in all cells during the last 10 days of the experiment.

At the beginning of the experiment, the variation of soil resistivity with distance from the anode was from 3.94 to 9.69 ohms.m for cell 1, from 3.94 to 13.94 ohms.m for cell 2, and from 3.94 to 12.04 ohms.m for cell 3. In the end, these values were 166.7 and 146.7 ohms.m for cell 1, 166.7 and 350.0 ohms.m for cell 2, and 166.7 and 143.3 ohms.m for cell 3. The distribution of resistivity in the anode area was the same for all cells. In some points, the resistivity of soil in cell 2 with the lowest concentration was superior to the other cells.

Figure 4.1.1

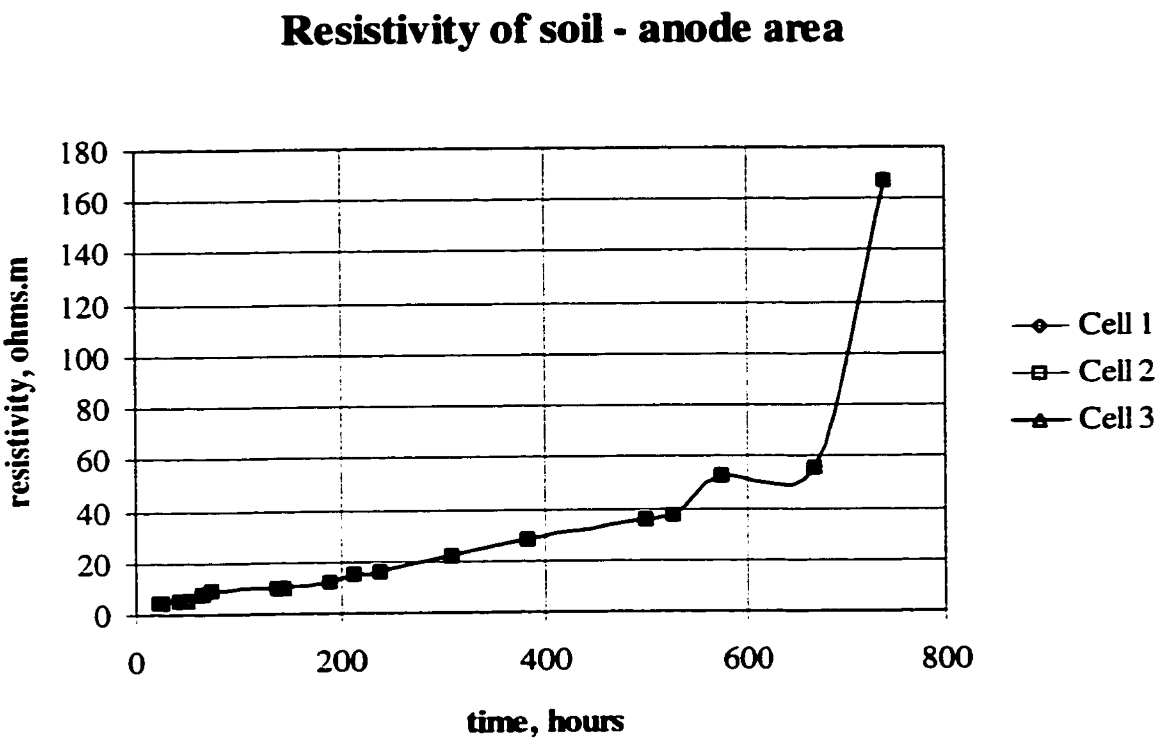
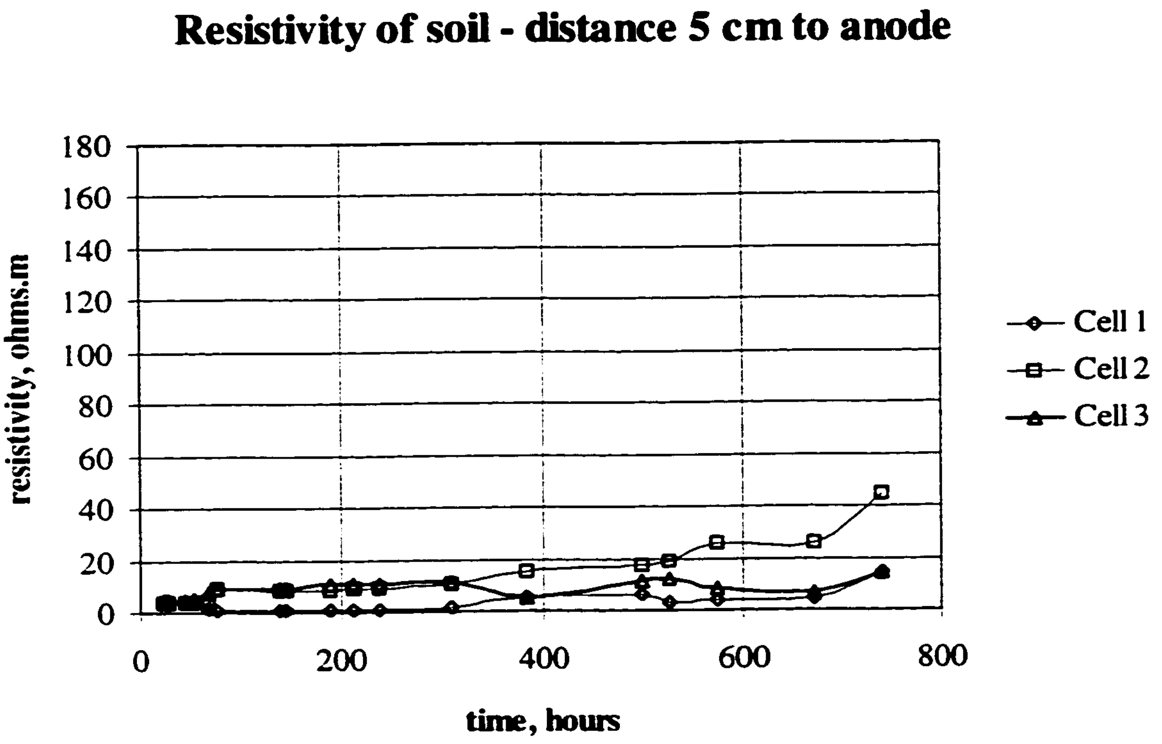

Resistivity of soil - anode area
resistivity, ohms.m
180
160
140
120
100
80
60
40
20
0
0
200
400
600
800
time, hours
Cell 1
Cell 2
Cell 3

Figure 4.1.2



Resistivity of soil - distance 5 cm to anode
180
160
140
120
100
80
60
40
20
0
resistivity, ohms.m
0
200
400
600
800
time, hours
Cell 1
Cell 2
Cell 3

Figure 4.1.3

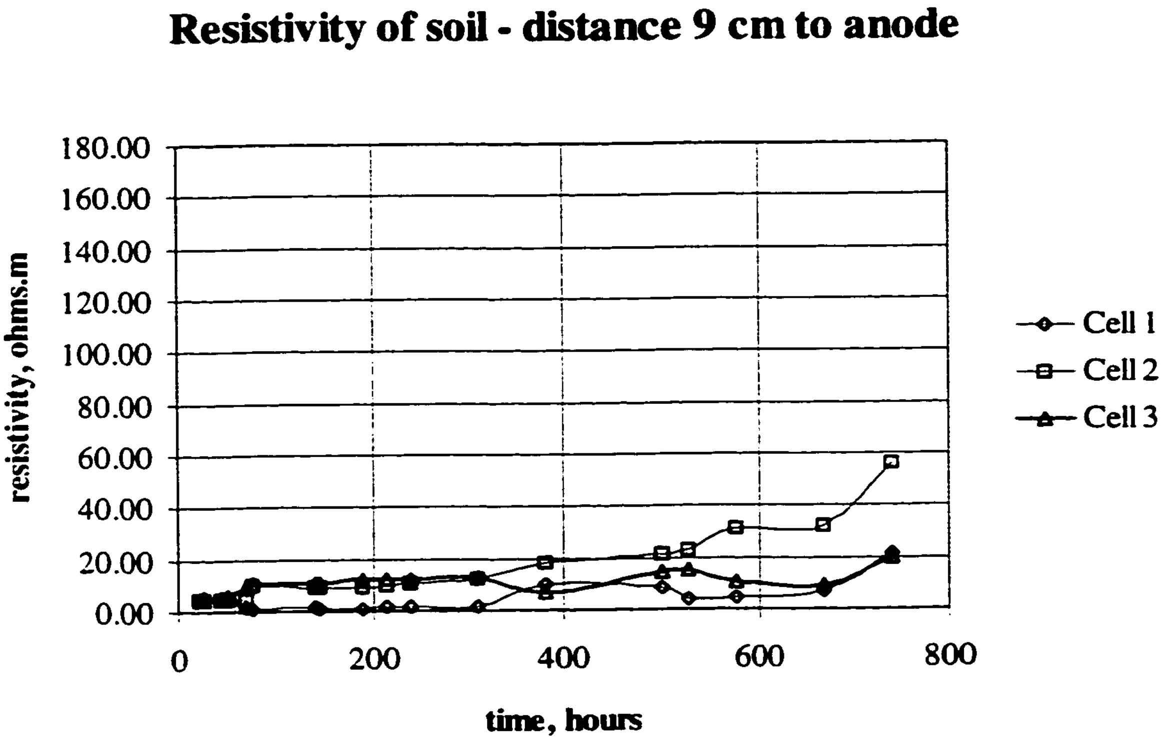

Resistivity of soil - distance 9 cm to anode
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
resistivity, ohms.m
0
200
400
600
800
time, hours
Cell 1
Cell 2
Cell 3

Figure 4.1.4

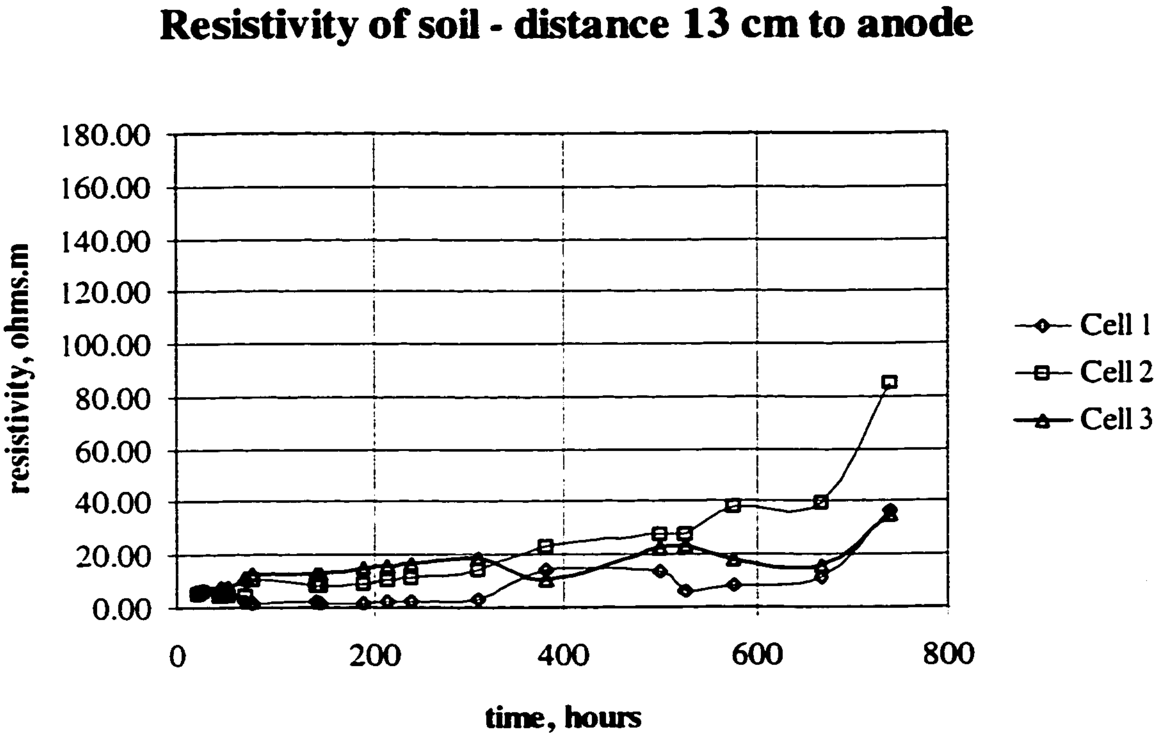

Resistivity of soil - distance 13 cm to anode
resistivity, ohms.m
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
200
400
600
800
time, hours
Cell 1
Cell 2
Cell 3

Figure 4.1.5

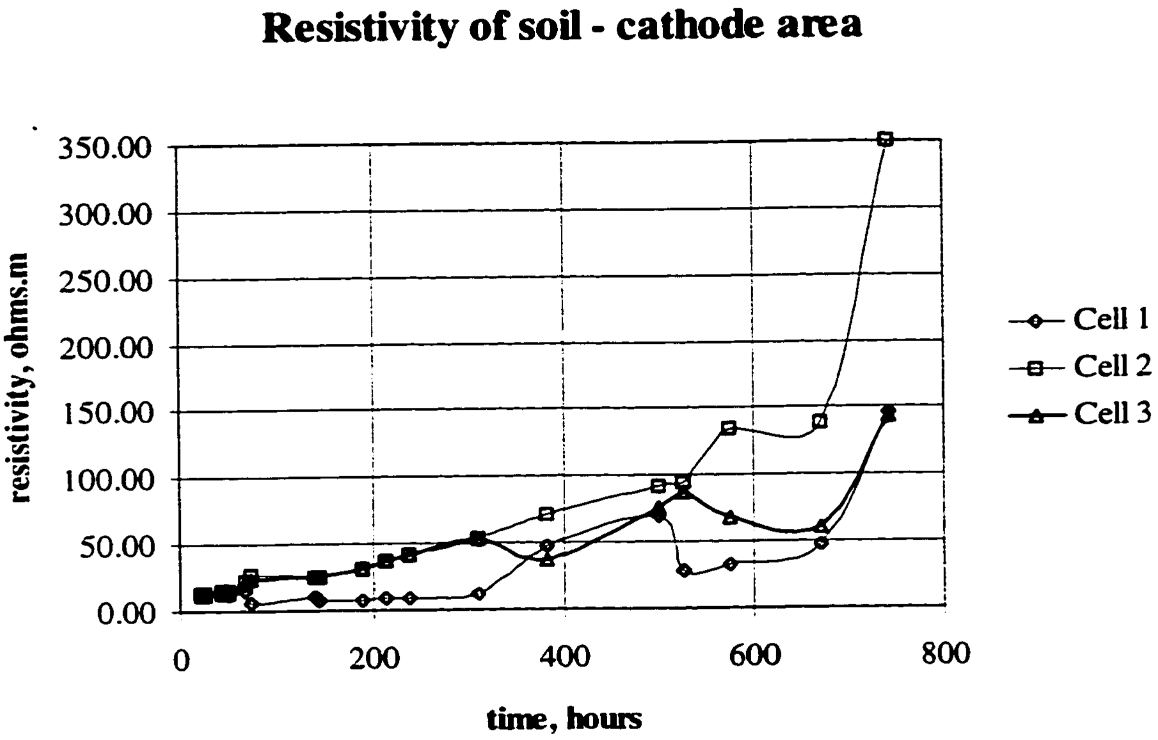

Resistivity of soil - cathode area
resistivity, ohms.m
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0
200
400
600
800
time, hours
Cell 1
Cell 2
Cell 3

Figure 4.1.6

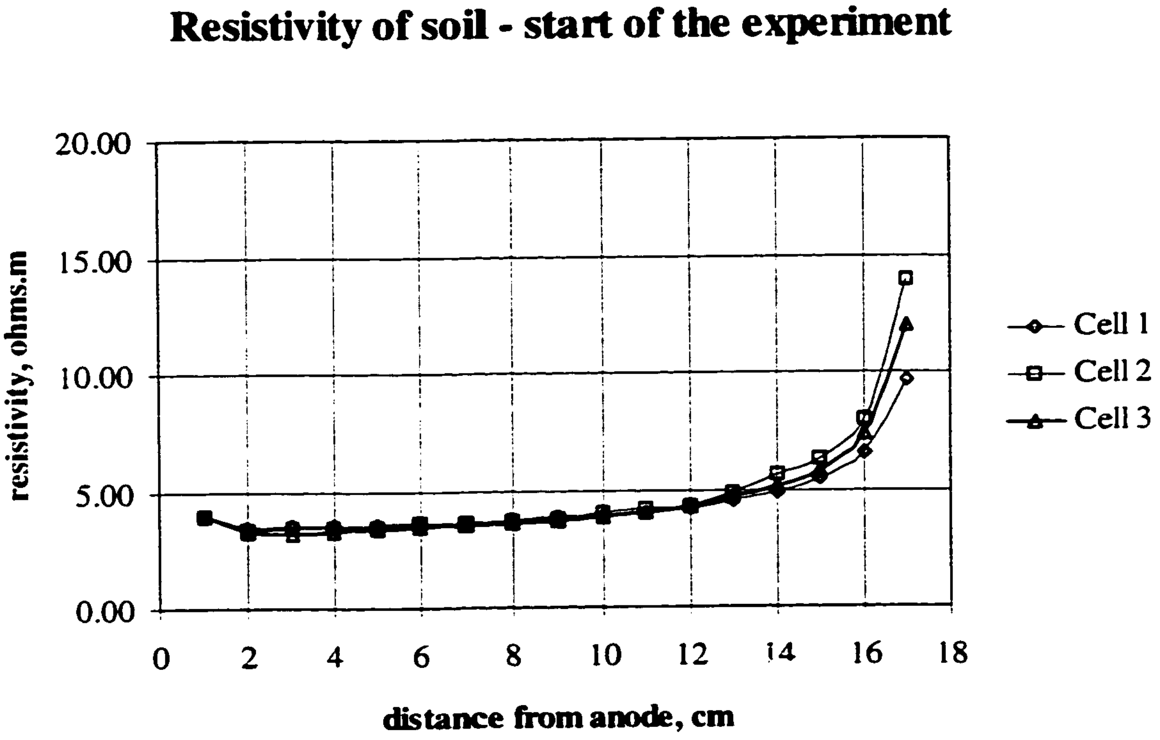
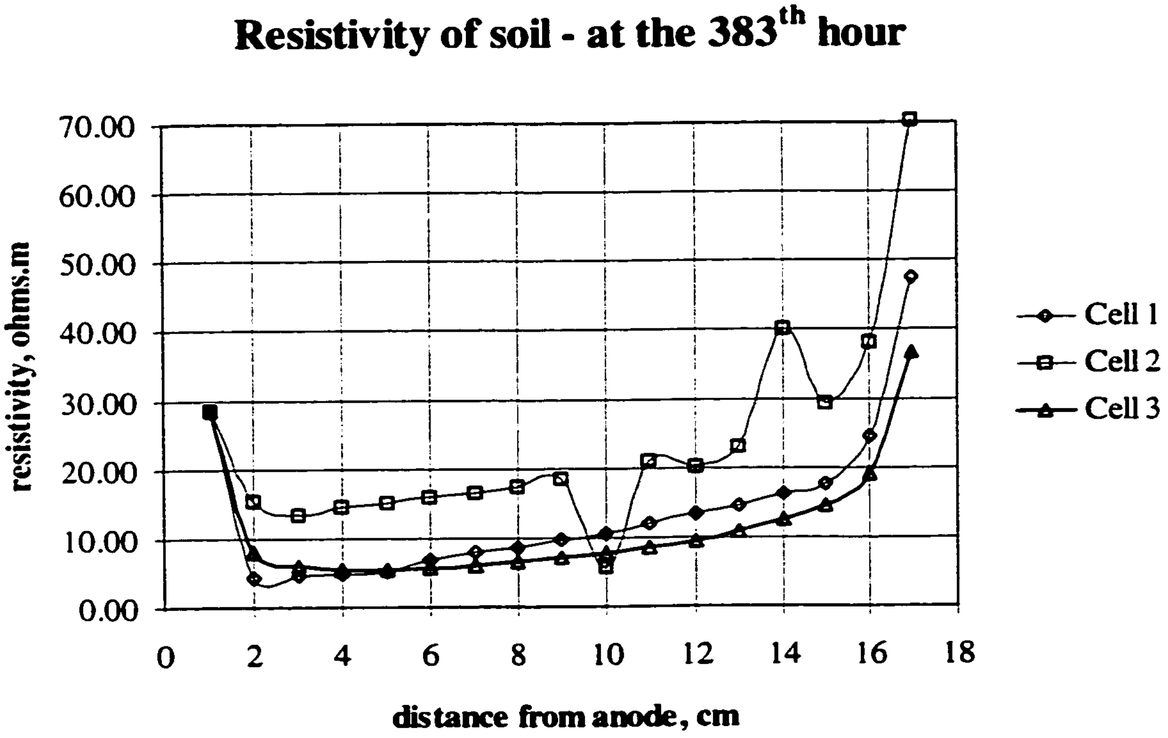
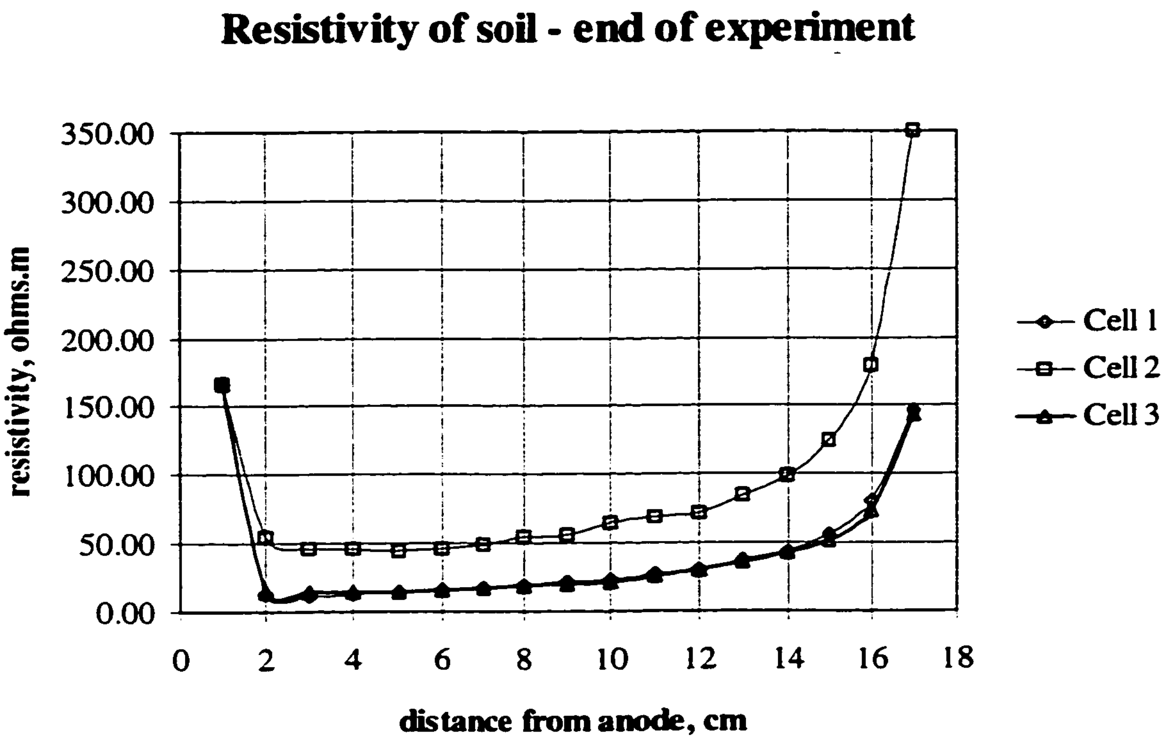

Resistivity of soil - start of the experiment
20.00
15.00
10.00
5.00
0.00
resistivity, ohms.m
0
2
4
6
8
10
12
14
16
18
distance from anode, cm
Cell 1
Cell 2
Cell 3

Figure 4.1.7


Resistivity of soil - at the 383th hour
resistivity, ohms.m
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
2
4
6
8
10
12
14
16
18
distance from anode, cm
Cell 1
Cell 2
Cell 3

Figufe 4.1.8


Resistivity of soil - end of experiment
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
resistivity, ohms.m
0
2
4
6
8
10
12
14
16
18
distance from anode, cm
Cell 1
Cell 2
Cell 3

4.2 Water content

After the disconnection of the experimental set-up and destructive sampling of each of the four cells, the changes in the water content with distance and depth were examined.

The initial water content of the soil in all cells was 31%. The average water content after 30 days of experiment changed to:

cell #	upper layer	bottom layer
cell 1	30.4%	30%
cell 2	33%	28%
cell 3	28.6%	27.7%
cell 4	26.6%	26.5%

The average value demonstrates slightly lower water content in the bottom layer than the upper layer (from 0.4% - 5%). This difference is more significant by increasing the electrode depth. The cell without the electrical field (cell 4) showed uniform vertical distribution. Cell 2, with lowest concentration of nutrients, demonstrated the highest difference between, the upper and bottom layers (5%).

The water content has a tendency to decrease from the anode to cathode. The highest values in the anode area were found in cell 2. Both values for top and bottom layers are higher then the plastic limit of soil. The horizontal distribution of water content in cell 2 demonstrated the highest value for top layer and the lowest value in the bottom layer among all testing cells. The lowest values for the top layer belonged to cell 4 without the presence of an electrical field. The highest value for the bottom layer was found in cell 1, with the highest concentration of nutrients.

A detailed distribution of the water content is presented in Table 7 in the Appendix.

The variation of the water content with distance from the anode is plotted in Fig. 4.2.1 (top layers) and Fig. 4.2.2 (bottom layers) .

Figure 4.2.1

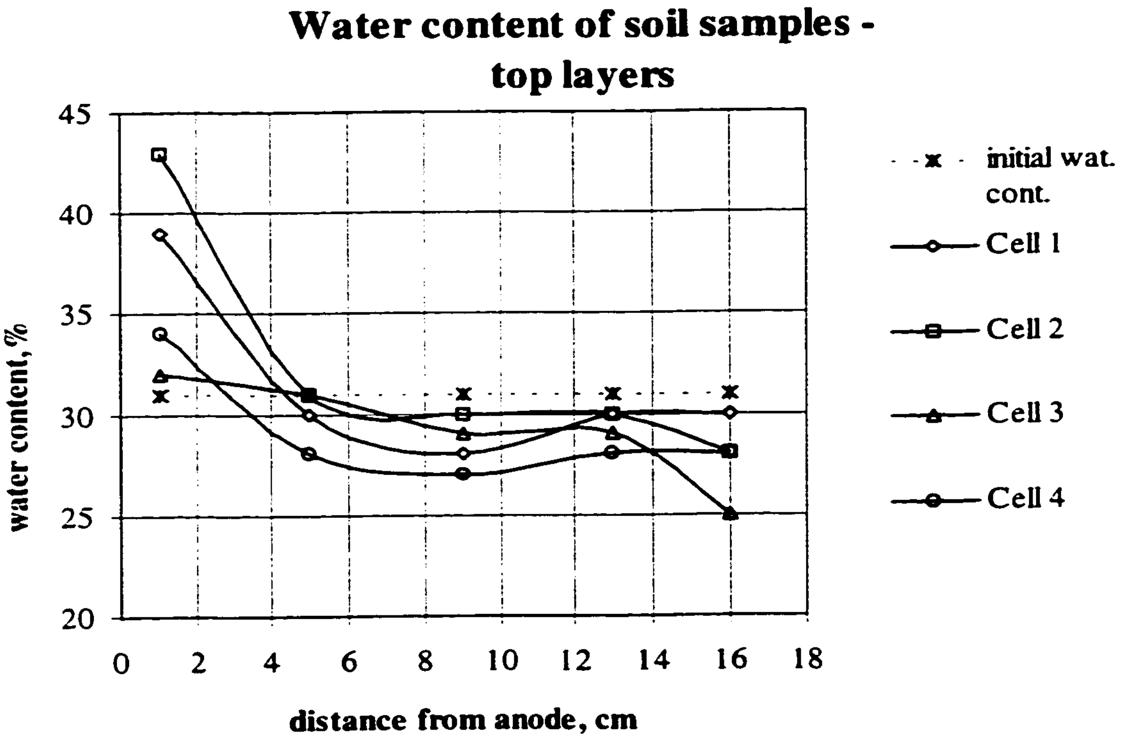
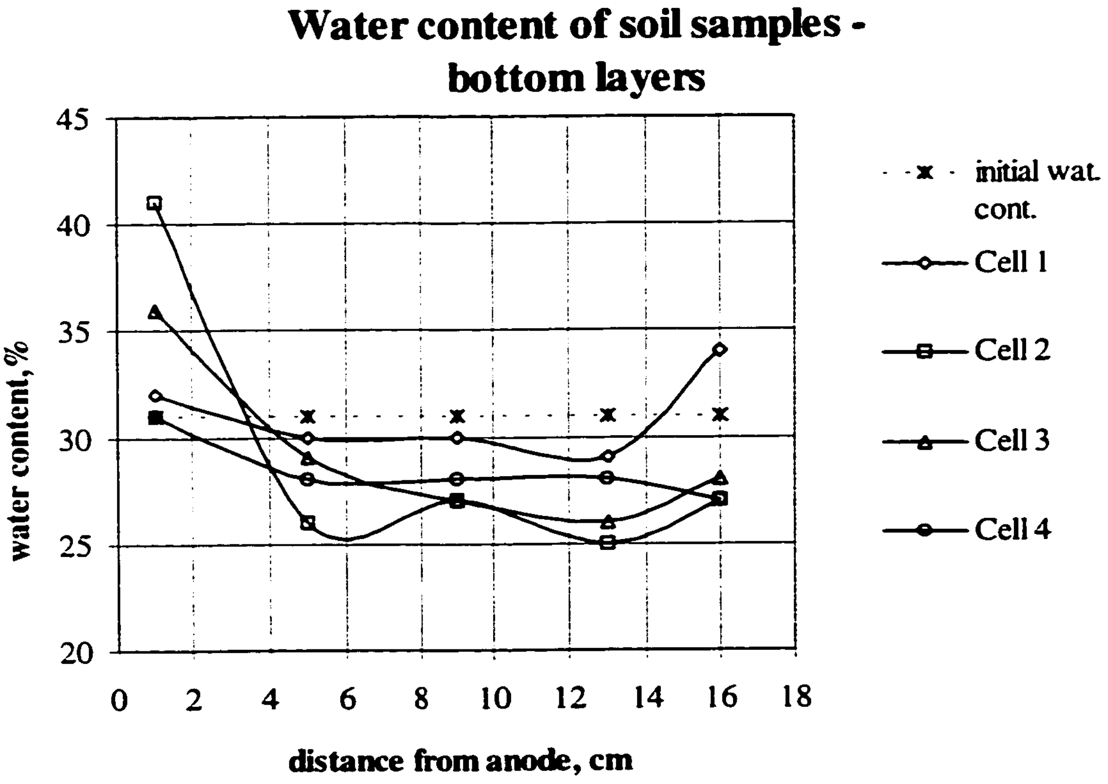

Water content of soil samples - top layers
45
40
35
30
25
20
water content, %
0
2
4
6
8
10
12
14
16
18
distance from anode, cm
initial wat. cont.
Cell 1
Cell 2
Cell 3
Cell 4

Figure 4.2.2


Water content of soil samples - bottom layers
45
40
35
30
25
20
0
2
4
6
8
10
12
14
16
18
water content, %
distance from anode, cm
initial wat. cont.
Cell 1
Cell 2
Cell 3
Cell 4

4.3 pH variation

4.3.1 pH of the system's liquids

The pH of the solution supplied through the anode, and that collected at the cathode, were measured throughout the duration of the experiment.

The initial values of pH for the solution with a concentration of 13 000 mg/L (cell 1), 100 mg/L (cell 2), 1 000 mg/L (cell 3), and 1 000 mg/L in cell 4 (without electrical field) were 6.1, 6.52, 6.64, 6.64, respectively. The changes of pH with time were in the following range:

pH	cell 1	cell 2	cell 3	cell 4
liquid in supply reservoirs[1]	5.83 - 2.4	6.52 - 2.3	6.64 - 2.29	6.64 - 6.63
collected liquid (effluent)[2]	9.6	9.45 - 8.4	9.45 - 8.88	-

The variation of pH as a function of time is plotted in Fig. 4.3.1 (pH of the influents) and in Fig. 4.3.2 (pH and volume of the collected effluents). The results of the measurements are presented in the Appendix in Tables 8 and 9.

During the first few hours, the pH of the influent decreased 3 times due to oxidation processes on the anode. The cell with the lowest concentration had the highest discharge of effluent, while the one with the highest concentration had the lowest

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[1] the first and second numbers are the values at the beginning and at the end of experiment, resp.

[2] the first and second numbers are the values when the first and last outflow occurred, resp.

discharge of effluent. The lowest concentration of nutrients caused the lowest pH value of effluent during all periods of the experiment.

Figure 4.3.1

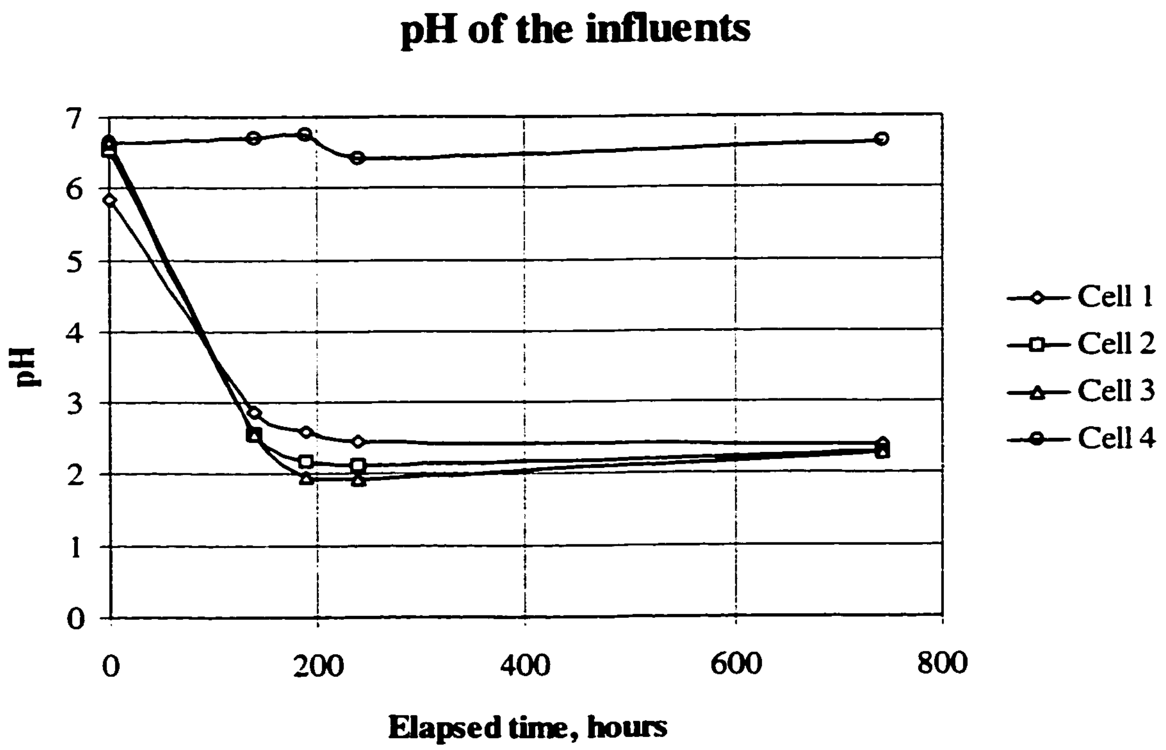
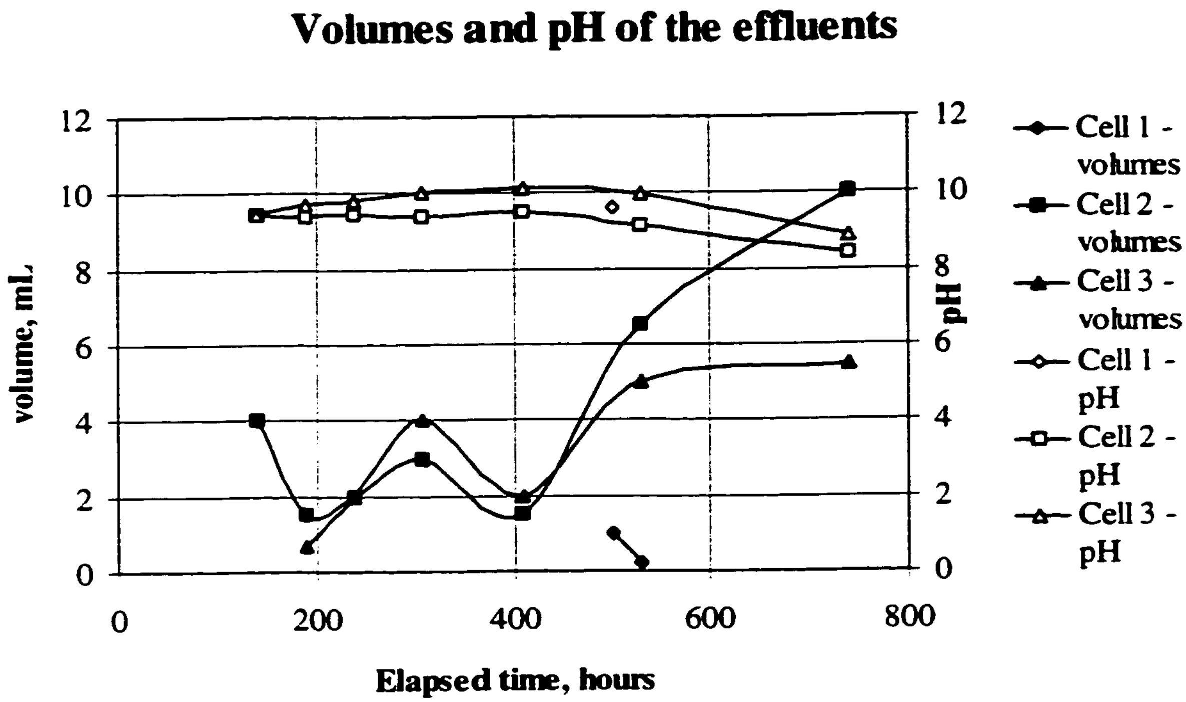


Figure 4.3.2



4.3.2 Soil pH distribution

The initial pH value of the natural non-contaminated soil used in the experiment was 7.55. After the destructive sampling of the soil, the pH of representative samples in length and depth of each cell was measured.

Due to the electrochemical transformations in cells No. 1, 2, and 3, the pH underwent corresponding changes, depending upon the position with regard to the electrodes. The changes in pH of the soil samples in the control cell (cell 4) were insignificant, which leads to the conclusion that possible biochemical reactions were negligible during this period of time. (Figures 4.3.3 and 4.3.4).

Table 10 with the pH values of the soil samples is included in the Appendix.

The pH in the cells with the lowest concentration of nutrient demonstrated the lowest value (5.39 in top layer and 4.49 in bottom layer) near the anode area.

Figure 4.3.3

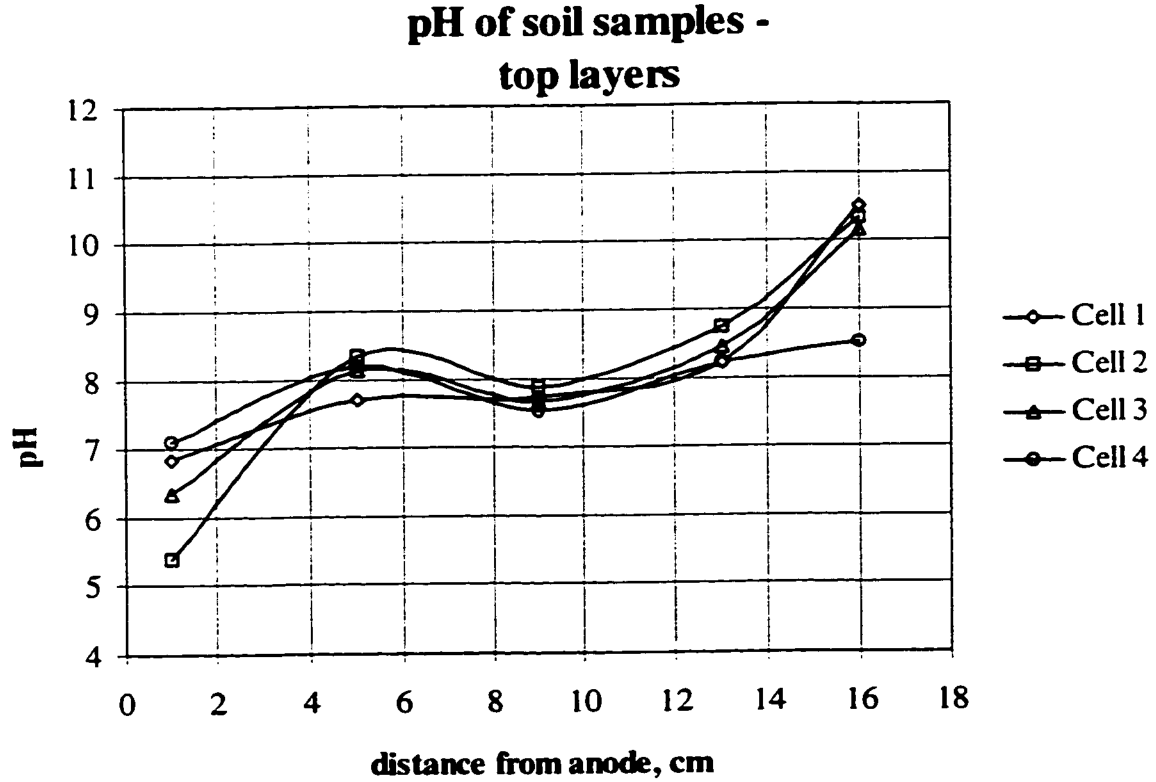
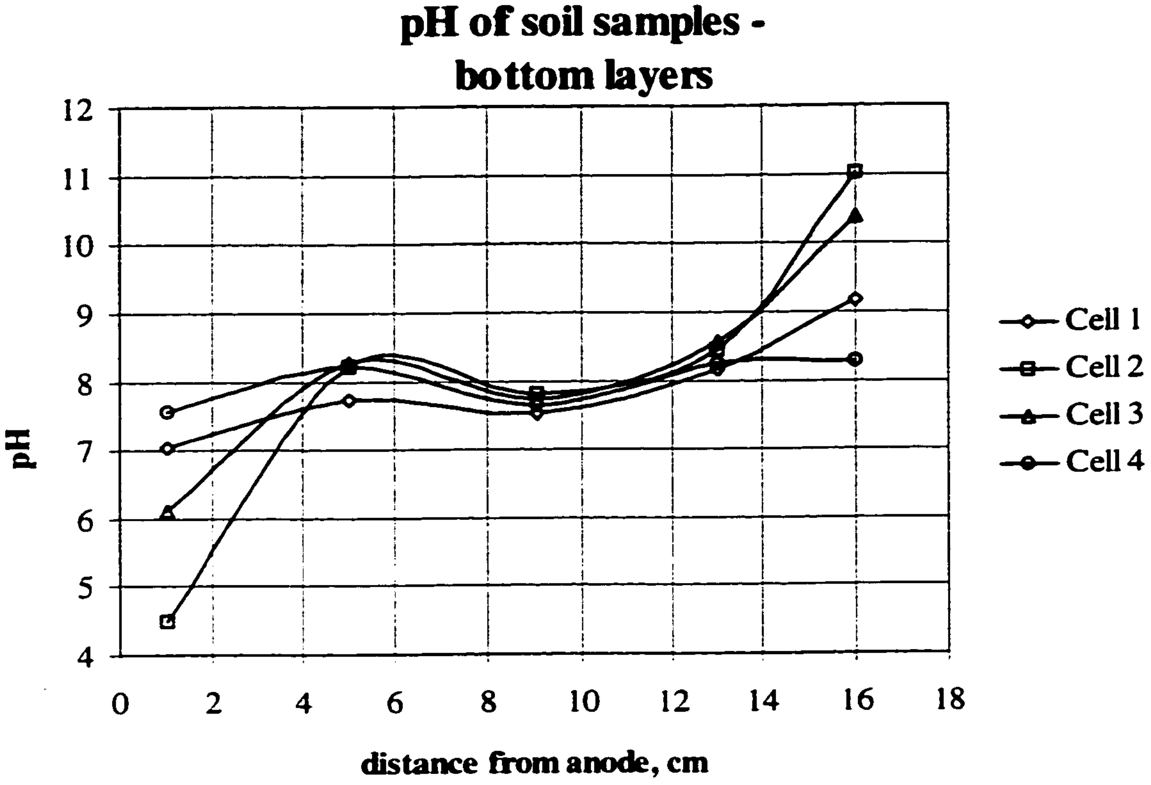


Figure 4.3.4



The increase of pH value was observed near the cathode area in all cells under the electrical field. The differences of the vertical pH value distributions are evident for all cells. The highest value (11.03) was observed in the bottom layer of the cell with the lowest concentration of nutrient. Relatively minimal changes in pH value (from 7.55 to 9.17) were observed in the bottom layer of the cell with the highest concentration of nutrient.

4.4 Distribution of nitrogen

Variations in the nitrogen content were determined in the two forms readily available for telluric microorganisms - as ammonium nitrogen and as nitrate (including any converted to nitrite) nitrogen.

4.4.1 Ammonium ion concentration

The following methodology was provided for ammonium measurements:

a) the concentration of the ammonium nitrogen in the nutrient solution from the supply reservoirs was monitored during the experiment.

b) five samples from each cell were tested - at the beginning and the end of the experiment, and at the 140th, 189.5th, and 239th hour.

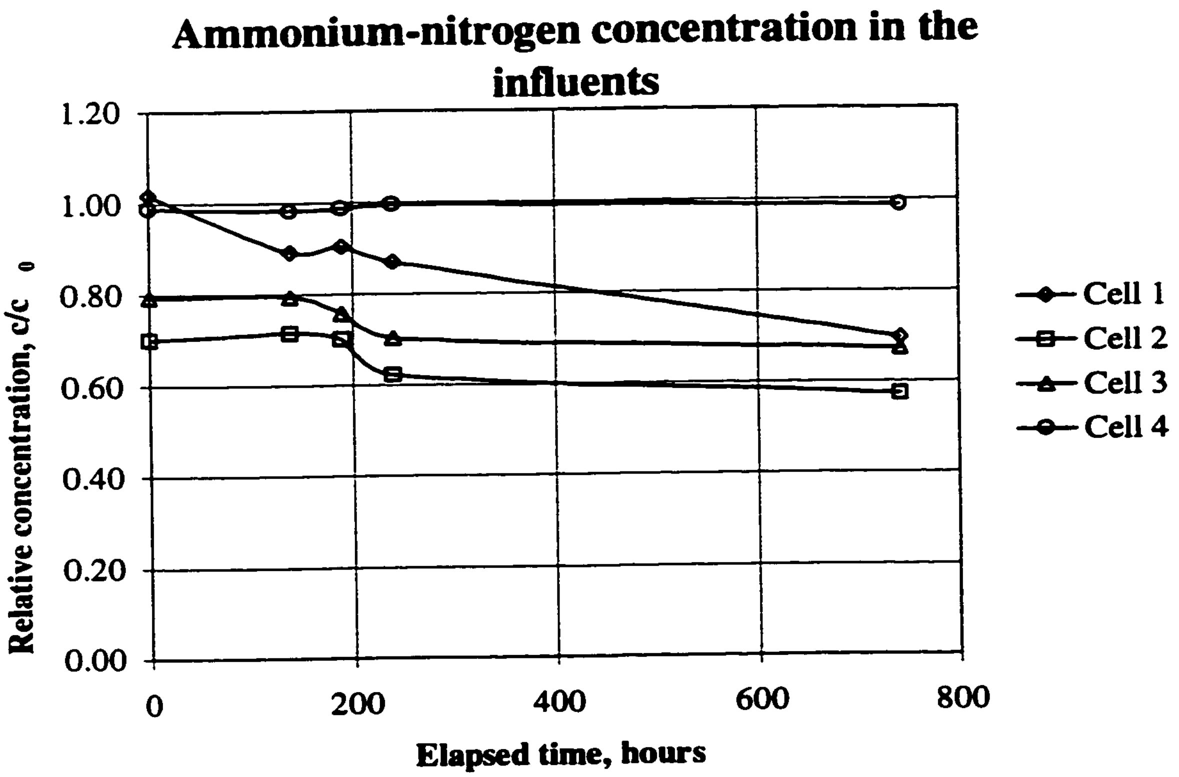
c) all the collected effluents were analyzed.

d) five samples from the top and five from the bottom soil layers of each cell were tested after the destructive sampling of the soil at the end of the experiment.

4.4.1.1 Ammonium ion concentration in the reservoirs

The results of the analysis and calculations are presented in Table 11 in the Appendix. The ammonium-nitrogen concentration in the supply reservoir of cell 1 dropped from 6 500 mg/L initially to 4 531 mg/L at the end of the experiment. The temporal variation of the ammonium - nitrogen in the reservoir of cell 2 and cell 3 had the same character (i.e. the concentration decreased from 35 mg/L to 29 mg/L and from 397 mg/L to 337 mg/L, respectively). These changes took place due to the oxidation state of the nitrogen compound under the influence of the electric field. The concentration in the its initial value throughout the experiment. The relative concentration c/c$_0$ (the ratio of the measured concentration **c** at time *i* to the initial concentration of the nutrient solution **c$_0$**) is plotted against the elapsed time in Fig. 4.4.1. Although the absolute value of the difference (c$_0$ - c = 1,969 mg/L) of ammonium-nitrogen by the end of the experiment was the highest for cell 1, the relative decrease in the concentration was the lowest. However, the rate of transformation was very high, and c/c$_0$ reached the value of the ratio for cell 3 at the end of the experiment. The most significant loss in comparison to the initial concentration occurred in cell 2 (42%), while for cell 1 it was 30%. The losses for cells 3 and 4 were 33% and 2%, respectively. The lower than 1.00 values of the relative concentrations of cells 2 and 3 at the beginning of the experiment were due to a lag in the connection to the power supply.

Figure 4.4.1



4.4.1.2 Ammonium ion concentration in the effluents

Nitrogen in ammonium form was found to be greatly reduced in the collected effluents. The detected concentrations were as follows: 24 mg/L and 22 mg/L in the two samples collected from cell 1, between 3.5 mg/L and 22 mg/L for cell 2, and from 2 mg/L to 17 mg/L for cell 3. Cell 4 did not yield any effluent.

Although the absolute concentrations of the effluent collected from cell 1 were the highest, the recovery was insignificant - less than 4%.

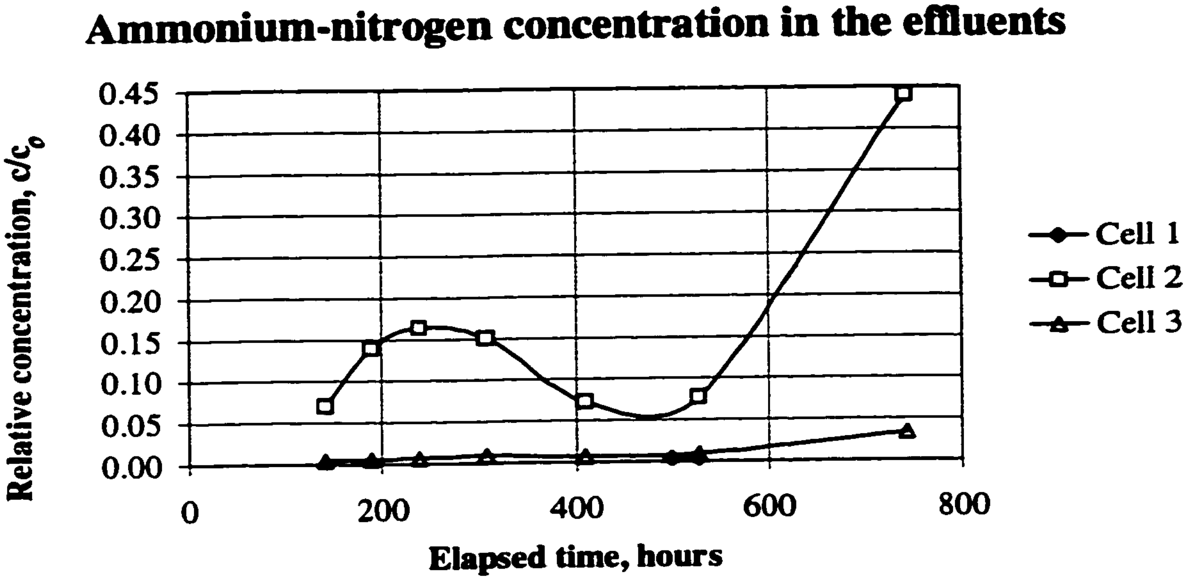
Ammonium nitrogen concentration in the effluents of cell 2 had an unstable character - it doubled between the 140th and 239th hour of the experiment, then dropped up to the 529th hour, and sharply increased in the end to reach a recovery of 44%.

The concentration of ammonium nitrogen in the collected samples from cell 3 compared to the concentration of the supplied solution was low, but comparatively constant in time - c/c_0 was approximately 1% with the tendency to an increase to 3% towards the end of the experiment.

The relative concentrations as a function of the elapsed time are plotted in Fig. 4.4.2 below.

The results of the analyses and calculations are presented in Table 16 in the Appendix.

Figure 4.4.2



4.4.1.3 Ammonium ion concentration in the soil

Ammonium nitrogen content of the soil was determined in both layers (top half and bottom half) of each cell at distances of 1, 5, 9, 13, and 16 cm from the wall bordering the supply reservoir (anode).

The results are presented graphically on Fig. 4.4.3 for the top layer and Fig. 4.4.4 for the bottom layer. The data from measurements and calculations are contained in the Appendix (Tables 18, 19, 20, and 21).

The maximal and minimal absolute values were as follows:

cell #	layer	max (mg/g dry soil)	min (mg/g dry soil)
cell 1	upper lower	2.07 2.05	0.05 0.12
cell 2	upper lower	0.08 0.04	0.02 0.01
cell 3	upper lower	0.14 0.14	0.01 0.01
cell 4	upper lower	0.3 0.31	0.00 0.00

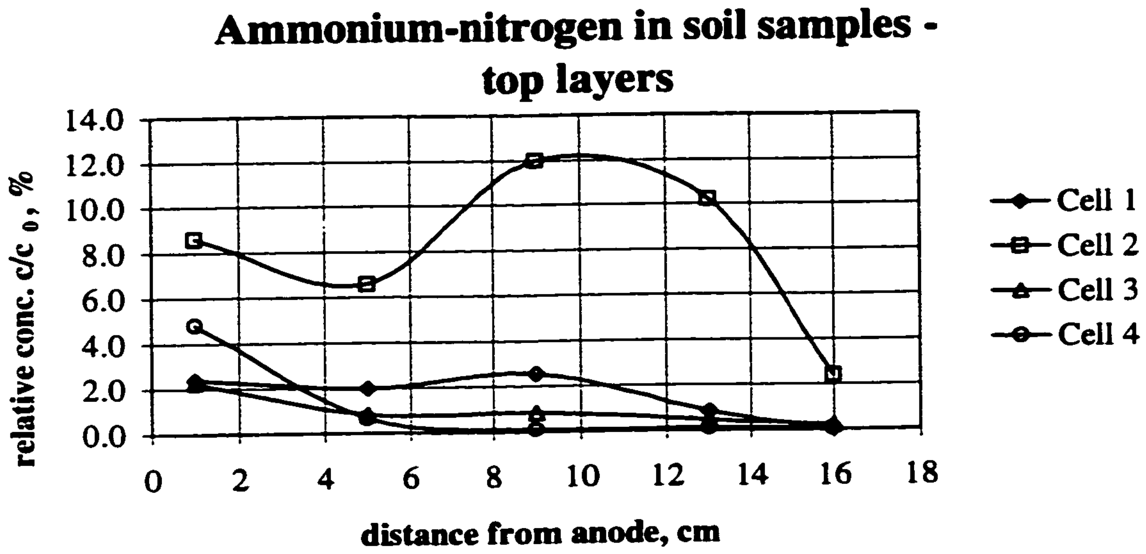
The distribution of nitrogen in ammonium form from the anode to the cathode had a different character for each cell.

For the upper layers of cell 1 and cell 2, the highest concentrations were detected in the middle cells and the lowest ones - near the cathodes. The nitrogen content decreased from the anode to a distance of 5 cm (approx. 1/4 of the length of the cell), then it reached its maximum at 9 cm from the anode, and dropped to its lowest value near the cathode. The peaks were smoother for cell 1 than for cell 2. In spite of the high absolute concentrations in cell 1, the relative concentrations were in the range of appr. 2%, while for cell 2 the maximum was as high as 12%.

For cells 3 and 4 the general tendency was towards a decrease from the anode to the cathode. Although the concentration of ammonium nitrogen in the section of cell 4 at the anode side was almost double the one in cell 3, it decreased exponentially and in the middle of the cell was close to zero. In cell 3 the drop was less abrupt and an average value of 0.045 mg/g soil was maintained in the second and third quarter of the length of the cell.

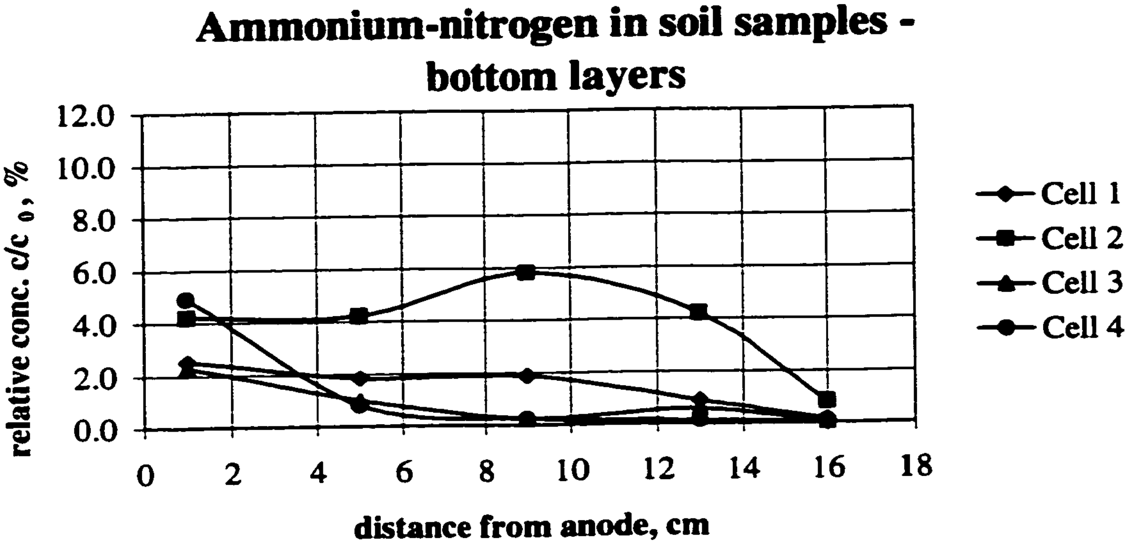
value of 0.045 mg/g soil was maintained in the second and third quarter of the length of the cell.

Figure 4.4.3



The distribution of ammonium-nitrogen in the bottom layers followed the same pattern as in the top ones with some exceptions, as can be seen in Fig. 4.4.3. The peaks were smoother for cell 1 and cell 2, and the absolute maximum values on average were lower than in the upper layers for all cells, except cell 4. The concentration of ammonium-nitrogen in the bottom layer of cell 4 was spread over longer distance than in the top one. The nitrogen content in the first five centimeters of cell 2 was constant (4.2%), then increased reaching a maximum of 5.8% at a distance of 10 cm from the anode. Afterwards, it decreased to a minimum of 0.8% near the cathode.

Figure 4.4.4


Ammonium-nitrogen in soil samples - bottom layers
relative conc. c/c $_0$, %
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
distance from anode, cm
Cell 1
Cell 2
Cell 3
Cell 4

4.4.2 Nitrate ion concentration

The nitrate-nitrogen content was determined in the same way as the ammonium-nitrogen (see Chap. 4.4.1).

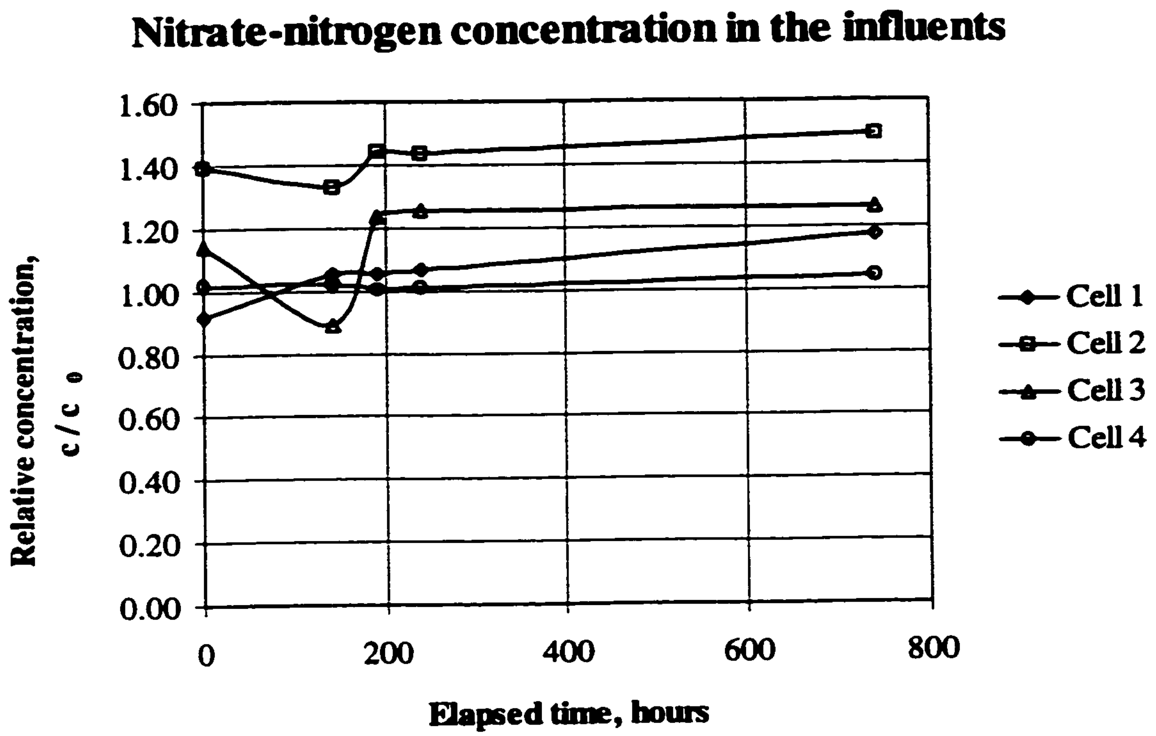
4.4.2.1 Nitrate ion concentration in the reservoirs

The nitrate-nitrogen concentration exhibited a tendency to increase with time in all cells and by the end of the experiment exceeded the initial concentration by 17% for cell 1; 50% for cell 2; 26% for cell 3; and 4% for cell 4. The last value is within the range of precision of the analytical method used for determination of nitrate-nitrogen, so it can be assumed that the nitrate content in the supply reservoir of cell 4 remained unchanged. The character of the changes can be clearly seen in Fig. 4.4.5.

The values of nitrate-nitrogen for cell 1 varied from 5,961 mg/L at the beginning of the experiment to 7,616 mg/L at the end. The respective concentrations were 70 mg/L and 75 mg/L for cell 2, 571 mg/L and 632 mg/L for cell 3, and 509 mg/L and 521 mg/L for cell 4.

The values of the measured potentials and the corresponding concentrations are presented in the Appendix (Tables 12, 13, 14, and 15).

Figure 4.4.5

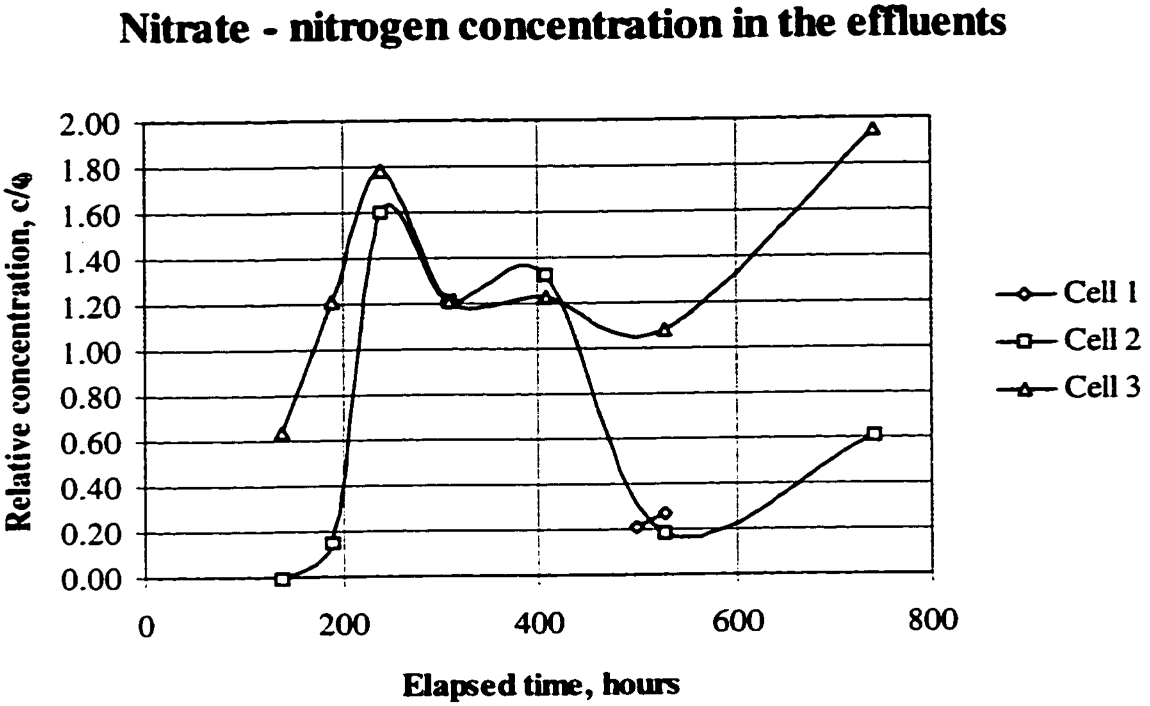


4.4.2.2 Nitrate ion concentration in effluents

The variations in the nitrate-nitrogen concentration had a very irregular character (with two maximums and two minimums) for the collected effluents from cell 2 and cell 3, as can be seen in Fig. 4.4.6. The highest relative concentration for cell 2 (1.60) was measured at the 239th hour (after 10 days) of the experiment and for cell 3 at the end of it (1.95). However, at the 239th hour cell 3 reached its second extremum (1.78).The absolute, as well as the relative concentration for cell 3 was higher than for cell 2, except for at the 409th hour.

Any judgment upon the tendency of cell 1 would be inaccurate, because only two effluent samples were collected for the whole duration of the electrokinetic test.

Figure 4.4.6



4.4.2.3 Nitrate ion concentration in the soil

The nitrate-nitrogen content int he soil samples is plotted versus the distance from the anode in Fig. 4.4.7 for the top layers and in Fig. 4.4.8 for the bottom layers of the cells.

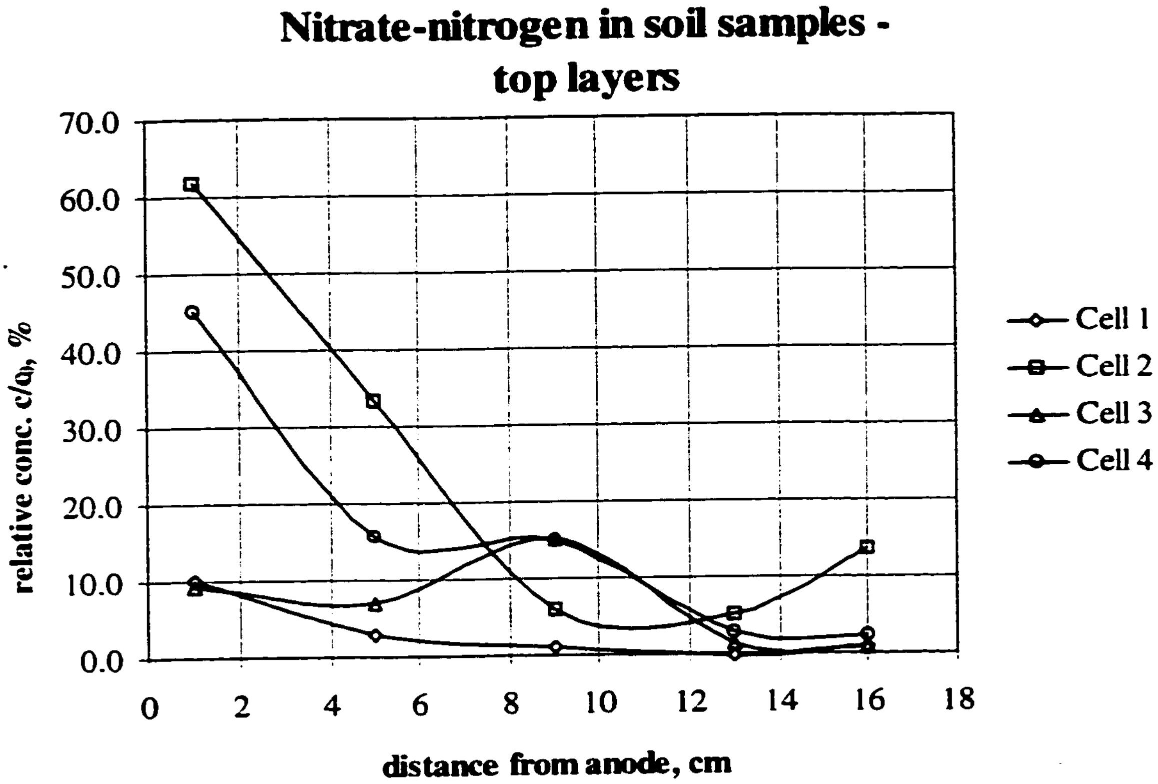
The maximum values for the top layers of all cells are in the anode area and the minimum values are at the cathodes. Two exceptions from the above are:

- in cell 2 the lowest concentrations are in the third quarter of the cell, from the anode

- in cell 3 a peak of higher values occurs in the middle third of the top layer of the cell.

The extreme absolute concentrations are: cell 1 - from 8.2 to 0.7 mg/g soil, cell 2 - from 0.39 to 0.03 mg/g soil, cell 3 - from 0.95 to 0.05 mg/g soil, and for cell 4 - from 2.82 to 0.15 mg/g soil.

Figure 4.4.7



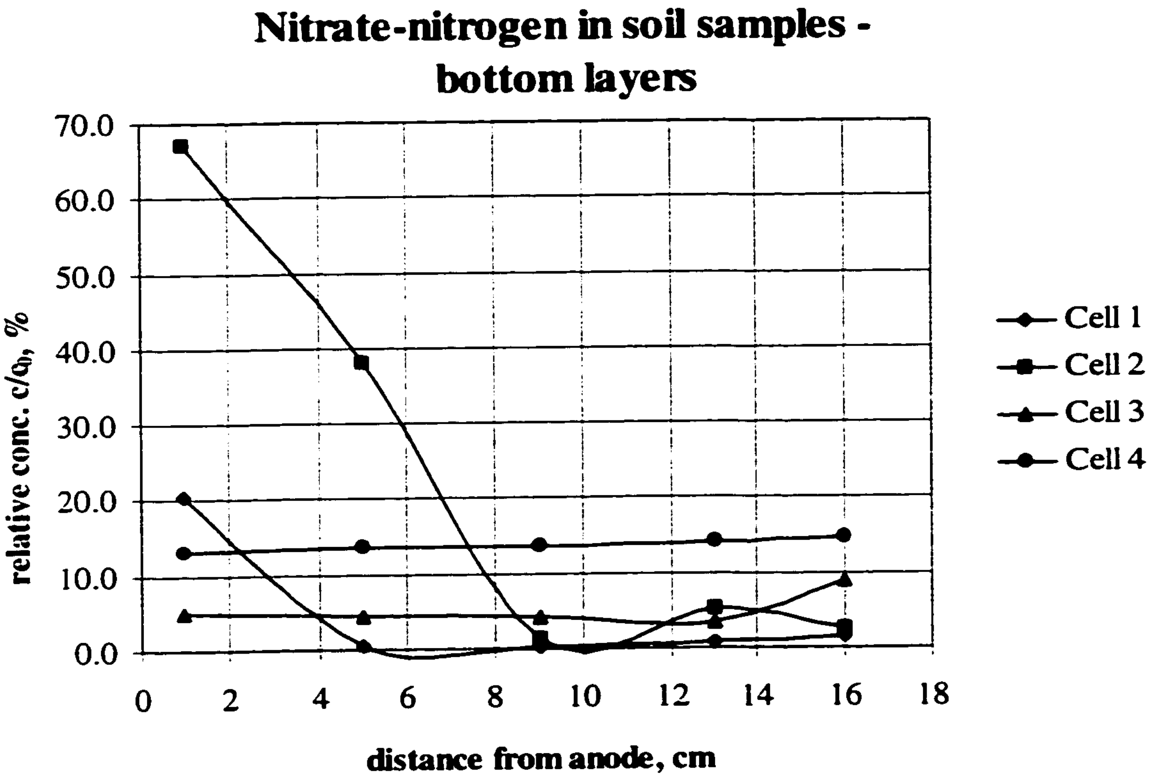
The distribution of the nitrate-nitrogen concentration in the bottom layers had the following character:

- it had again the highest value near the anode for cell 1 and then sharply decreased to reach a negligible relative concentration at a distance of 5 cm, which was maintained to the cathode. The recovery of nitrate was as low as 20% at its maximum in the anode area.

- the nitrate-nitrogen distribution had a similar distribution in cell 2, but the maximum relative concentration was much higher than in cell 1 (67.1%) and reached a minimum at a distance of 9 cm.

- In cell 3 and cell 4 the nitrate concentration spread uniformly lengthwise with an average relative concentration of 4% for cell 3 and 13.5% for cell 4.

Figure 4.4.8



CHAPTER 5

DISCUSSION

5.1 Nitrogen distribution

5.1.1 Ammonium content

The distribution of ammonium-nitrogen was relatively uniform, especially for the two higher concentrations. The positively charged ammonium had a tendency to move smoothly from anode to cathode. However, the sorption capability of the soil seems to play an important role particularly for low concentrations of ammonium.

The comparison between the two cells with equal concentrations (with and without electric field) shows that the front of the nutrient moved twice the distance under the potential gradient. Presumably, with an increase of the distance between the electrodes, the distribution of ammonium will have the same character.

The results show the necessity of a longer experimental period for the lowest concentration of nutrient.

The decrease of the ammonium-nitrogen concentration in the supply reservoirs corresponds to the movement of the ammonium ions from the solution to the soil under the influence of the electric field. The unchanged concentration in the cell that was not connected to the power supply confirms this assumption.

The most significant changes occurred in the supply reservoir of the cell with the highest initial concentration.

The variations with time in the concentration of the collected liquids from the cell with an initial concentration of 100 mg/L had the highest relative values.

5.1.2 Nitrate content

The results demonstrated a difference in the movement of the front of the nitrate-nutrient in the soil. The influent concentrations close to 1000 mg/L gave the optimal nitrate distribution. In both cases of extremal concentrations (13 000 and 100 mg/L) the anode played a role of the "attracting" electrode of negatively charged nitrates.

The increase of the nitrate concentration is dependent on the initial concentration of the solution - it has a relative maximum in the case of the lowest initial concentration.

The interference between the oppositely charged ions (ion pairing) in the case of very high concentrations explains the low effectiveness (low relative concentration in soil).

More effective distribution of nitrates presumably can be reached by using other arrangements of in-situ installation.

The nitrate-nitrogen concentration in the supply reservoirs showed a slight tendency towards increase. This change can be explained by the electroosmotic removal of water and ammonium ions and retention of the nitrate anions at the positive pole of the system. The constant, close to the initial concentration of nitrate in the control cell, supports this statement.

5.2 pH variation

The soil pH distribution in a horizontal direction has three zones in both top and bottom layers - an acidic zone in the anode area, an alkaline zone near the cathodes, and a neutral zone between them. The difference between the lowest and highest values increased with the decrease in concentration of the delivered solution (e.g. the soil pH at the anode was the lowest and at the cathode was the highest for the solution with a concentration of 100 mg/L).

Low pH in general corresponded to high values of concentration of ammonium- and nitrate-nitrogen. Conversely, high pH corresponded to low values of nutrient concentration. This distribution is valid for both layers.

The soil pH variation was insignificant for the control cell. These changes presumably were provoked by some influence from the electric field in the cell next to it.

The relatively minimal changes in pH value (from 7.55 initially, to 9.17) that were observed in the bottom layer of the cell with the highest concentration of nutrient are the lowest ones ever observed in electrokinetic application. Consequently, the nutrient application can be used to decrease the pH value in the cathode area for the purpose of electrokinetic removal of contaminants from the soil.

5.3 Resistivity of soil

The changes in resistivity of soil in all cells as a function of time were towards gradual increase. The areas near the electrodes were exceptions. These were especially dramatic in the last 100 hours (appr. 4 days) of the experiment, presumably due to carbonate precipitation and corrosion of the anode, leading to changes in the intensity of the electric field.

At the end of the experiment, the lowest concentration of nutrient (100 mg/L - cell 2) corresponded to the highest resistivity near the cathode and was twice the value in the anode area. For the nutrient solutions with concentrations of 1 000 and 13 000 mg/L, the resistivity varied within a narrower range lengthwise and had a slightly lower value in the cathode area. Apparently, a concentration below 1 000 mg/L has a greater impact on resistivity changes in soil.

5.4 Soil water content

The inflow of nutrient solution in the cells connected to the power supply was more efficient. Total effluents of 1.2, 31.5, and 23.8 mL, respectively from cell 1, cell 2, and cell 3, were collected during the experiment. The cells were correspondingly recharged and, as a result, the water content in these cells was higher compared to the initial value.

The horizontal distribution of the water content was relatively uniform with the exception of the electrode areas for both top and bottom layers.

For the top layer the extremes were observed as follows: the maximums near anodes and the minimums near cathodes. These findings reflect quite accurately the distribution of nitrogen in the ammonium and nitrate forms.

The distribution of water content in the cathode area in the bottom layer had a different character (increased in contrast to the water content in the top layer) and was inversely proportional to the concentration of nutrient.

A bigger distance between the electrodes would probably provide more uniform distribution of water content.

A higher value of the water content near the anodes than the initial one was caused by the constant recharge from the supply reservoirs. Although the electrokinetic water flow was directed from anode to cathode, the discharge immediately before the cathode prevented a total increase of the moisture content (the upper layer was drained, while the lower layer was partially recharged from it).

The decrease in the moisture content in the cell without the electric field (cell 4) could have been induced by evaporation, although precautions were taken to prevent it maximally and discharge from it never occurred. The low hydraulic permeability (10^{-7}-10^{-6} cm/sec) of the soil did not allow complete recharge of the system .

5.5 Conclusions

The experiment proves the effectiveness of the electrokinetic method for enhancement of the transport of nitrogen-containing nutrients in fine soil.

Ammonium nitrogen can be distributed uniformly in-situ using a correct arrangement of anodes and cathodes and a carefully selected nutrient concentration.

Intermediate concentrations (1 000 mg/L) gave the best results.

The controlled electroosmotic flow prevents any risk of nitrate contamination by leaching that exists when the nutrient is delivered by other means (by gravity or forced injection).

The changes in the physico-chemical parameters during the application of the electrokinetic method confirm the creation of favorable conditions for the development of telluric microorganisms. Consequently, this method can be used for a nutrient supply during site bioremediation.

5. 6 Recommendations

Investigation into the feasibility of improving the system could be achieved by further work in the following areas:

1) Studying the influence of alternating the place of anode and cathode, and the delivering point along with it, to improve the distribution ratio of ammonium- and nitrate-nitrogen.

2) Testing the effect of the supply of nutrients in the area between the electrodes.

3) Verifying the effectiveness of the system with lower potential gradients.

4) Investigating the influence of the electric field on the biomass growth.

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APPENDIX

Table 1 EX-SITU REMEDIAL STRATEGIES APPLIED TO EXCAVATED SOIL

1	2	3	4	5	6
TYPE TECHNO LOGY	**TECHNIQUE & STATUS**	**TREATABLE CONTAMINANTS**	**EFFEC-TIVENESS**	**MODI-FICA-TION REQUIREME NTS**	**ADDITIVES, REAGENTS**
EXTRACTION	SOIL WASHING-			pH	
	- with acid/base - field study	soluble organics, cyanides & heavy metals	potentially low to medium		acids,bases
	-with sodium carbonate/detergents/organic solvents - field study	soluble organics	potentially low to medium	pH	acids, bases, Na_2CO_3, detergents, organic solvents
	STEAM STRIPPING laboratory	volatile organics & inorganics (H_2S, NH_3)	potentially low to medium		
PHYSICAL SEPARATION	GRAVITY SEPARATION				
	SOIL FLUSHING-based on difference in specific density-field study	substances with lower density and non-miscible with the flushing liquid	potentially low to medium	-------	water or other suitable liquid
	SEDIMENTATION field study	miscible organics, heavy metals, cyanides	potentially low to medium	------	water

Table 1 EX-SITU REMEDIAL STRATEGIES APPLIED TO EXCAVATED SOIL

1	2	3	4	5	6
	DRY CLASSIFICATION field study	organics and inorganics with different settling velocity	variable with limited applicability	soil moisture	-----
	CENTRIFUGATION laboratory	organics and inorganics	medium with limited applicability	------	water
	FLOTATION field	organics and inorganics, potentially emulsion forming	medium with limited applicability	------	water, flotating agent,air
	SIEVING -dry field study	organics and inorganics with different particle size from that of soil	medium with limited applicability	------	------
	-wet field study	organics and inorganics with different particle size from that of soil	medium with limited applicability	------	water
	MAGNETIC SEPARATION laboratory	heavy metals with magnetic properties	medium with limited applicability	------	water
	THERMAL DESORPTION -evaporation by direct heat transfer - field	volatile organics, cyanides, sublimable metals	low to medium with limited applicability	T^0, soil moisture	hot air or combustion gases

Table 1 EX-SITU REMEDIAL STRATEGIES APPLIED TO EXCAVATED SOIL

1	2	3	4	5	6
	-evaporation by indirect heat transfer	volatile organics, cyanides, sublimable metals	low to medium with limited applicability	T^0, soil moisture	------
DESTRUCTION	INCINERATION field study	organics, cyanides	medium	T^0, soil moisture	-----
DEGRADATION	CHEMICAL laboratory, field study NEUTRALIZATION				
		inorganics acids, bases	potentially high	------	lime, acids
	OXIDATION	inorganics, organics	potentially moderate	pH	oxidizing agents, UV
	REDUCTION	heavy metals	potentially moderate	pH	SO_2, SO_3^-, Fe^{+2},Al^{+3}
	HYDROLYSIS	cyanides, organics	potentially moderate	T^0,pressure	Cl_2, acids, alcali, enzyme catalysts
	OZONATION	organics, inorganics	potentially low	------	with or without water
	ELECTROLYSIS	organics, heavy metals	potentially low	-----	electrolyte
	CHLORINOLYSIS	organics	potentially low	T^0, pressure	chlorine
	PHOTOLYSIS laboratory	organics, inorganics	potentially low	-----	-----

Table 1 EX-SITU REMEDIAL STRATEGIES APPLIED TO EXCAVATED SOIL

1	2	3	4	5	6
	<u>MICROBIOLOGICAL</u> AEROBIC - field	inorganics, biodegradable organics	variable	O_2 content	nutrients, water, aerobic micro-organisms
	METHANOTROPHIC - concept	biodegradable volatile organics	potentially moderate with limited applicability	pH, O_2 content	methane, methanotrophs
	ANAEROBIC concept	inorganics, biodegradable organics	potentially moderate	O_2 content	nutrients, water, anaerobic micro-organisms

Table 2 IN-SITU REMEDIAL STRATEGIES

1	2	3	4	5	6	7
TYPE TECHNOLOGY	**TECHNIQUE &STATUS**	**TREATABLE CONTAMINANTS**	**EFFECTIVENESS**	**MODIFICATION REQUIREMENTS**	**ADDITIVES, REAGENTS**	**APPLICABILITY MEDIA**
EXTRACTION	SOIL FLUSHING-laboratory	soluble organics & inorganics	variable	pH,T°	water,acids,bases,surfactants	air,groundwater,surface water,soil
IMMOBILIZATION	SORPTION HEAVY METALS -with organics-laboratory	heavy metals	effective,but degradation & release may occur	pH	agricult. products & by-products	groundwater surface water soil
	-with activated carbon-concept	" "	unknown	pH	activated carbon & lime	" "
	-chelation-laboratory	" "	potentially high	pH	tetren,lime; optionally clay	" "
	ORGANICS - reduction of soil moisture-concept	not strongly sorbed non-volatile organics-$k_d<10$	potentially high	moisture	-------	" "

Table 2 IN-SITU REMEDIAL STRATEGIES

1	2	3	4	5	6	7
	-organic matter-laboratory	organics	potentially high	-------	organic matter	" "
	-activated carbon- field	high-molecular weight organics with low wat. solubility, low polarity, low degree of ionization (pestic.& herbic.)	low to high	pH	activated carbon	" "
	<u>ION EXCHANGE</u> with clays (bento-nite)-laboratory	organic & inorganic cationic compounds	low to high	----	clay	ground-water, surface water
	-with synthetic resins-laboratory	organics & inorganics	variable	----	resins	" "
	-with zeolites-concept	heavy metals	unknown	pH	zeolites, lime	" "
	<u>PRECIPITATION</u> -as sulfides- concept	heavy metals(Cu, Cd, Pb, Hg, Zn)	promising to be high	----	CaS or NaS	ground-water, surface water,soil
	-as carbonates, phosphates or hydroxides-lab.	heavy metals	unknown	pH	$CaCO_3$& treble super-phosphate fertilizer	" "

Table 2 IN-SITU REMEDIAL STRATEGIES

1	2	3	4	5	6	7
	VITRIFICATION-field-experimental	organics,inorganics	very high	soil moisture	-----	soil
	SOLIDIFICATION	organics,inorganics	very high	----	solidification agents-cement,lime, thermoplas-tic materials	soil
DEGRA-DATION	CHEMICAL OXIDATION -soil catalyzed-field,lab,concept	water soluble organics with half-cell potential below the redox potent. of a well oxidized soil	variable	soil moisture	clay	air,ground-water,sur-face water, soil
	-oxidizing agent (ozone, H_2O_2)- lab, field	organics except for highly halogenated compounds,cyanides	potentially high	-----	ozone H_2O_2	" "
	REDUCTION					" "
	-of organics-field study	chlorinated organics, unsaturated aromatics & aliphatics	potentially high	soil moisturee	catalyzed metal powder or $NaBH_4$	
	-of Cr- field study	hexavalent Cr	potentially high	pH	reducing,oxidizing &liming agents	" "
	of Se- concept	hexavalent SeO_4^{-2}	potentially high	pH	acidifying & re-ducing agents	" "

Table 2 IN-SITU REMEDIAL STRATEGIES

1	2	3	4	5	6	7
	-of PCBs & di-oxines-field - developmental	PCBs & dioxines	high	soil moisture	reducing agent	" "
	POLYMERIZATION field-experimental	organics with more than one double bond (aliphatic,aromatic & oxigenated monomers)	variable	----	catalysts &activators	
	-altering soil pH-field	organics	high	soil pH	liming or acidifying agent	
	-addition of nutrients- field	organics	high	nutrient content	fertilizers-N or P	
	MICROBIOLOGICAL APPROACH -inoculation by enrichment cultur-ing-lab,field study	organics	potentially low to high	increase of conta-minant concentration	analogue of contami-nant treated	
	-inoculation by genetic manipu-lation - laboratory	organics	potentially high	----	pre-packaged degraders	
	<u>PHOTOLYSIS</u> - addition of proton donors - lab, field study	photodegradeble organics	potentially high	----	proton donor (tri-ethylamine)	

Table 2 IN-SITU REMEDIAL STRATEGIES

1	2	3	4	5	6	7
	-enhancement of volatilization- concept	compounds with low water solubility,highly photoreactive with short atmospheric half-lives	potentially high	soil moisture	----	
ATTE-NUATION	- of metals field	wastes containing metals	high	pH	lime, soil	air
	-of organics field study	organics	potentially high	soil moisture	soil (optional)	
REDUCTION OF VOLATI-LIZATION	- soil vapor volume- laboratory	volatile organics & inorganics	low to medium	soil moisture	irrigation water	air
	-soil cooling	volatile organics	low to medium	soil moisture	cooling agents, water	

Table 3 CLASSES OF ORGANIC COMPOUNDS SUSCEPTIBLE TO BIOREMEDIATION[1]

CLASS	EXAMPLE	AEROBIC	ANAEROBIC
Monochlorinated aromatic compounds	Chlorobenzene	x	
"BTX" (benzene, toluene, and xylene)		x	x
Nonhalogenated phenolics and cresols	2-methyl phenol	x	x
Polynuclear aromatic hydrocarbons	**Creosote**	x	
Alkanes and alkenes	Fuel oil	x	
PCBs (polychlorinated biphenyls)	Trichlorobiphenol	x	x
Chlorophenols	Pentachlorophenol	x	x
Nitrogen heterocyclics	Pyridine	x	x
Chlorinated solvents			
Alkanes	Chloroform	x	x
Alkenes	Trichloroethylene	x	x

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[1] Source: U.S. EPA, 1991

Table 4 ELECTRICAL PARAMETERS - CELL I

date	time,	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
	hours		dist.toC	17.0	16.0	15.0	14.0	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0
date 07.03	0	25.4	U, V	8.50	7.00	6.70	6.29	5.87	5.45	5.05	4.72	4.38	3.97	3.60	3.22	2.88	2.48	2.08	1.67	1.23
hour 13.40			R, ohms	334.7	275.6	263.8	247.6	231.1	214.6	198.8	185.8	172.4	156.3	141.7	126.8	113.4	97.6	81.9	65.8	48.4
			r, ohms.cm	393.7	344.5	351.7	353.8	355.5	357.6	361.5	371.7	383.2	390.7	404.9	422.6	453.5	488.2	545.9	657.5	968.5
date 07.03	4	24.6	U, V	8.50	6.98	6.83	6.49	6.12	5.71	5.36	5.02	4.69	4.31	3.94	3.60	3.22	2.86	2.48	2.11	1.73
hour 17.30			R, ohms	345.5	283.7	277.6	263.8	248.8	232.1	217.9	204.1	190.7	175.2	160.2	146.3	130.9	116.3	100.8	85.8	70.3
			r, ohms.cm	406.5	354.7	370.2	376.9	382.7	386.9	396.2	408.1	423.7	438.0	457.6	487.8	523.6	581.3	672.1	857.7	1406.5
date 08.03	23	23.5	U, V	8.50	7.05	6.94	6.73	6.46	6.10	5.80	5.49	5.15	4.78	4.44	4.05	3.51	2.94	2.27	1.69	1.39
hour 12.30			R, ohms	361.7	300.0	295.3	286.4	274.9	259.6	246.8	233.6	219.2	203.4	188.9	172.3	149.4	125.1	96.6	71.9	59.2
			r, ohms.cm	425.5	375.0	393.8	409.1	422.9	432.6	448.7	467.2	487.0	508.5	539.8	574.5	597.4	625.5	644.0	719.1	1183.0
date 08.03	26.5	22.8	U, V	8.50	6.85	6.76	6.58	6.33	6.01	5.70	5.40	5.10	4.70	4.36	3.96	3.44	2.84	2.17	1.66	1.37
hour16.00			R, ohms	372.8	300.4	296.5	288.6	277.6	263.6	250.0	236.8	223.7	206.1	191.2	173.7	150.9	124.6	95.2	72.8	60.1
			r, ohms.cm	438.6	375.5	395.3	412.3	427.1	439.3	454.5	473.7	497.1	515.4	546.4	578.9	603.5	622.8	634.5	728.1	1201.8
date09.03	44.5	20	U, V	8.50	6.84	6.79	6.69	6.52	6.29	5.98	5.65	5.32	4.89	4.42	3.92	3.21	2.51	1.93	1.55	1.32
hour10.00			R, ohms	424.2	341.3	267.3	263.4	256.7	247.6	235.4	222.4	209.5	192.5	174.0	154.3	126.4	98.8	96.3	77.4	65.9
			r, ohms.cm	499.0	426.6	356.4	376.3	394.9	412.7	428.1	444.9	465.4	481.3	497.2	514.4	505.5	494.1	642.0	773.5	1317.4
date	52.5	19.2	U, V	8.50	6.81	6.73	6.65	6.39	5.95	5.73	5.42	5.12	4.79	4.21	3.79	3.12	2.44	1.76	1.39	1.19
hour 18.00			R, ohms	442.7	354.7	273.6	270.3	259.8	241.9	232.9	220.3	208.1	194.7	171.1	154.1	126.8	99.2	91.7	72.4	62.0
			r, ohms.cm	520.8	443.4	364.8	386.2	399.6	403.1	423.5	440.7	462.5	486.8	489.0	513.6	507.3	495.9	611.1	724.0	1239.6
date10.03	68.5	12.5	U, V	8.50	1.78	1.77	1.77	1.77	1.71	1.68	1.63	1.59	1.52	1.41	1.38	1.25	1.15	1.05	0.96	0.94
hour10.00			R, ohms	680.0	142.4	75.3	75.3	75.3	72.8	71.5	69.4	67.7	64.7	60.0	58.7	53.2	48.9	84.0	76.8	75.2
			r, ohms.cm	800.0	178.0	100.4	107.6	115.9	121.3	130.0	138.7	150.4	161.7	171.4	195.7	212.8	244.7	560.0	768.0	1504.0
date	76.5	10.9	U, V	8.50	0.48	0.47	0.44	0.46	0.44	0.43	0.42	0.42	0.40	0.40	0.40	0.37	0.35	0.37	0.35	0.36
hour 18.00			R, ohms	779.8	44.0	43.1	40.4	42.2	40.4	39.5	38.5	38.5	36.7	36.7	36.7	33.9	32.1	33.9	32.1	33.0

Table 4 ELECTRICAL PARAMETERS - CELL 1

date	time,	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
			r, ohms.cm	917.4	55.0	57.5	57.7	64.9	67.3	71.7	77.1	85.6	91.7	104.8	122.3	135.8	160.6	226.3	321.1	660.6
date 13.03	140	10.1	U, V	8.50	0.71	0.70	0.67	0.69	0.67	0.65	0.64	0.63	0.63	0.63	0.63	0.59	0.57	0.55	0.53	0.54
hour9.30			R, ohms	841.6	70.3	69.3	66.3	68.3	66.3	64.4	63.4	62.4	62.4	62.4	62.4	58.4	56.4	54.5	52.5	53.5
			r, ohms.cm	990.1	87.9	92.4	94.8	105.1	110.6	117.0	126.7	138.6	155.9	178.2	207.9	233.7	282.2	363.0	524.8	1069.3
date	146	10.2	U, V	8.50	0.56	0.55	0.53	0.55	0.53	0.51	0.49	0.49	0.48	0.48	0.47	0.45	0.43	0.41	0.39	0.41
hour 15.30			R, ohms	833.3	54.9	53.9	52.0	53.9	52.0	50.0	48.0	48.0	47.1	47.1	46.1	44.1	42.2	40.2	38.2	40.2
			r, ohms.cm	980.4	68.6	71.9	74.2	83.0	86.6	90.9	96.1	106.8	117.6	134.5	153.6	176.5	210.8	268.0	382.4	803.9
date15.03	189.5	8.1	U, V	8.50	0.45	0.44	0.42	0.43	0.42	0.40	0.38	0.37	0.36	0.36	0.36	0.34	0.33	0.31	0.29	0.29
hour 11.00			R, ohms	1049.4	55.6	54.3	51.9	53.1	51.9	49.4	46.9	45.7	44.4	44.4	44.4	42.0	40.7	38.3	35.8	35.8
			r, ohms.cm	1234.6	69.4	72.4	74.1	81.7	86.4	89.8	93.8	101.5	111.1	127.0	148.1	167.9	203.7	255.1	358.0	716.0
date16.03	213.5	6.7	U, V	8.50	0.45	0.44	0.42	0.44	0.42	0.40	0.38	0.38	0.36	0.36	0.36	0.35	0.35	0.32	0.30	0.29
hour 11.00			R, ohms	1268.7	67.2	65.7	62.7	65.7	62.7	59.7	56.7	56.7	53.7	53.7	53.7	52.2	52.2	47.8	44.8	43.3
			r, ohms.cm	1492.5	84.0	87.6	89.6	101.0	104.5	108.5	113.4	126.0	134.3	153.5	179.1	209.0	261.2	318.4	447.8	865.7
date 17.03	239	6.1	U, V	8.50	0.44	0.44	0.42	0.43	0.42	0.40	0.38	0.38	0.36	0.36	0.35	0.35	0.34	0.31	0.30	0.29
hour12.30			R, ohms	1393.4	72.1	72.1	68.9	70.5	68.9	65.6	62.3	62.3	59.0	59.0	57.4	57.4	55.7	50.8	49.2	47.5
			r, ohms.cm	1639.3	90.2	96.2	98.4	108.4	114.8	119.2	124.6	138.4	147.5	168.6	191.3	229.5	278.7	338.8	491.8	950.8
date20.03	309.5	4.6	U, V	8.50	0.44	0.43	0.42	0.43	0.42	0.40	0.38	0.37	0.36	0.35	0.35	0.34	0.33	0.31	0.29	0.28
hour 11.00			R, ohms	1847.8	95.7	93.5	91.3	93.5	91.3	87.0	82.6	80.4	78.3	76.1	76.1	73.9	71.7	67.4	63.0	60.9
			r, ohms.cm	2173.9	119.6	124.6	130.4	143.8	152.2	158.1	165.2	178.7	195.7	217.4	253.6	295.7	358.7	449.3	630.4	1217.4
date22.03	362.5	1.7	U, V	8.50	5.69	5.60	5.66	5.60	5.53	5.45	5.24	5.14	5.02	4.84	4.45	3.77	3.01	2.23	1.70	1.46
hour 15.45			R, ohms	5000.0	3347.1	3294.1	3329.4	3294.1	3252.9	3205.9	3082.4	3023.5	2952.9	2847.1	2617.7	2217.7	1770.6	1311.8	1000.0	858.8
			r, ohms.cm	5882.4	4183.8	4392.2	4756.3	5067.9	5421.6	5828.9	6164.7	6719.0	7382.4	8134.5	8725.5	8870.6	8852.9	8745.1	10000.0	17176.5
date23.03	383	3.5	U, V	8.50	1.23	1.16	1.16	1.15	1.42	1.55	1.51	1.52	1.49	1.46	1.39	1.27	1.13	0.93	0.86	0.83
hour 12.30			R, ohms	2428.6	351.4	331.4	331.4	328.6	405.7	442.9	431.4	434.3	425.7	417.1	397.1	362.9	322.9	265.7	245.7	237.1
			r, ohms.cm	2857.1	439.3	441.9	473.5	505.5	676.2	805.2	862.9	965.1	1064.3	1191.8	1323.8	1451.4	1614.3	1771.4	2457.1	4742.9

Table 4 ELECTRICAL PARAMETERS - CELL 1

date	time,	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
hour14.30			R, ohms	6071.4	4014.3	3957.1	3957.1	3864.3	3757.1	3757.1	3642.9	3821.4	3521.4	3400.0	3021.4	2771.4	2357.1	1664.3	1257.1	1057.1
			r, ohms.cm	7142.9	5017.9	5276.2	5653.1	5945.1	6261.9	6831.2	7285.7	8492.1	8803.6	9714.3	10071.4	11085.7	11785.7	11095.2	12571.4	21142.9
date28.03	500	2.8	U, V	8.50	1.15	1.11	1.12	1.12	1.12	1.12	1.11	1.10	1.07	1.05	1.05	0.96	0.98	0.97	0.97	0.98
hour9.30			R, ohms	3035.7	410.7	396.4	400.0	400.0	400.0	400.0	396.4	392.9	382.1	375.0	375.0	342.9	350.0	346.4	346.4	350.0
			r, ohms.cm	3571.4	513.4	528.6	571.4	615.4	666.7	727.3	792.9	873.0	955.4	1071.4	1250.0	1371.4	1750.0	2309.5	3464.3	7000.0
date 29.03	528	2.7	U, V	8.50	0.52	0.48	0.48	0.48	0.48	0.48	0.46	0.46	0.44	0.44	0.42	0.41	0.39	0.37	0.36	0.37
hour 13.30			R, ohms	3148.2	192.6	177.8	177.8	177.8	177.8	177.8	170.4	170.4	163.0	163.0	155.6	151.9	144.4	137.0	133.3	137.0
			r, ohms.cm	3703.7	240.7	237.0	254.0	273.5	296.3	323.2	340.7	378.6	407.4	465.6	518.5	607.4	722.2	913.6	1333.3	2740.7
date31.03	576	1.9	U, V	8.50	0.47	0.42	0.45	0.45	0.43	0.44	0.42	0.42	0.42	0.42	0.40	0.39	0.35	0.34	0.32	0.31
hour13.30			R, ohms	4473.7	247.4	221.1	236.8	236.8	226.3	231.6	221.1	221.1	221.1	221.1	210.5	205.3	184.2	179.0	168.4	163.2
			r, ohms.cm	5263.2	309.2	294.7	338.3	364.4	377.2	421.1	442.1	491.2	552.6	631.6	701.8	821.1	921.1	1193.0	1684.2	3263.2
date04.04	670.5	1.8	U, V	8.50	0.57	0.51	0.55	0.55	0.54	0.54	0.53	0.54	0.54	0.54	0.52	0.51	0.48	0.45	0.43	0.42
hour12.00			R, ohms	4722.2	316.7	283.3	305.6	305.6	300.0	300.0	294.4	300.0	300.0	300.0	288.9	283.3	266.7	250.0	238.9	233.3
			r, ohms.cm	5555.6	395.8	377.8	436.5	470.1	500.0	545.5	588.9	666.7	750.0	857.1	963.0	1133.3	1333.3	1666.7	2388.9	4666.7
date07.04	741.5	0.6	U, V	8.50	0.59	0.53	0.57	0.57	0.56	0.58	0.56	0.57	0.55	0.56	0.55	0.55	0.52	0.50	0.48	0.44
hour 11.15			R, ohms	14166.7	983.3	883.3	950.0	950.0	933.3	966.7	933.3	950.0	916.7	933.3	916.7	916.7	866.7	833.3	800.0	733.3
			r, ohms.cm	16666.7	1229.2	1177.8	1357.1	1461.5	1555.6	1757.6	1866.7	2111.1	2291.7	2666.7	3055.6	3666.7	4333.3	5555.6	8000.0	14666.7

Table 5 ELECTRICAL PARAMETERS CELL 2

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
	hours		dist.toC	17.0	16.0	15.0	14.0	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0
date 07.03	0	25.4	U, V	8.50	6.86	6.53	6.13	5.75	5.47	5.08	4.67	4.29	4.14	3.70	3.24	3.08	2.84	2.39	2.02	1.77
hour 13.40			R, ohms	334.7	270.1	257.1	241.3	226.4	215.4	200.0	183.9	168.9	163.0	145.7	127.6	121.3	111.8	94.1	79.5	69.7
			r, ohms.cm	393.7	337.6	342.8	344.8	348.3	358.9	363.6	367.7	375.3	407.5	416.2	425.2	485.0	559.1	627.3	795.3	1393.7
date 07.03	4	24.6	U, V	8.50	6.75	6.44	6.03	5.74	5.40	5.14	4.84	4.50	4.22	3.81	3.37	3.14	2.94	2.51	2.15	1.83
hour 17.30			R, ohms	345.5	274.4	261.8	245.1	233.3	219.5	208.9	196.8	182.9	171.5	154.9	137.0	127.6	119.5	102.0	87.4	74.4
			r, ohms.cm	406.5	343.0	349.1	350.2	359.0	365.9	379.9	393.5	406.5	428.9	442.5	456.6	510.6	597.6	680.2	874.0	1487.8
date 08.03	23	23.5	U, V	8.50	6.93	6.64	6.28	5.95	5.63	5.29	5.00	4.66	4.39	4.01	3.44	3.16	2.69	2.00	1.73	1.49
hour 12.30			R, ohms	361.7	294.9	282.6	267.2	253.2	239.6	225.1	212.8	198.3	186.8	170.6	146.4	134.5	114.5	85.1	73.6	63.4
			r, ohms.cm	425.5	368.6	376.7	381.8	389.5	399.3	409.3	425.5	440.7	467.0	487.5	487.9	537.9	572.3	567.4	736.2	1268.1
date 08.03	26.5	22.8	U, V	8.50	6.92	6.65	6.37	6.05	5.75	5.42	5.16	4.83	4.54	4.11	3.56	3.37	2.97	2.41	1.95	1.59
hour16.00			R, ohms	372.8	303.5	291.7	279.4	265.4	252.2	237.7	226.3	211.8	199.1	180.3	156.1	147.8	130.3	105.7	85.5	69.7
			r, ohms.cm	438.6	379.4	388.9	399.1	408.2	420.3	432.2	452.6	470.8	497.8	515.0	520.5	591.2	651.3	704.7	855.3	1394.7
date09.03	44.5	20	U, V	8.50	6.93	6.70	6.44	6.17	5.86	5.51	5.21	4.83	4.51	3.96	3.10	2.72	2.50	2.09	1.77	1.46
hour10.00			R, ohms	424.2	345.8	263.8	253.5	242.9	230.7	216.9	205.1	190.2	177.6	155.9	122.1	107.1	98.4	104.3	88.3	72.9
			r, ohms.cm	499.0	432.3	351.7	362.2	373.7	384.5	394.4	410.2	422.6	443.9	445.4	406.8	428.3	492.1	695.3	883.2	1457.1
date	52.5	19.2	U, V	8.50	6.93	6.71	6.48	6.23	5.89	5.52	5.21	4.83	4.50	3.93	3.07	2.69	2.43	2.08	1.72	1.44
hour 18.00			R, ohms	442.7	360.9	272.8	263.4	253.3	239.4	224.4	211.8	196.3	182.9	159.8	124.8	109.4	98.8	108.3	89.6	75.0
			r, ohms.cm	520.8	451.2	363.7	376.3	389.6	399.1	408.0	423.6	436.3	457.3	456.4	416.0	437.4	493.9	722.2	895.8	1500.0
date10.03	68.5	12.5	U, V	8.50	6.93	6.74	6.53	6.22	5.91	5.58	5.25	4.84	4.47	3.90	2.90	2.45	2.21	1.85	1.61	1.38
hour10.00			R, ohms	680.0	294.9	286.8	277.9	264.7	251.5	237.5	223.4	206.0	190.2	166.0	123.4	104.3	94.0	148.0	128.8	110.4
			r, ohms.cm	800.0	368.6	382.4	397.0	407.2	419.1	431.7	446.8	457.7	475.5	474.2	411.3	417.0	470.2	986.7	1288.0	2208.0
date	76.5	10.9	U, V	8.50	6.94	6.77	6.55	6.26	6.03	5.72	5.45	5.00	4.63	4.02	3.16	2.84	2.44	1.98	1.68	1.42
hour 18.00			R, ohms	779.8	636.7	621.1	600.9	574.3	553.2	524.8	500.0	458.7	424.8	368.8	289.9	260.6	223.9	181.7	154.1	130.3
			r, ohms.cm	917.4	795.9	828.1	858.5	883.6	922.0	954.1	1000.0	1019.4	1061.9	1053.7	966.4	1042.2	1119.3	1211.0	1541.3	2605.5
date 13.03	140	10.1	U, V	8.50	6.36	6.17	5.90	5.60	5.30	4.94	4.66	4.23	3.90	3.32	2.50	2.14	1.93	1.67	1.49	1.30
hour9.30			R, ohms	841.6	629.7	610.9	584.2	554.5	524.8	489.1	461.4	418.8	386.1	328.7	247.5	211.9	191.1	165.4	147.5	128.7

Table 5 ELECTRICAL PARAMETERS CELL 2

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
			r, ohms.cm	990.1	787.1	814.5	834.5	853.0	874.6	889.3	922.8	930.7	965.3	939.2	825.1	847.5	955.4	1102.3	1475.2	2574.3
date	146	10.2	U, V	8.50	6.28	6.06	5.82	5.47	5.17	4.81	4.56	4.16	3.85	3.27	2.54	2.14	1.92	1.67	1.49	1.30
hour 15.30			R, ohms	833.3	615.7	594.1	570.6	536.3	506.9	471.6	447.1	407.8	377.5	320.6	249.0	209.8	188.2	163.7	146.1	127.5
			r, ohms.cm	980.4	769.6	792.2	815.1	825.0	844.8	857.4	894.1	906.3	943.6	916.0	830.1	839.2	941.2	1091.5	1460.8	2549.0
date15.03	189.5	8.1	U, V	8.50	4.94	4.69	4.42	4.19	4.01	3.76	3.57	3.33	3.12	2.76	2.24	1.88	1.72	1.52	1.40	1.27
hour 11.00			R, ohms	1049.4	609.9	579.0	545.7	517.3	495.1	464.2	440.7	411.1	385.2	340.7	276.5	232.1	212.4	187.7	172.8	156.8
			r, ohms.cm	1234.6	762.3	772.0	779.5	795.8	825.1	844.0	881.5	913.6	963.0	973.5	921.8	928.4	1061.7	1251.0	1728.4	3135.8
date16.03	213.5	6.7	U, V	8.50	4.51	4.29	4.04	3.82	3.68	3.43	3.28	3.06	2.88	2.57	2.02	1.79	1.66	1.47	1.36	1.25
hour 11.00			R, ohms	1268.7	673.1	640.3	603.0	570.2	549.3	511.9	489.6	456.7	429.9	383.6	301.5	267.2	247.8	219.4	203.0	186.6
			r, ohms.cm	1492.5	841.4	853.7	861.4	877.2	915.4	930.8	979.1	1014.9	1074.6	1095.9	1005.0	1068.7	1238.8	1462.7	2029.9	3731.3
date 17.03	239	6.1	U, V	8.50	4.30	4.11	3.86	3.64	3.52	3.27	3.15	2.94	2.78	2.49	1.96	1.74	1.62	1.44	1.34	1.24
hour12.30			R, ohms	1393.4	704.9	673.8	632.8	596.7	577.1	536.1	516.4	482.0	455.7	408.2	321.3	285.3	265.6	236.1	219.7	203.3
			r, ohms.cm	1639.3	881.1	898.4	904.0	918.0	961.7	974.7	1032.8	1071.0	1139.3	1166.3	1071.0	1141.0	1327.9	1573.8	2196.7	4065.6
date20.03	309.5	4.6	U, V	8.50	3.78	3.45	3.37	3.16	3.03	2.86	2.75	2.59	2.48	2.24	1.87	1.60	1.49	1.37	1.29	1.22
hour 11.00			R, ohms	1847.8	821.7	750.0	732.6	687.0	658.7	621.7	597.8	563.0	539.1	487.0	406.5	347.8	323.9	297.8	280.4	265.2
			r, ohms.cm	2173.9	1027.2	1000.0	1046.6	1056.9	1097.8	1130.4	1195.7	1251.2	1347.8	1391.3	1355.1	1391.3	1619.6	1985.5	2804.3	5304.3
date22.03	362.5	1.7	U, V	8.50	3.12	2.90	2.76	2.62	2.56	2.44	2.39	2.26	2.21	2.06	1.77	1.73	1.58	1.43	1.28	1.20
hour 15.45			R, ohms	5000.0	1835.3	1705.9	1623.5	1541.2	1505.9	1435.3	1405.9	1329.4	1300.0	1211.8	1041.2	1017.7	929.4	841.2	752.9	705.9
			r, ohms.cm	5882.4	2294.1	2274.5	2319.3	2371.0	2509.8	2609.6	2811.8	2954.2	3250.0	3462.2	3470.6	4070.6	4647.1	5607.8	7529.4	14117.6
date23.03	383	3.5	U, V	8.50	4.27	3.48	3.58	3.45	3.33	3.17	3.06	2.90	0.79	2.57	2.13	2.01	2.80	1.54	1.33	1.23
hour 12.30			R, ohms	2428.6	1220.0	994.3	1022.9	985.7	951.4	905.7	874.3	828.6	225.7	734.3	608.6	574.3	800.0	440.0	380.0	351.4
			r, ohms.cm	2857.1	1525.0	1325.7	1461.2	1516.5	1585.7	1646.8	1748.6	1841.3	564.3	2098.0	2028.6	2297.1	4000.0	2933.3	3800.0	7028.6
date 24.03	409	1.4	U, V	8.50	2.96	2.61	2.55	2.43	1.36	2.24	2.23	2.13	2.09	1.94	1.64	1.64	1.50	1.39	1.27	1.20
hour14.30			R, ohms	6071.4	2114.3	1864.3	1821.4	1735.7	971.4	1600.0	1592.9	1521.4	1492.9	1385.7	1171.4	1171.4	1071.4	992.9	907.1	857.1
			r, ohms.cm	7142.9	2642.9	2485.7	2602.0	2670.3	1619.0	2909.1	3185.7	3381.0	3732.1	3959.2	3904.8	4685.7	5357.1	6619.0	9071.4	17142.9
date28.03	500	2.8	U, V	8.50	4.16	3.62	3.41	3.20	3.12	2.93	2.97	2.65	2.53	2.36	2.10	1.92	1.71	1.47	1.33	1.28
hour9.30			R, ohms	3035.7	1485.7	1292.9	1217.9	1142.9	1114.3	1046.4	1060.7	946.4	903.6	842.9	750.0	685.7	610.7	525.0	475.0	457.1

Table 5 ELECTRICAL PARAMETERS CELL 2

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
			r, ohms.cm	3571.4	1857.1	1723.8	1739.8	1758.2	1857.1	1902.6	2121.4	2103.2	2258.9	2408.2	2500.0	2742.9	3053.6	3500.0	4750.0	9142.9
date 29.03	528	2.7	U, V	8.50	4.38	3.83	3.53	3.31	3.19	2.96	2.94	2.76	2.72	2.43	2.07	1.86	1.69	1.56	1.40	1.27
hour 13.30			R, ohms	3148.2	1622.2	1418.5	1307.4	1225.9	1181.5	1096.3	1088.9	1022.2	1007.4	900.0	766.7	688.9	625.9	577.8	518.5	470.4
			r, ohms.cm	3703.7	2027.8	1891.4	1867.7	1886.0	1969.1	1993.3	2177.8	2271.6	2518.5	2571.4	2555.6	2755.6	3129.6	3851.9	5185.2	9407.4
date31.03	576	1.9	U, V	8.50	4.57	3.75	3.46	3.22	3.12	2.96	2.88	2.69	2.58	2.38	2.04	1.81	1.62	1.51	1.39	1.28
hour13.30			R, ohms	4473.7	2405.3	1973.7	1821.1	1694.7	1642.1	1557.9	1515.8	1415.8	1357.9	1252.6	1073.7	952.6	852.6	794.7	731.6	673.7
			r, ohms.cm	5263.2	3006.6	2631.6	2601.5	2607.3	2736.8	2832.5	3031.6	3146.2	3394.7	3578.9	3578.9	3810.5	4263.2	5298.2	7315.8	13473.7
date04.04	670.5	1.8	U, V	8.50	5.24	3.53	3.26	3.02	2.93	2.79	2.72	2.58	2.49	2.31	2.04	1.79	1.58	1.44	1.34	1.25
hour12.00			R, ohms	4722.2	2911.1	1961.1	1811.1	1677.8	1627.8	1550.0	1511.1	1433.3	1383.3	1283.3	1133.3	994.4	877.8	800.0	744.4	694.4
			r, ohms.cm	5555.6	3638.9	2614.8	2587.3	2581.2	2713.0	2818.2	3022.2	3185.2	3458.3	3666.7	3777.8	3977.8	4388.9	5333.3	7444.4	13888.9
date07.04	741.5	0.6	U, V	8.50	2.59	2.04	1.91	1.75	1.64	1.60	1.63	1.51	1.54	1.44	1.29	1.28	1.18	1.12	1.08	1.05
hour 11.15			R, ohms	14166.7	4316.7	3400.0	3183.3	2916.7	2733.3	2666.7	2716.7	2516.7	2566.7	2400.0	2150.0	2133.3	1966.7	1866.7	1800.0	1750.0
			r, ohms.cm	16666.7	5395.8	4533.3	4547.6	4487.2	4555.6	4848.5	5433.3	5592.6	6416.7	6857.1	7166.7	8533.3	9833.3	12444.4	18000.0	35000.0

Table 6 ELECTRICAL PARAMETERS - CELL 3

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
	hours		dist.toC	17.0	16.0	15.0	14.0	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0
date 07.03	0	25.4	U, V	8.5	6.71	6.14	5.84	5.51	5.24	4.89	4.58	4.26	3.95	3.61	3.27	2.98	2.61	2.2	1.88	1.53
hour 13.40			R, ohms	334.7	264.2	241.7	229.9	216.9	206.3	192.5	180.3	167.7	155.5	142.1	128.7	117.3	102.8	86.6	74.0	60.2
			r, ohms.cm	393.7	330.2	322.3	328.5	333.7	343.8	350.0	360.6	372.7	388.8	406.1	429.1	469.3	513.8	577.4	740.2	1204.7
date 07.03	4	24.6	U, V	8.5	6.72	6.17	5.92	5.58	5.32	4.98	4.69	4.38	4.06	3.76	3.46	3.17	2.83	2.44	2.08	1.62
hour 17.30			R, ohms	345.5	273.2	250.8	240.7	226.8	216.3	202.4	190.7	178.1	165.0	152.9	140.7	128.9	115.0	99.2	84.6	65.9
			r, ohms.cm	406.5	341.5	334.4	343.8	349.0	360.4	368.1	381.3	395.7	412.6	436.7	468.8	515.4	575.2	661.2	845.5	1317.1
date 08.03	23	23.5	U, V	8.5	6.82	6.43	6.16	5.87	5.61	5.29	5.04	4.72	4.43	4.17	3.89	3.61	3.15	2.4	1.6	1.32
hour 12.30			R, ohms	361.7	290.2	273.6	262.1	249.8	238.7	225.1	214.5	200.9	188.5	177.5	165.5	153.6	134.0	102.1	68.1	56.2
			r, ohms.cm	425.5	362.8	364.8	374.5	384.3	397.9	409.3	428.9	446.3	471.3	507.0	551.8	614.5	670.2	680.9	680.9	1123.4
date 08.03	26.5	22.8	U, V	8.5	6.84	6.48	6.2	5.93	5.67	5.38	5.13	4.85	4.57	4.3	4.02	3.72	3.25	2.48	1.64	1.32
hour16.00			R, ohms	372.8	300.0	284.2	271.9	260.1	248.7	236.0	225.0	212.7	200.4	188.6	176.3	163.2	142.5	108.8	71.9	57.9
			r, ohms.cm	438.6	375.0	378.9	388.5	400.1	414.5	429.0	450.0	472.7	501.1	538.8	587.7	652.6	712.7	725.1	719.3	1157.9
date09.03	44.5	20	U, V	8.5	6.88	6.63	6.41	6.15	5.9	5.6	5.33	5.02	4.73	4.45	4.1	3.66	3.14	2.3	1.56	1.32
hour10.00			R, ohms	424.2	343.3	330.8	319.9	306.9	294.4	279.4	266.0	250.5	236.0	222.1	204.6	182.6	156.7	114.8	77.8	65.9
			r, ohms.cm	499.0	429.1	441.1	456.9	472.1	490.7	508.1	531.9	556.7	590.1	634.4	682.0	730.5	783.4	765.1	778.4	1317.4
date	52.5	19.2	U, V	8.5	6.89	6.65	6.44	6.19	5.91	5.65	5.34	5.05	4.74	4.43	4	3.6	3.1	2.29	1.54	1.3
hour 18.00			R, ohms	442.7	358.9	346.4	335.4	322.4	307.8	294.3	278.1	263.0	246.9	230.7	208.3	187.5	161.5	119.3	80.2	67.7
			r, ohms.cm	520.8	448.6	461.8	479.2	496.0	513.0	535.0	556.3	584.5	617.2	659.2	694.4	750.0	807.3	795.1	802.1	1354.2
date10.03	68.5	12.5	U, V	8.5	6.9	6.72	6.54	6.29	6.07	5.76	5.47	5.13	4.78	4.37	3.25	3.51	2.99	2.19	1.53	1.25
hour10.00			R, ohms	680.0	552.0	537.6	523.2	503.2	485.6	460.8	437.6	410.4	382.4	349.6	260.0	280.8	239.2	175.2	122.4	100.0
			r, ohms.cm	800.0	690.0	716.8	747.4	774.2	809.3	837.8	875.2	912.0	956.0	998.9	866.7	1123.2	1196.0	1168.0	1224.0	2000.0
date	76.5	10.9	U, V	8.5	6.91	6.71	6.54	6.31	6.07	5.77	5.48	5.13	4.73	4.31	3.85	3.45	2.92	2.15	1.5	1.28
hour 18.00			R, ohms	779.8	633.9	615.6	600.0	578.9	556.9	529.4	502.8	470.6	433.9	395.4	353.2	316.5	267.9	197.3	137.6	117.4
			r, ohms.cm	917.4	792.4	820.8	857.1	890.6	928.1	962.5	1005.5	1045.9	1084.9	1129.8	1177.4	1266.1	1339.4	1315.0	1376.1	2348.6
date 13.03	140	10.1	U, V	8.5	6.81	6.52	6.35	6.13	5.89	5.59	5.26	4.88	4.52	4.14	3.74	3.3	2.75	1.83	1.4	1.26

Table 6 ELECTRICAL PARAMETERS - CELL 3

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
hour9.30			R, ohms	841.6	674.3	645.5	628.7	606.9	583.2	553.5	520.8	483.2	447.5	409.9	370.3	326.7	272.3	181.2	138.6	124.8
			r, ohms.cm	990.1	842.8	860.7	898.2	933.7	971.9	1006.3	1041.6	1073.7	1118.8	1171.1	1234.3	1306.9	1361.4	1207.9	1386.1	2495.0
date	146	10.2	U, V	8.5	6.81	6.5	6.33	6.11	5.87	5.56	5.23	4.88	4.52	4.12	3.73	3.31	2.77	1.87	1.42	1.27
hour 15.30			R, ohms	833.3	667.7	637.3	620.6	599.0	575.5	545.1	512.8	478.4	443.1	403.9	365.7	324.5	271.6	183.3	139.2	124.5
			r, ohms.cm	980.4	834.6	849.7	886.6	921.6	959.2	991.1	1025.5	1063.2	1107.8	1154.1	1219.0	1298.0	1357.8	1222.2	1392.2	2490.2
date15.03	189.5	8.1	U, V	8.5	6.18	5.82	5.63	5.39	5.17	4.9	4.63	4.32	4.01	3.68	3.36	2.99	2.52	1.76	1.42	1.26
hour 11.00			R, ohms	1049.4	763.0	718.5	695.1	665.4	638.3	604.9	571.6	533.3	495.1	454.3	414.8	369.1	311.1	217.3	175.3	155.6
			r, ohms.cm	1234.6	953.7	958.0	992.9	1023.7	1063.8	1099.9	1143.2	1185.2	1237.7	1298.1	1382.7	1476.5	1555.6	1448.6	1753.1	3111.1
date16.03	213.5	6.7	U, V	8.5	5.19	4.89	4.69	4.52	4.32	4.1	3.89	3.66	3.42	3.16	2.91	2.62	2.28	1.71	1.42	1.25
hour 11.00			R, ohms	1268.7	774.6	729.9	700.0	674.6	644.8	611.9	580.6	546.3	510.5	471.6	434.3	391.0	340.3	255.2	211.9	186.6
			r, ohms.cm	1492.5	968.3	973.1	1000.0	1037.9	1074.6	1112.6	1161.2	1213.9	1276.1	1347.5	1447.8	1564.2	1701.5	1701.5	2119.4	3731.3
date 17.03	239	6.1	U, V	8.5	4.79	4.48	4.27	4.1	3.93	3.72	3.53	3.33	3.11	2.9	2.69	2.47	2.16	1.63	1.39	1.24
hour12.30			R, ohms	1393.4	785.3	734.4	700.0	672.1	644.3	609.8	578.7	545.9	509.8	475.4	441.0	404.9	354.1	267.2	227.9	203.3
			r, ohms.cm	1639.3	981.6	979.2	1000.0	1034.0	1073.8	1108.8	1157.4	1213.1	1274.6	1358.3	1469.9	1619.7	1770.5	1781.4	2278.7	4065.6
date20.03	309.5	4.6	U, V	8.5	4.77	3.72	3.54	3.37	3.22	3.06	2.91	2.75	2.6	2.44	2.28	2.11	1.86	1.5	1.31	1.21
hour 11.00			R, ohms	1847.8	1037.0	808.7	769.6	732.6	700.0	665.2	632.6	597.8	565.2	530.4	495.7	458.7	404.4	326.1	284.8	263.0
			r, ohms.cm	2173.9	1296.2	1078.3	1099.4	1127.1	1166.7	1209.5	1265.2	1328.5	1413.0	1515.5	1652.2	1834.8	2021.7	2173.9	2847.8	5260.9
date22.03	362.5	1.7	U, V	8.5	5.02	3.07	2.84	2.71	2.64	2.52	2.38	2.27	2.17	2.06	1.95	1.83	1.65	1.4	1.23	1.15
hour 15.45			R, ohms	5000.0	2952.9	1805.9	1670.6	1594.1	1552.9	1482.4	1400.0	1335.3	1276.5	1211.8	1147.1	1076.5	970.6	823.5	723.5	676.5
			r, ohms.cm	5882.4	3691.2	2407.8	2386.6	2452.5	2588.2	2695.2	2800.0	2967.3	3191.2	3462.2	3823.5	4305.9	4852.9	5490.2	7235.3	13529.4
date23.03	383	3.5	U, V	8.5	2.21	1.55	1.29	1.25	1.22	1.16	1.14	1.1	1.06	1.03	0.98	0.94	0.87	0.76	0.67	0.64
hour 12.30			R, ohms	2428.6	631.4	442.9	368.6	357.1	348.6	331.4	325.7	314.3	302.9	294.3	280.0	268.6	248.6	217.1	191.4	182.9
			r, ohms.cm	2857.1	789.3	590.5	526.5	549.5	581.0	602.6	651.4	698.4	757.1	840.8	933.3	1074.3	1242.9	1447.6	1914.3	3657.1
date 24.03	409	1.4	U, V	8.5	0.94	1.02	0.83	0.8	0.78	0.77	0.75	0.73	0.71	0.69	0.68	0.67	0.65	0.59	0.55	0.53
hour14.30			R, ohms	6071.4	671.4	728.6	592.9	571.4	557.1	550.0	535.7	521.4	507.1	492.9	485.7	478.6	464.3	421.4	392.9	378.6
			r, ohms.cm	7142.9	839.3	971.4	846.9	879.1	928.6	1000.0	1071.4	1158.7	1267.9	1408.2	1619.0	1914.3	2321.4	2809.5	3928.6	7571.4

Table 6 ELECTRICAL PARAMETERS - CELL 3

date	time	I, mA	point	c/a	c/1	c/2	c/3	c/4	c/5	c/6	c/7	c/8	c/9	c/10	c/11	c/12	c/13	c/14	c/15	c/16
date28.03	500	2.8	U, V	8.5	3.02	2.32	2.2	2.11	2.05	1.97	1.9	1.83	1.77	1.7	1.63	1.55	1.45	1.27	1.11	1.06
hour9.30			R, ohms	3035.7	1078.6	828.6	785.7	753.6	732.1	703.6	678.6	653.6	632.1	607.1	582.1	553.6	517.9	453.6	396.4	378.6
			r, ohms.cm	3571.4	1348.2	1104.8	1122.4	1159.3	1220.2	1279.2	1357.1	1452.4	1580.4	1734.7	1940.5	2214.3	2589.3	3023.8	3964.3	7571.4
date 29.03	528	2.7	U, V	8.5	2.97	2.31	2.18	2.1	2.03	1.96	1.91	1.85	1.78	1.71	1.65	1.58	1.48	1.32	1.18	1.17
hour 13.30			R, ohms	3148.2	1100.0	855.6	807.4	777.8	751.9	725.9	707.4	685.2	659.3	633.3	611.1	585.2	548.2	488.9	437.0	433.3
			r, ohms.cm	3703.7	1375.0	1140.7	1153.4	1196.6	1253.1	1319.9	1414.8	1522.6	1648.1	1809.5	2037.0	2340.7	2740.7	3259.3	4370.4	8666.7
date31.03	576	1.9	U, V	8.5	1.29	1.13	1.08	1.03	1.01	0.99	0.96	0.94	0.92	0.89	0.87	0.84	0.81	0.73	0.66	0.64
hour13.30			R, ohms	4473.7	679.0	594.7	568.4	542.1	531.6	521.1	505.3	494.7	484.2	468.4	457.9	442.1	426.3	384.2	347.4	336.8
			r, ohms.cm	5263.2	848.7	793.0	812.0	834.0	886.0	947.4	1010.5	1099.4	1210.5	1338.3	1526.3	1768.4	2131.6	2561.4	3473.7	6736.8
date04.04	670.5	1.8	U, V	8.5	0.91	0.87	0.81	0.76	0.76	0.74	0.73	0.73	0.71	0.71	0.69	0.69	0.67	0.6	0.56	0.54
hour12.00			R, ohms	4722.2	505.6	483.3	450.0	422.2	422.2	411.1	405.6	405.6	394.4	394.4	383.3	383.3	372.2	333.3	311.1	300.0
			r, ohms.cm	5555.6	631.9	644.4	642.9	649.6	703.7	747.5	811.1	901.2	986.1	1127.0	1277.8	1533.3	1861.1	2222.2	3111.1	6000.0
date07.04	741.5	0.6	U, V	8.5	0.67	0.64	0.59	0.57	0.56	0.55	0.54	0.54	0.53	0.53	0.53	0.53	0.52	0.47	0.44	0.43
hour 11.15			R, ohms	14166.7	1116.7	1066.7	983.3	950.0	933.3	916.7	900.0	900.0	883.3	883.3	883.3	883.3	866.7	783.3	733.3	716.7
			r, ohms.cm	16666.7	1395.8	1422.2	1404.8	1461.5	1555.6	1666.7	1800.0	2000.0	2208.3	2523.8	2944.4	3533.3	4333.3	5222.2	7333.3	14333.3

Table 7 WATER CONTENT OF SOIL

dist.from anode	sample#	dish	dish+wet	dish+dry	wat. cont.-top	sample#	dish	dish+wet	dish+dry	wat. cont.-bottom
1	2	3	4	5	6	7	8	9	10	11
cell 1										
1	t101	0.46	6.29	4.65	39	b101	0.4	9.05	6.95	32
2	t102	0.41	8.09	6.24	32	b102	0.37	7.53	5.86	30
3	t103	0.44	5.58	4.43	29	b103	0.45	5.12	4.08	29
4	t104	0.43	5.57	4.39	30	b104	0.46	3.97	3.16	30
5	t105	0.46	6.29	4.98	29	b105	0.47	6.1	4.81	30
6	t106	0.46	4.8	3.8	30	b106	0.46	6.34	4.97	30
7	t107	0.41	5.71	4.53	29	b107	0.39	5.58	4.36	31
8	t108	0.4	5.01	4	28	b108	0.38	5.51	4.34	30
9	t109	0.41	5.13	4.05	30	b109	0.41	7.16	5.66	29
10	t110	0.3	4.96	3.96	27	b110	0.31	6.7	5.31	28
11	t111	0.3	5.87	4.6	30	b111	0.28	7.83	6.17	28
12	t112	0.28	7.13	5.56	30	b112	0.3	5.11	4.04	29
13	t113	0.29	6.76	5.24	31	b113	0.27	7.44	5.81	29
14	t114	0.28	5.28	4.05	33	b114	0.27	5.93	4.62	30
15	t115	0.25	4.41	3.41	32	b115	0.24	5.98	4.66	30
16	t116	0.28	8.43	6.54	30	b116	0.28	6.97	5.28	34

Table 7 WATER CONTENT OF SOIL

1	2	3	4	5	6	7	8	9	10	11
					cell 2					
1	t201	0.26	6.3	4.48	43	b201	0.26	5.67	4.11	41
2	t202	0.24	7.28	5.5	34	b202	0.24	8.11	6.24	31
3	t203	0.23	6.65	5.14	31	b203	0.23	5.95	4.7	28
4	t204	0.23	4.16	3.22	31	b204	0.22	4.7	3.78	26
5	t205	0.23	6.31	4.95	29	b205	0.23	6.29	5.1	24
6	t206	0.23	5.4	4.11	33	b206	0.23	6.42	5.1	27
7	t207	0.24	5.81	4.2	41	b207	0.24	6.97	5.34	32
8	t208	0.22	5.36	4.18	30	b208	0.24	4.01	3.2	27
9	t209	0.22	5.56	4.32	30	b209	0.24	7.1	5.67	26
10	t210	0.23	7.15	5.12	42	b210	0.23	7.57	5.89	30
11	t211	0.23	6.57	5.11	30	b211	0.22	5	4.03	25
12	t212	0.24	5.49	4.28	30	b212	0.23	5.44	4.41	25
13	t213	0.22	5.29	4.13	30	b213	0.22	9.16	7.53	22
14	t214	0.22	4.52	3.33	38	b214	0.22	4.41	3.3	36
15	t215	0.21	5.63	4.46	28	b215	0.21	5.24	4.23	25
16	t216	0.22	9.34	7.33	28	b216	0.22	8.66	6.84	27

Table 7 WATER CONTENT OF SOIL

1	2	3	4	5	6	7	8	9	10	11
cell 3										
1	t301	0.21	7.44	5.68	32	b301	0.22	6.75	5.03	36
2	t302	0.23	6.39	4.94	31	b302	0.23	7.8	6.09	29
3	t303	0.22	6.41	5.1	27	b303	0.22	9.33	7.36	28
4	t304	0.22	6.21	4.81	31	b304	0.21	4.35	3.42	29
5	t305	0.24	4.92	3.91	28	b305	0.22	6.08	4.87	26
6	t306	0.22	6.05	4.76	28	b306	0.26	5.03	4.01	27
7	t307	0.22	5.89	4.62	29	b307	0.23	7.15	5.74	26
8	t308	0.22	6.52	5.1	29	b308	0.24	7.67	6.08	27
9	t309	0.24	5.9	4.72	26	b309	0.23	6.02	4.81	26
10	t310	0.25	7.14	5.62	28	b310	0.25	5.99	4.81	26
11	t311	0.24	4.15	3.26	29	b311	0.24	6.63	5.22	28
12	t312	0.25	5.63	4.43	29	b312	0.24	5.18	4.16	26
13	t313	0.25	7.09	5.53	30	b313	0.22	8.12	6.58	24
14	t314	0.23	5.44	4.28	29	b314	0.23	5.31	4.26	26
15	t315	0.25	5.33	4.23	28	b315	0.21	5.77	4.5	30
16	t316	0.22	6.86	5.52	25	b316	0.22	6.67	5.24	28

Table 7 WATER CONTENT OF SOIL

1	2	3	4	5	6	7	8	9	10	11
cell 4										
1	t401	0.22	6.97	5.25	34	b401	0.21	7.26	5.58	31
2	t402	0.25	6.26	4.84	31	b402	0.23	6.79	5.26	30
3	t403	0.22	10.13	7.99	28	b403	0.21	12.16	9.51	28
4	t404	0.22	10.13	7.99	28	b404	0.21	12.16	9.51	28
5	t405	0.22	10.13	7.99	28	b405	0.21	12.16	9.51	28
6	t406	0.22	10.13	7.99	28	b406	0.21	12.16	9.51	28
7	t407	0.22	10.13	7.99	28	b407	0.21	12.16	9.51	28
8	t408	0.21	5.27	4.19	27	b408	0.2	4.73	3.73	28
9	t409	0.2	4.96	3.96	27	b409	0.19	6.65	5.3	26
10	t410	0.22	9.82	7.73	28	b410	0.21	8.78	6.93	28
11	t411	0.22	9.82	7.73	28	b411	0.21	8.78	6.93	28
12	t412	0.22	9.82	7.73	28	b412	0.21	8.78	6.93	28
13	t413	0.22	9.82	7.73	28	b413	0.21	8.78	6.93	28
14	t414	0.22	9.82	7.73	28	b414	0.21	8.78	6.93	28
15	t415	0.21	4.39	3.5	27	b415	0.2	5.34	4.22	28
16	t416	0.22	4.29	3.4	28	b416	0.22	6.06	4.82	27

Table 8 pH INFLUENTS

dates	time, hours	cell 1	cell 2	cell 3	cell 4
7/3-13.30	0	5.83	6.52	6.64	6.64
13/3-9.30	140	2.87	2.55	2.55	6.7
15/3-11.00	189.5	2.58	2.17	1.97	6.74
17/3-12.30	239	2.45	2.13	1.94	6.42
7/4-11.00	741.5	2.4	2.3	2.29	6.63

Table 9 VOLUMES AND PH OF THE EFFLUENTS

dates	time, hours	cell 1		cell 2		cell 3	
		volume	pH	volume	pH	volume	pH
13/3-9.30	140	-	-	4	9.45	2.1	9.45
15/3-11.00	189.5	-	-	1.5	9.4	0.7	9.72
17/3-12.30	239	-	-	2	9.45	2	9.79
20/3-11.00	309.5	-	-	3	9.4	4	10
24/3-14.30	409	-	-	1.5	9.5	2	10.1
28/3-9.30	500	1	9.6	-	-	-	-
29/3-13.30	528	0.2	not meas.	6.5	9.15	5	9.96
7/4-11.00	741.5	-	-	10	8.4	5.5	8.88

Table 10 SOIL PH

		cell 1		cell 2		cell 3		cell 4	
	dist.to A	sample #	pH	sample #	pH	sample #	pH	sample #	pH
top	1	t101	6.83	t201	5.39	t301	6.35	t401	7.1
	5	t104	7.71	t204	8.33	t304	8.13	t404	8.18
	9	t108	7.73	t208	7.86	t308	7.68	t408	7.52
	13	t112	8.22	t212	8.75	t312	8.46	t412	8.21
	16	t116	10.51	t216	10.32	t316	10.15	t416	8.5
bottom	1	b101	7.04	b201	4.49	b301	6.12	b401	7.55
	5	b104	7.72	b204	8.23	b304	8.28	b402	8.22
	9	b108	7.51	b208	7.81	b308	7.74	b408	7.64
	13	b112	8.17	b212	8.45	b312	8.56	b412	8.24
	16	b116	9.17	b216	11.03	b316	10.37	b416	8.27

Table 11 AMMONIUM-NITROGEN CONCENTRATION IN THE RESERVOIRS

dates	time, hours	cell 1			cell 2			cell 3			cell 4		
		potential mv	NH_4, mg/L	NH_4, c/c_0	potential mv	NH_4, mg/L	NH_4, c/c_0	potential mv	NH_4, mg/L	NH_4, c/c_0	potential mv	NH_4, mg/L	NH_4, c/c_0
initial conc.			6500			50			500			500	
7/3-13.30	0	-230.2	6617	1.02	-107	35	0.70	-164.1	397	0.79	-169.2	494	0.99
13/3-9.30	140	-227.1	5800	0.89	-107.5	36	0.71	-164.1	397	0.79	-169.1	491	0.98
15/3-11.00	189.5	-227.4	5874	0.90	-107	35	0.70	-163	379	0.76	-169.2	494	0.99
17/3-12.30	239	-226.5	5653	0.87	-104.2	31	0.62	-161.2	351	0.70	-169.4	498	1.00
7/4-11.00	741.5	-221.3	4531	0.70	-102.3	29	0.57	-160.2	337	0.67	-169.2	494	0.99

Table 12 NITRATE-NITROGEN CONCENTRATION IN THE RESERVOIR OF CELL 1

dates	time, hours	NH_4	NH_4+NO_3			NO_3	
		mg/L	mv	dilution	conc	mg/L	c/c_0
7/3-13.30	0	6617	-39.6	1/1000	12578	5961	0.92
13/3-9.30	140	5800	-39.7	1/1000	12651	6852	1.05
15/3-11.00	189.5	5874	-39.8	1/1000	12725	6851	1.05
17/3-12.30	239	5653	-39.6	1/1000	12578	6925	1.07
7/4-11.00	741.5	4531	-39	1/1000	12147	7616	1.17

Table 13 NITRATE-NITROGEN CONCENTRATION IN THE RESERVOIR OF CELL 2

dates	time, hours	NH_4	NH_4+NO_3			NO_3	
		mg/L	mv	dilution	conc	mg/L	c/c_0
7/3-13.30	0	35	-24.5	1/20	105	70	1.39
13/3-9.30	140	36	-24.1	1/20	102	67	1.33
15/3-11.00	189.5	35	-24.9	1/20	107	72	1.44
17/3-12.30	239	31	-24.2	1/20	103	72	1.44
7/4-11.00	741.5	29	-24.3	1/20	103	75	1.50

Table 14 NITRATE-NITROGEN CONCENTRATION IN THE RESERVOIR OF CELL 3

dates	time, hours	NH_4	NH_4+NO_3			NO_3	
		mg/L	mv	dilution	conc	mg/L	c/c_0
7/3-13.30	0	397	-35.1	1/100	969	571	1.14
13/3-9.30	140	397	-32.7	1/100	843	445	0.89
15/3-11.00	189.5	379	-35.6	1/100	997	618	1.24
17/3-12.30	239	351	-35.3	1/100	980	629	1.26
7/4-11.00	741.5	337	-35.1	1/100	969	632	1.26

Table 15 NITRATE-NITROGEN CONCENTRATION IN THE SUPPLY RESERVOIR OF CELL 4

dates	time, hours	NH_4	NH_4+NO_3			NO_3	
		mg/L	mv	dilution	conc	mg/L	c/c_0
7/3-13.30	0	494	-35.7	1/100	1003	509	1.02
13/3-9.30	140	491	-35.7	1/100	1003	511	1.02
15/3-11.00	189.5	494	-35.6	1/100	997	503	1.01
17/3-12.30	239	498	-35.7	1/100	1003	505	1.01
7/4-11.00	741.5	494	-35.9	1/100	1015	521	1.04
24/3-14.30	409	-	-	1.5	9.5	2	10.1
28/3-9.30	500	1	9.6	-	-	-	-
29/3-13.30	528	0.2	not meas.	6.5	9.15	5	9.96
7/4-11.00	741.5	-	-	10	8.4	5.5	8.88

Table 16 AMMONIUM-NITROGEN CONCENTRATION OF THE EFFLUENTS

dates	time, hours	cell 1			cell 2			cell#3		
		mv	mg/l	c/c_0	mv	mg/l	c/c_0	mv	mg/l	c/c_0
13/3-9.30	140	-	-	-	-53	3.5	0.07	-39.7	2	0.00
15/3-11.00	189.5	-	-	-	-69.2	7	0.14	-46	3	0.01
17/3-12.30	239	-	-	-	-73	8	0.16	-52	3	0.01
20/3-11.00	309.5	-	-	-	-71	8	0.15	-58	4	0.01
24/3-14.30	409	-	-	-	-53.7	4	0.07	-53.7	4	0.01
28/3-9.30	500	-59.9	24	0.00	-	-	-	-	-	
29/3-13.30	528	-58.2	22	0.00	-55.3	4	0.08	-57.7	4	0.01
7/4-11.00	741.5	-	-	-	-96.1	22	0.44	-89.6	17	0.03

Table 17 NITRATE-NITROGEN CONCENTRATION OF THE EFFLUENTS

cell#	dates	time, hours	NH4+NO3			NO_3	
			mv	dilution	mg/l	mg/l	NO_3,c/c$_0$
cell 1	28/3-9.30	500	-41	1/100	1388	1365	0.21
	29/3-13.30	528	-45.3	1/100	1751	1729	0.27
cell 2	13/3-9.30	140	-14.2	no dilut.	2.9	-0.6	0.0
	15/3-11.00	189.5	-42	no dilut.	14	7	0.1
	17/3-12.30	239	-33.5	1/10	88	80	1.6
	20/3-11.00	309.5	-29	1/10	68	60	1.2
	24/3-14.30	409	-29.4	1/10	70	66	1.3
	29/3-13.30	528	-39.9	no dilut.	13	9	0.2
	7/4-11.00	741.5	-24.5	1/10	52	30	0.6
cell 3	13/3-9.30	140	-16	1/100	319	317	0.63
	15/3-11.00	189.5	-66.7	1/10	607	604	1.21
	17/3-12.30	239	-51.8	1/100	894	891	1.78
	20/3-11.00	309.5	-44.6	1/100	609	605	1.21
	24/3-14.30	409	-44.8	1/100	616	612	1.22
	29/3-13.30	528	-42.4	1/100	542	537	1.07
	7/4-11.00	741.5	-53.7	1/100	989	973	1.95

Table 18 AMMONIUM-NITROGEN CONCENTRATION IN THE SOIL - CELL 1

	dist.to A	sample #	NH_4-N			
			mv	mg/L	c/c_0	mg/g soil
top	1	t101	-97.1	154.2	2.4	1.93
	5	t104	-92.7	128.8	2.0	1.61
	9	t108	-98.8	165.4	2.5	2.07
	13	t112	-71.4	53.7	0.8	0.67
	16	t116	-5.5	3.6	0.1	0.05
bottom	1	b101	-98.6	164	2.5	2.05
	5	b104	-91	120.1	1.8	1.50
	9	b108	-91.2	121.1	1.9	1.51
	13	b112	-72.6	56.5	0.9	0.71
	16	b116	-28.9	9.4	0.1	0.12

Table 19 AMMONIUM-NITROGEN CONCENTRATION IN THE SOIL - CELL 2

	dist.to A	sample #	NH_4-N			
			mv	mg/L	c/c_0	mg/g soil
top	1	t201	-9.7	4.3	8.6	0.05
	5	t204	-3.2	3.3	6.6	0.04
	9	t208	-17.9	6	12.0	0.08
	13	t212	-14.1	5.1	10.2	0.06
	16	t216	21.4	1.2	2.4	0.02
bottom	1	b201	8.1	2.1	4.2	0.03
	5	b204	7.1	2.1	4.2	0.03
	9	b208	0.0	2.9	5.8	0.04
	13	b212	8.0	2.1	4.2	0.03
	16	b216	48.8	0.4	0.8	0.01

Table 20 AMMONIUM-NITROGEN CONCENTRATION IN THE SOIL - CELL 3

	dist.to A	sample #	NH$_4$-N			
			mv	mg/L	c/c$_0$	mg/g soil
top	1	t301	-33.5	11.4	2.3	0.14
	5	t304	-9.2	4.2	0.8	0.05
	9	t308	-8.5	4.1	0.8	0.05
	13	t312	6.6	2.2	0.4	0.03
	16	t316	25.0	1	0.2	0.01
bottom	1	b301	-33.7	11.4	2.3	0.14
	5	b304	-13.1	4.9	1.0	0.06
	9	b308	-17.9	1.2	0.2	0.02
	13	b312	0.1	2.9	0.6	0.04
	16	b316	51.0	0.4	0.1	0.01

Table 21 AMMONIUM-NITROGEN CONCENTRATION IN THE SOIL - CELL 4

	dist.to A	sample #	NH_4-N			
			mv	mg/L	c/c_0	mg/g soil
top	1	t401	-51.8	24.1	4.8	0.3
	5	t404	-3.5	3.3	0.7	0.04
	9	t408	45.1	0.5	0.1	0.01
	13	t412	44.3	0.5	0.1	0.01
	16	t416	59.0	0.3	0.1	0
bottom	1	b401	-52.1	24.4	4.9	0.31
	5	b402	-8.4	4.1	0.8	0.05
	9	b408	22.2	1.2	0.2	0.02
	13	b412	43.8	0.5	0.1	0.01
	16	b416	57.2	0.3	0.1	0

Table 22 NITRATE-NITROGEN CONCENTRATION IN THE SOIL - CELL 1

	dist.to A	sample #	total mineral N			NO3-N		
			mv	N-mg/L	N-mg/g soil	mg/L	c/c_0,%	mg/g soil
top	1	t101	-41.8	810	10.13	655.80	10.1	8.2
	5	t104	-33.4	310	3.88	181.20	2.8	2.27
	9	t108	-30.8	230	2.88	64.60	1.0	0.71
	13	t112	-13.2	30	0.38	-23.70	-0.4	-0.29
	16	t116	-19.2	60	0.75	56.40	0.9	0.7
bottom	1	b101	-47.0	1480	18.50	1316.00	20.2	16.45
	5	b104	-27.7	160	2.00	39.90	0.6	0.5
	9	b108	-26.5	140	1.75	18.90	0.3	0.24
	13	b112	-23.6	100	1.25	43.50	0.7	0.54
	16	b116	-24.5	110	1.38	100.60	1.5	1.26

Table 23 NITRATE-NITROGEN CONCENTRATION IN THE SOIL - CELL 2

	dist.to A	sample #	total mineral N			NO3-N		
			mv	N-mg/L	N-mg/g soil	mg/L	c/c_0,%	mg/g soil
top	1	t201	-13.2	35.21	0.44	30.91	61.8	0.39
	5	t204	-8.6	19.97	0.25	16.67	33.3	0.21
	9	t208	-2.1	9.01	0.11	3.01	6.0	0.03
	13	t212	-38.2	7.63	0.10	2.53	5.1	0.04
	16	t216	-38.6	7.97	0.10	6.77	13.5	0.08
bottom	1	b201	-13.3	35.64	0.45	33.54	67.1	0.42
	5	b204	-9.0	21.12	0.26	19.02	38.0	0.23
	9	b208	-32.0	3.53	0.04	0.63	1.3	0
	13	b212	-34.3	4.68	0.06	2.58	5.2	0.03
	16	b216	-25.9	1.67	0.02	1.27	2.5	0.01

Table 24 NITRATE-NITROGEN CONCENTRATION IN THE SOIL - CELL 3

	dist.to A	sample #	total mineral N			NO3-N		
			mv	N-mg/L	N-mg/g soil	mg/L	c/c_0,%	mg/g soil
top	1	t301	-36.0	57.9	0.72	46.50	9.3	0.58
	5	t304	-32.7	38.52	0.48	34.32	6.9	0.43
	9	t308	-38.6	79.7	1.00	75.60	15.1	0.95
	13	t312	-20.1	8.23	0.10	6.03	1.2	0.07
	16	t316	-15.4	4.61	0.06	3.61	0.7	0.05
bottom	1	b301	-32.3	36.76	0.46	25.36	5.1	0.32
	5	b304	-29.6	26.54	0.33	21.64	4.3	0.27
	9	b308	-28.2	22.3	0.28	21.10	4.2	0.26
	13	b312	-27.2	19.7	0.25	16.80	3.4	0.21
	16	b316	-33.8	44.19	0.55	43.79	8.8	0.54

Table 25 NITRATE-NITROGEN CONCENTRATION IN THE SOIL - CELL 4

	dist.to A	sample #	total mineral N			NO3-N		
			mv	N-mg/L	N-mg/g soil	mg/L	c/c_0,%	mg/g soil
top	1	t401	-47.9	249.7	3.12	225.60	45.1	2.82
	5	t404	-38.8	81.2	1.02	77.90	15.6	0.98
	9	t408	-38.1	74.9	0.94	74.40	14.9	0.93
	13	t412	-25.1	15.17	0.19	14.67	2.9	0.18
	16	t416	-23.3	12.2	0.15	11.90	2.4	0.15
bottom	1	b401	-39.6	90.09	1.13	65.69	13.1	0.82
	5	b402	-37.7	71.53	0.89	67.43	13.5	0.84
	9	b408	-37.4	69.1	0.86	67.90	13.6	0.84
	13	b412	-37.7	71.05	0.89	70.55	14.1	0.88
	16	b416	-37.9	73.11	0.91	72.81	14.6	0.91