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The physical enhancement of electrokinetic soil decontamination

Batu Tarman
Lehigh University

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The Physical Enhancement of Electrokinetic Soil Decontamination

by

Batu Tarman

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Date

Professor Sibel Pamukcu
Thesis Advisor

Professor I. J. Kugelman
Chairman of Department

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Abstract

Electrokinetic phenomena have been studied for a long time. Electrokinetic techniques have been used extensively for the stabilization of soft soils and other dewatering operations. Yet, the notion that electrokinetic phenomena may be applicable to hazardous waste remediation is relatively new. In electrokinetic remediation, electrodes are implanted in the soil, and a direct current is imposed between the electrodes. The application of direct current leads to two effects: ionic species in the soil-water solution will migrate to the oppositely charged electrode (electromigration), and concomitant with this migration, a bulk flow of water is induced toward the cathode (electrosmosis). Electrokinetics is a cost effective method of decontamination and proves to be a feasible remediation process if a high degree of removal can be attained.

This study investigates further procedures that may be applicable to physically enhance the removal of the trichloroethylene which is a toxic organic contaminant and increase the efficiency of electrokinetic process. Two methods of enhancement were investigated. The first method was the increased migration potential of contaminants by increasing the temperature of the pore fluid. In the second method low amplitude-high frequency shear waves were applied.

Thermal enhancement by increasing the temperature of the pore fluid increased the amount of water flow through the soil samples considerably. The chemical analysis of treated soils showed no evidence of contaminant in the soil after the thermally enhanced electrokinetic runs when compared with chemical analysis of treated soils with no enhancement.

The results of electrokinetic tests with shear wave enhancement showed no appreciable improvement over electrokinetic process.Yet, monitoring over the entire system and interpetation of the electronic signals and readout brought up the need for further improvement on configuration of test set-up.

Chapter 1

Introduction

1.1 Statement of Problem

Early remedial methods for contaminated soils consisted primarily of excavation and disposal at a landfill site. More emphasis is now placed on insitu treatment technologies for cost effectiveness and reduction of environmental risk. Electrokinetics is a relatively new but a promising insitu process capable of removing heavy metals and organic species economically from soil.

Electrokinetics refer to the movement of water, ions, and charged colloids relative to one another under an applied direct current electric field. In soil, contaminated pore fluid may be made to flow to a collection system which would facilitate one of several treatment methods such as electroplating at the electrode, precipitation or co-precipitation at the electrode, pumping of water near the electrode, or complexing with ion-exchange resins. However, it is generally recognized that a better understanding of, and control on the electrokinetic phenomena are essential before it can be converted to a safe and an efficient method of soil decontamination.

Electroosmosis, which is one of the electrokinetic mechanisms, mobilizes the nonionic species such as organics in soil and it is dependent on soil minerology. The process could be made to work better by physically enhancing the electrokinetic effects on the transport of contaminants.

Previous testing showed that nonionic species such as organics adsorbed onto the soil particles and did not respond well to an electric field due to their non-polar chemistry. Therefore the need to enhance electroosmotic transport, which is the responsible electrokinetic mechanism for removal of nonionic species, appeared. Other results of physical enhancement are expected to be the release of relatively loosely held contaminants on soil surfaces and also promotion of emulsification of same organic contaminants.

1.2 Objectives of Research

The objective of this study is to investigate the physical enhancement of the electrokinetic process in order to achieve the highest possible degree of removal and also removal rate of contaminants from soil in a feasible manner.

The emphasis is made on trichloroethylene - an organic strongly adsorbed onto the soil, thus relatively difficult to clean out. Procedures are also applied to blank soil samples for the basic understanding of the components of enhanced electrokinetic phenomena. The enhancement methods focused upon are :

i. Increased migration potential of contaminants by increasing the temperature of the pore fluid. The idea is based on the principle that thermal expansion of soils cause significant pore pressures and volume changes which would result in higher pore water flow rates.

ii. The application of low amplitude-high frequency shear waves based on the phenomenon of seismic waves causing temporary instability condition in the ground by increasing pore water pressures progressively. The progressive increase in pore water pressures would in turn increase the tendency of the water to flow out of the soil pores.

A new experimental set-up was designed and constructed for each one of the enhancement methods mentioned above to carry out the electrokinetic tests in the laboratory. All tests discussed in this study were conducted on pure kaolinite clay.

1.3 Technology Scope of Research

In this study an investigation of the fundamentals of electroosmotic flow in kaolinite clay was conducted to augment the electrokinetically enhanced transport. Custom manufactured electroosmotic cells were modified in order to facilitate the physical enhancements mentioned above. Electrokinetic experiments conducted in the laboratory were divided in two groups. First group constituded the blank kaolinite samples that were tested for the better understanding of physically enhanced electrokinetic phenomena. In the second group, decontamination experiments were conducted to remove trichloroethylene from artificially contaminated kaolinite. The electroosmotic flow characteristics observed during these experiments and the removal attained is compared with the results obtained from base experiments with replicate unenhanced specimens.

Chapter 2

Background

2.1 The Electrokinetic Process

A soil particle in contact with water will typically acquire a net excess charge at its surface that produces an electrical potential difference between the solid and the aqueous phases [Overbeek and Bijsterbosch, 1979]. Since the overall system must maintain electrical neutrality, the excess surface charge is balanced by an equal and opposite charge in solution. The charge in solution is distributed over a finite distance from the solid surface; this excess charge in solution is the well-known electrical double layer [Hunter, 1981].

The presence of the electrical double layer gives rise to some interesting transport phenomena in solid-liquid systems; these phenomena are collectively known as the electrokinetic phenomena. The electrokinetic phenomena pertinent to in-situ remediation include electroosmosis (movement of water in response to electrical field), electrophoresis (movement of a charged particle or colloid in an electrical field), and electromigration (movement of solute ions in the electrical field).

A full understanding of the process requires knowledge of clay chemistry, surface chemistry, electrochemistry, and the behavior of soils under an electric gradient. Below are brief discussions on the pertinent components of electrokinetics.

2.1.1 The Electric Double Layer: Details of double layer is widely available in literature [Van Olphen, 1963]. A brief description is also provided here. An electric double layer is considered to develop on the surface of a charged colloid which is in contact with a solution. Figure 2.1 shows schematically the negatively charged surface of a clay particle in contact with a water solution containing ions. The negatively charged surface will attract positively charged ions from the water solution. If the ions were influenced by the electrostatic force only, the charged surface would adsorb only enough positive ions required for neutralization. This would result in a single layer of

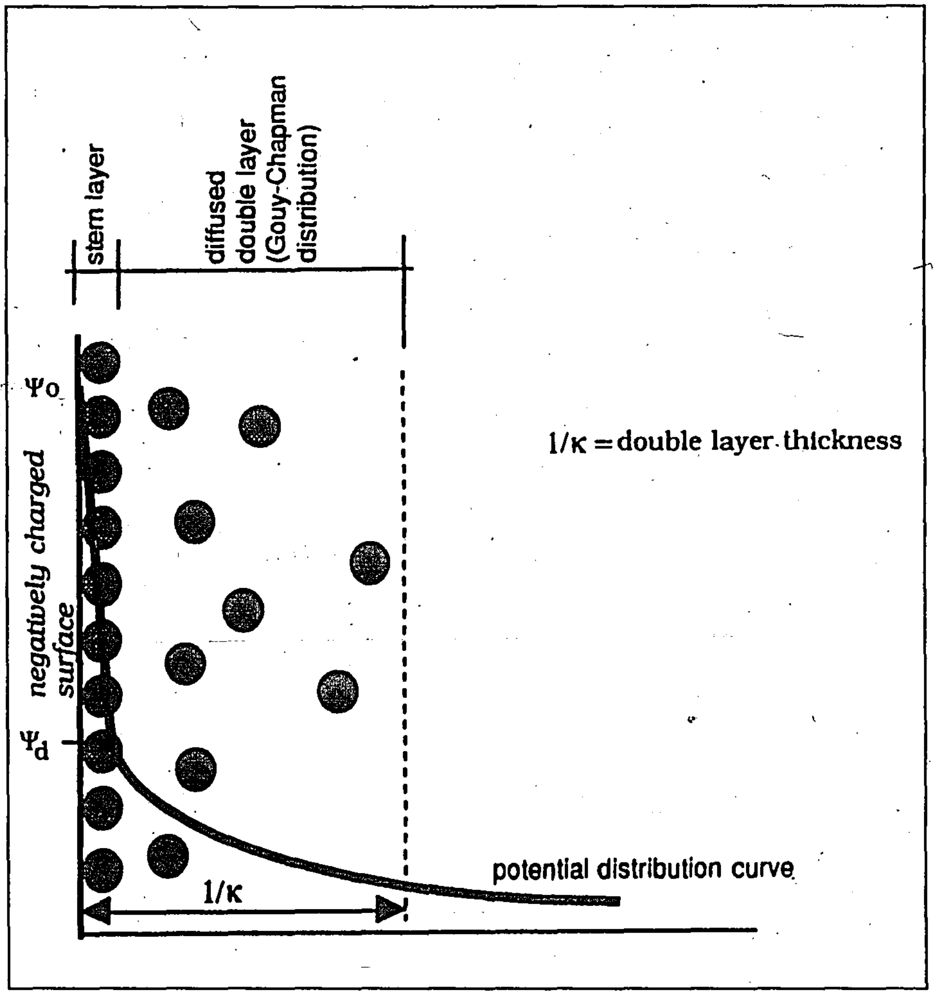

Figure 2.1. Potential Distribution in the electrokinetic double layer

positive ions. However, this is not the case since the counter ions tend to move away from the surface due to a random 'Brownian Motion'. This results in a distribution of the ions over an area rather than a single layer. Generally, this distributed layer of the counter ions is termed the double layer. According to Stern [1924], the double layer has two components-the Stern layer which is firmly held to the surface, and the diffused double layer in which the ions are free to move randomly under an electric gradient. In the Stern layer the potential distribution is linear, and in the diffused layer the potential distribution is given by Gouy-Chapman [1910] theory.

Three electrokinetic phenomena are believed to occur when a DC voltage gradient is applied to a soil-water system. These are as follows:

2.1.2 Electroosmosis: The movement of a liquid phase toward an electrode while the solid phase remains stationary is called electroosmosis. In a soil-water system, the water moves toward the negative electrode (cathode) while the soil particles remain in place. Flow of the pore water is in the direction of the cathode because the positive ions in the double layer are attracted to the negative electrode. If the clay particles are not allowed to move, the cations in the double layer migrate towards the cathode, dragging the pore fluid with them. Thus electroosmotic flow causes a net water transfer through the soil towards the cathode. A schematic representation of electroosmotic process is shown in Fig. 2.2.

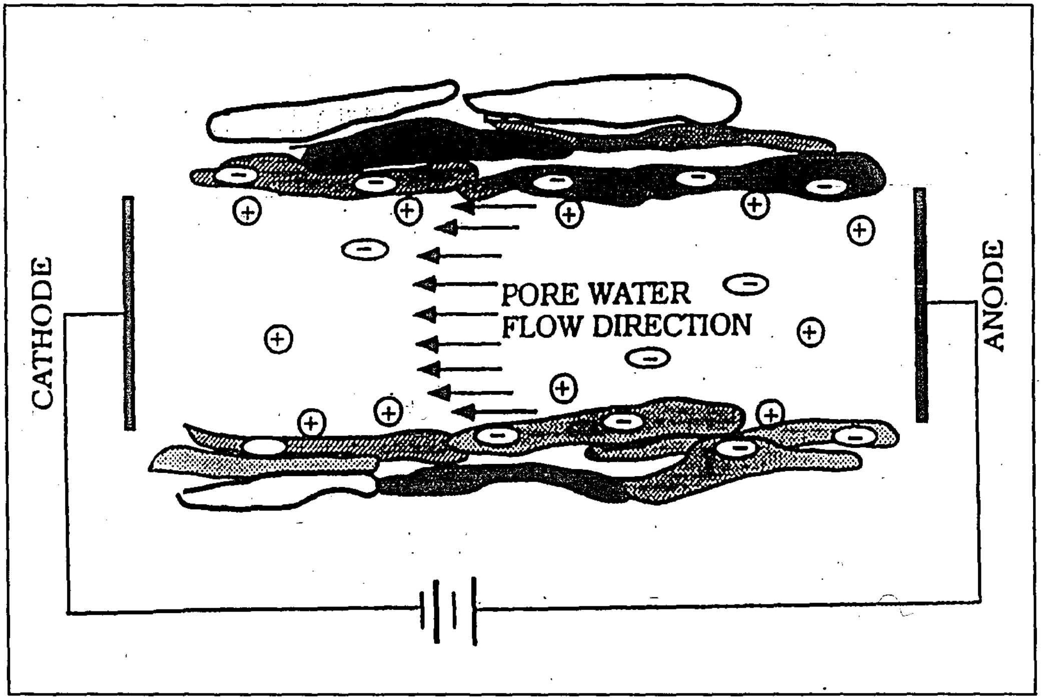

Figure 2.2 Schematic Diagram of a soil pore showing electroosmotic flow

2.1.3 Electrophoresis: The migration of charged colloids in a solid-liquid mixture is called electrophoresis. In a compact system, electrophoresis should be of less significance since the solid phase is restrained from movement. In some cases, however, electrophoresis may play a major role in decontamination if the migrating colloids carry the chemical species of interest adsorbed onto them.

2.1.4 Electrolytic Migration and Electrolysis: The movement of ions in the free water of soil pores under an electric gradient is termed electrolytic migration, and the disassociation of water molecules into their ionic components is termed electrolysis. These are responsible for conducting the bulk of the current in the soil-water system. The chemical reactions inherent in electrolysis decompose water in the vicinity of the electrodes. These reactions are:

$$H_2O - 4e^- = O_2 + 4H^+ \quad \text{(anode reaction)} \qquad [2.1]$$
$$4H_2O - 4e^- = H_2 + 4OH^- \quad \text{(cathode reaction)}$$

Water is reduced to hydrogen gas at the cathode. The removal of the hydrogen results in the increase in pH at the cathode site. Similarly, water is oxidized to oxygen at the anode site and thereby lowers the pH.

Soil decontamination by electrokinetic method is based on the assumption that most of the contaminant is present in pore water solution. While non-ionic species will be removed through electroosmotic flow alone, ionic species will have a flow velocity affected by both electroosmosis and their response to the electric field. Cations will migrate towards the cathode and anions will migrate towards the anode. Since the electroosmotic flow in a clay-water system is toward the cathode, the movement of cations will be accelerated while the extraction of anions will be retarded by electroosmosis.

2.2 Engineering Applications of Electrokinetic Flow Processes

Electrokinetics may be used for many different purposes. Some of its common uses are listed below:

2.2.1 Geotechnical Engineering Applications :

1. The stabilization of slopes, embankments, and dams (Casagrande 1952a, 1962, 1983);
2. Rendering large excavations stable for construction (Casagrande 1952a, 1962, 1983);
3. Strengthening of subgrades and sub-bases under pavement (Simon et. al. 1956; Gladwell 1965);
4. Dewatering and consolidating fine grained soils effectively, and increasing the soil shear strength considerably (Wan and Mitchell 1976; Gray and Somogyi 1977; Baglin and McIntosh 1987) ;
5. In the reduction of negative skin friction of piles, or to facilitate the pullout of used sheet piles (Casagrande 1962; Nikolaev 1962);
6. Injection of bentonite suspension into low permeability soils (Holmes 1963) ;
7. Prevention of moisture rise in capillary systems (Gray 1969).

2.2.2 Environmental Engineering Applications :

1. Concentration, dewatering and consolidation of wastewater sludges, slimes, coal washeries, mine tailings or dredged materials;
2. Injection of grouts to control ground water flow;
3. Injection of cleaning agents into contaminated soils;
4. Injection of vital nutrients for the growth of micro-organisms essential to the biodegradation of specific wastes;
5. Electrokinetic barriers to contaminant transport through compacted clay landfill liners or slurry walls;
6. Electrokinetic extraction of contaminants from polluted soils;
7. Modification of the flow pattern of ground water, and manipulation of the movement and size of a contaminant plume;
8. Rapid and reliable in-situ determination of the hydraulic conductivity of compacted clay landfill liners;
9. In-situ characterization of contaminants in the soil pore fluid;
10. In-situ generation of reactants for cleanup and/or electrolysis of contaminants;
11. Retrofitting of leaking in-service geomembrane liner.

2.3 Historical Development of Electrokinetics

A historical review of electrokinetics, which will be summarized here, has been given by Abramson [1934].

The study of electrokinetics is a very mature field. The first observations of electroosmosis and electphoresis are generally credited to Reuss [1809]. He connected two tubes filled with water to a wet clay and applied a DC current. He noticed that the water level rose on the cathode side and dropped on the anode side.

In 1846, Napier studied the relationship between electroosmosis and electrolysis. He reported that the measurable electroosmosis was greatest when the electrolytic decomposition was least.

Wiedemann [1852] showed that the amount of liquid transported though a porous diaphragm under an electric gradient was proportional to the current. Additionally, he found that the ratio of weight of water transported to current was independent of the area of flow and inversely proportional to the electrical conductivity of the liquid.

The use of electrokinetics in practical field problems is more recent, but is still quite mature. Casagrande [1949] pioneered the use of electroosmosis for the dewatering and stabilization of soft soils, and civil engineers have extensively used electroosmosis to stabilize soils in preparation for pile driving [Nikolaev, 1962].

Lockhart [1982] performed astudy of the dewatering of sediment suspensions from sodium kaolinite clay. He found that higher voltages produced more rapid dewatering; to produce an equilibrium of 37 percent solids at the cathode, natural drainage required 4 to 6 days, the application of 1 volt took 1 day, and the application of 50 volts required less than 15 minutes.

The notion that electrokinetic phenomena may be applicable to hazardous waste remediation appears to stem from the work of Segall et al. [1980], who found that electrokinetically dewatering dredging sludges generated extracted water, rich in heavy metals. Ironically, Segall et al. considered this to be an inhibitation to the use of electrokinetics in the field, since it produced a toxic liquid waste that requires further treatment.

By mid-1980's, numerous researchers, apparently simultaneously, realized that separations of heavy metals from soils posed a potential contamination solution rather than a potential contamination problem. Mitchell [1986] and Renaud and Probstein [1987] described the possibility of removing contaminants by electroosmosis from fine-grained saturated soils.

Shapiro et al. [1989] have described removing small soluble organic contaminants from columns of saturated clays in the laboratory. In similar bench-scale experiments, Acar, et al. [1989] and Hamed et al. [1989] described the removal of heavy metals from clays. In each of these experiments the concept has been to convect contaminants with water using electroosmosis as a separation mechanism. Runnells and Larson [1986] demonstrated the removal of cationic copper from sand in a bench-scale experiment, without considering whether electroosmosis or electromigration caused the removal.

So far there has been few field demonstrations of electrokinetic remediation. Lageman [1989] has described field-scale attempts to remove heavy metals from saturated soils in The Netherlands. A field-scale trial funded by EPA for the removal of chromium contamination from soils hsa met with partial success, but the success was limited by inadequate site characterization [Banerjee, 1988].

Acar et al. [1991] and Hamed et al. [1991] showed that the movement of the acid front from the anode to the cathode end is important in the removal of heavy metals from clay soils. Through their experiments they were able to show that the migration of H+ ion front helped release Pb (lead) from the soil surface into the water phase. The contaminant was then extracted with the electroosmotic flow.

Khan and coworkers [1989] showed that the cations lithium (Li^+) and sodium (Na^+) have the ability to enhance electroosmotic flow, and that soil densification will not occur if water is injected during the application of an electric field.

Pamukcu and coworkers [1991] found that zinc may be removed simultaneously through the anode and cathode ends. The decrease in pH at the anode end enhances zinc dissolution and diffusion in the region, and the electric current causes a migration of the pore water to the cathode.

2.4 Theoretical Development

The electrokinetic phenomena were first handled analytically by Helmholtz in 1879. He developed an equation for electroosmotic velocity which was modified by Smoluchowski in 1921 to apply to electrophoretic velocity. The equation is known as the Helmholtz-Smoluchowski equation and reads as follows:

$$u_{EO} = \frac{\varepsilon \varsigma \partial \phi}{\mu \partial \chi} \qquad [2.2]$$

u_{EO} = electroosmotic or electrophoretic velocity

ε = permittivity of the liquid (water) in free space

ς = zeta potential (the electric potential at an arbitrary distance from the solid surface resulting from the interaction between the surface and the electrolyte)

μ = viscosity of the fluid

$\partial \phi / \partial \chi$ = electric gradient

This equation has been modified by Pellat, who introduced the dielectric constant in 1904. Schmid [1950] presented another notable approach to quantifying electroosmosis. He proposed that the mobile ions in solution are uniformly distributed within the clay pore. This theory replaced the notion of zeta potential at the slipping plane with the Donnan quantity, which is defined by the total charge per unit volume of pore fluid.

Khan [1991] and Pamukcu et al. [1992] porposed a modified theory of electroosmotic velocity of water u_{EO} through soil. In this theory, the *true* electroosmotic flow is directly proportional to the current carried by the charged solid surfaces in soil. In this approach, the zeta potential used in the Helmholtz-Smoluchowski theory is replaced by a constant surface potential, Ψ_d, which is invariable with ionic concentration and pH of the pore fluid. Therefore,

$$u_{EO} = \{\varepsilon D \Psi_d / \mu\} I_s R_s / L \qquad [2.3]$$

where, I_s = surface current
R_s = surface resistance of soil

Equation [2.3] further reduces to the following with $\Psi_d R_S$ shown to remain fairly constant for a wide range of electrolyte concentration of the pore fluid:

$$u_{EO} = K I_s$$

where, $K = \{\varepsilon D \Psi_d / \mu\} R_s / L$ = constant

This agrees with Gray and Mitchell's [1967] observations and the much earlier observations of Napier [1846] who stated : "The measurable endosmose (electroosmosis) seems to be greater when the current has greatest difficulty to pass through, and when the decomposition of water was least." This follows that the true electroosmotic flow is large when the ratio of the surface current to the electrolytic current (carried by the ions in the pore fluid) is large, due to the reduced concentration of ions in the pore fluid. The modified theory basically emphasizes that the surface conductivity of the porous compact medium is the most essential precondition for electroosmotic flow.

Chapter 3

Methodology and Approach-Background Electrokinetic Testing

3.1 Introduction

The design and development of a new apparatus was necessary to simulate the electrokinetic phenomena in the laboratory and to monitor the controlling parameters for a better understanding of the electrokinetic process. A consolidation apparatus was also designed and manufactured to prepare homogeneous replicate specimens from well mixed soil slurries.

This chapter presents the description and operation of the custom manufactured electrokinetic apparatus and the consolidation apparatus, both used previously in background electrokinetic testing. Modifications made on the original electrokinetic cell and other system features of the new set-up to facilitate the physical enhancements mentioned in section 1.2 of Chapter 1 are described in Chapters 4. with pertinent operation procedures.

3.2 Facilities and Equipment

3.2.1 Consolidation Apparatus

A schematic diagram of the consolidation apparatus is given in Figure 3.1. It consists of a frame supporting a pneumatic cylinder into which pressurized air enters from the top, causing a piston and plate assembly to exert vertical pressure on the column of slurry. The slurry is filled in a 19.35 cm long cylindrical acrylic container joining the "guide tube" and the "sample tube" together. The sample tube, approximately 8.5 cm long with an inner diameter of approximately 3.5 cm, fits neatly into the guide tube at it's top and is removed after consolidation, by which time the slurry has been reduced to a dense soil within it. This sample tube is then mounted in the E-K cell , minimizing the disturbance effects of extrusion. Fluid is drained through the bottom of the sample via a porous stone resting on the base and another porous stone contained in the piston cap during consolidation. Air pressure is applied to the unit through an adjustable regulator (not shown in the schematic diagram).

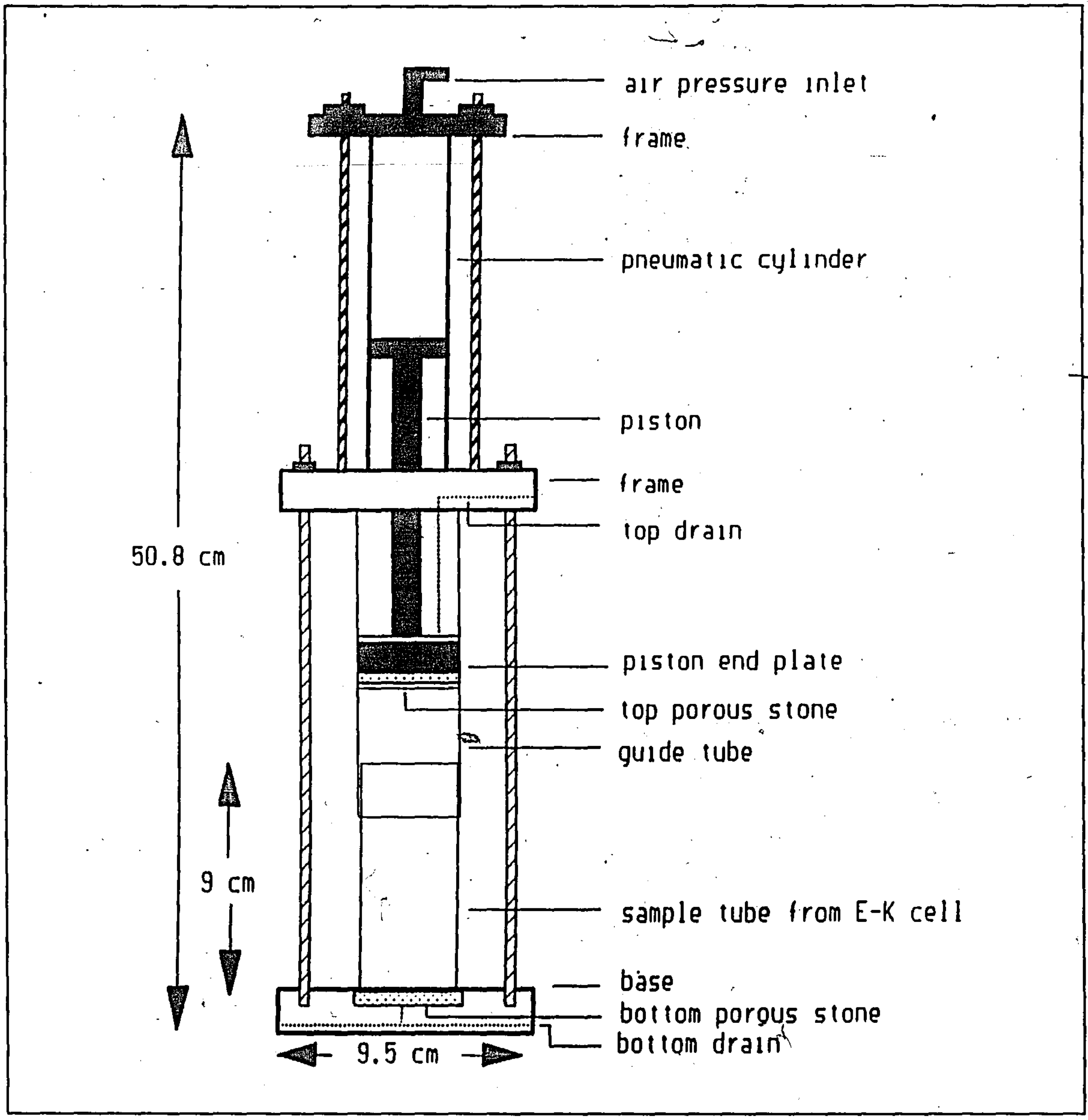

Figure 3.1. The Specimen Consolidation Apparatus

3.2.2 Electrokinetic Test Apparatus

The apparatus consisted of two parts: an electrokinetic cell and a flow control panel. A schematic diagram of the system is given in Figure 3.2. The details of the cell assembly is shown schematically in Figure 3.3.

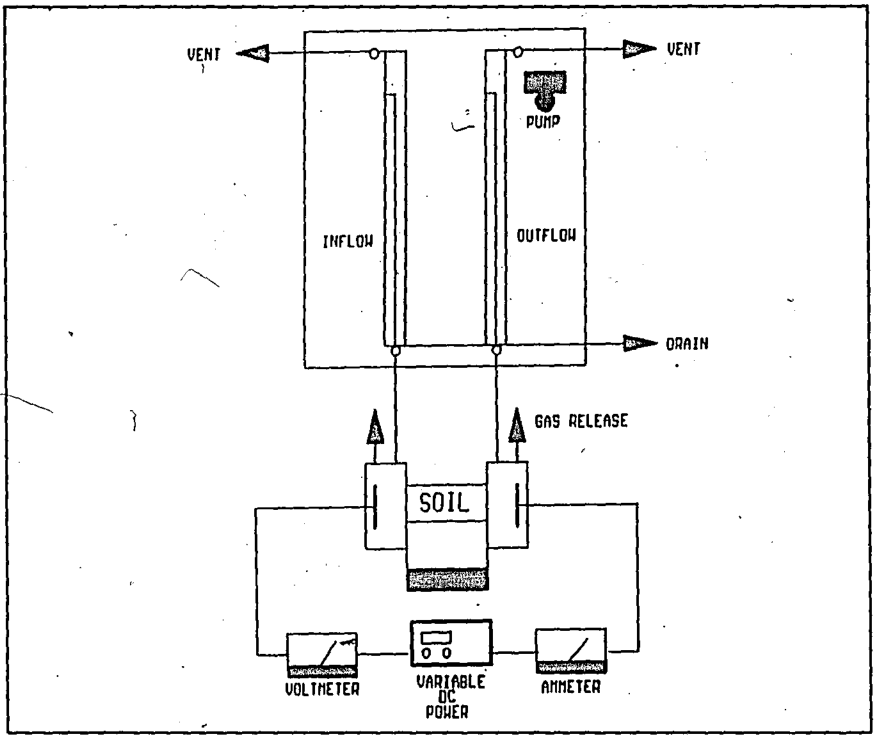

Figure 3.2. Schematic diagram of the electrokinetic apparatus and control panel

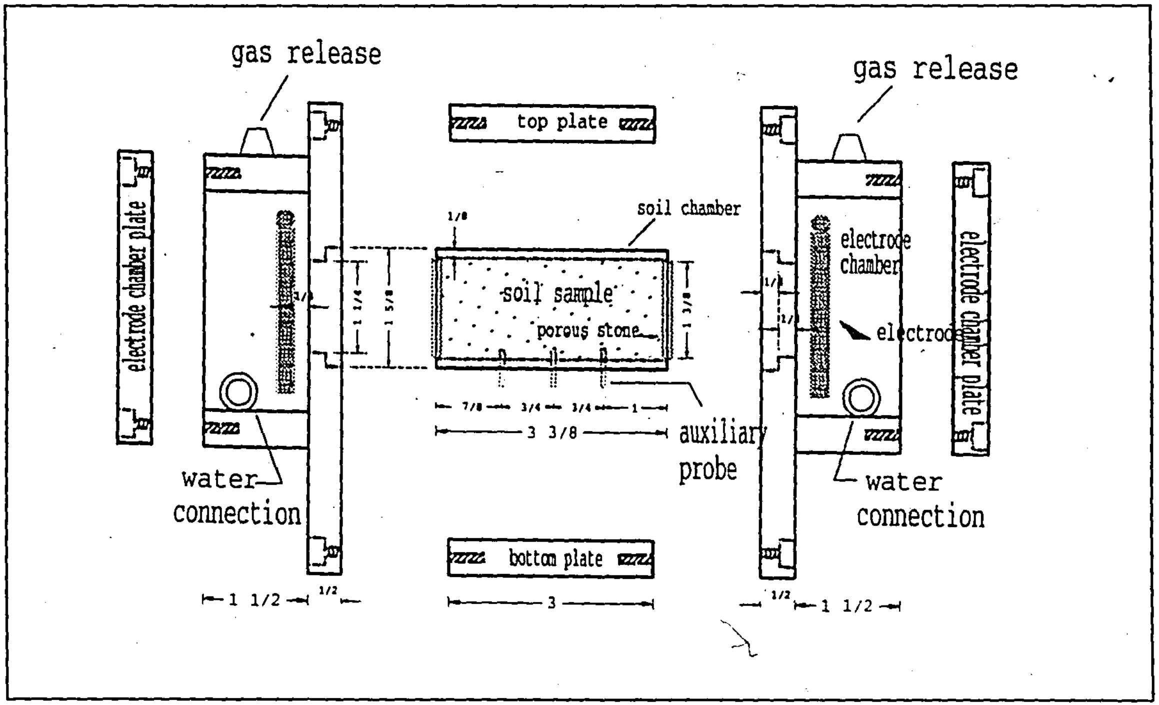

Figure 3.3 Details of Electrokinetic Cell Assembly

The electrokinetic test apparatus used in this research was developed from the following considerations:

i. Electrodes should be isolated from to the soil to prevent deposition and reduce the effect of electrode reactions on the soil to a minimum;
ii. A convenient method for gas ventilation should be provided to accurately measure the water transport, since the electrode reactions will produce gas at the electrode surfaces;
iii. The electrode surface has to be larger than the soil cross-sectional area so that a low current density at the electrodes will produce a relatively large current density in the soil;
iv. Ports for extracting inflow and outflow fluid samples have to be provided for the analysis and monitoring process.

Following these considerations, the electrode surface area was made to be six times larger than the soil sample cross-sectional area. Clear acrylic plastic was selected for all cell parts to provide visibility and also detect gas generation at the electrode compartments, at the soil-water interface, and possibly in the soil. One other advantage of acrylic material is that it allows further modifications. The electrode are made of high grade graphite rods to minimize electrode deterioration.

A. The electrokinetic cell, shown in Figure 3.3, has the following components:
Sample tube: The sample tube is a 3.55 cm ID and 8.55 cm long clear acrylic tube that contains the soil sample. Three auxiliary graphite electrodes (0.9 mm diameter) penetrate the sample through tube, separated an equal distance along one side. Voltage gradients within the soil can be measured through these electrodes during the experiment. The tube is assembled between the electrode chambers with O-rings placed inside the housings cut on the inner walls (facing the sample tube) of the chambers.
Porous stones: Carborundum porous stones are placed at each end of the sample tube to hold the soil sample in place durind the experiments. The porous stones have a permeability of 10^{-3} cm/sec., which is highly porous compares to the clay soils tested with hydraulic permeabilities ranging form 10^{-6} to 10^{-8} cm/sec. Therefore, they do not influence the rate of flow through soil.
Electrode chambers: These chambers are approximately 146.5 cm^3 in volume and house the electrodes at each end of the sample tube. The end plates are removable for filling with and emptying these chambers of fluid. It also facilitates cleaning of the chambers and the electrodes after each test run. Teflon membrane gaskets situated at these ends ensure that the unit is water and air tightness.

Electrodes: Electrode assemblies with a surface area of 22.6 cm^2 were constructed of graphite rods held together with conductive adhesive. The electrode assemblies are adhesively bonded into a small hole in the top back wall of each chamber. The rods are 0.635 cm in diameter. The assembly's connecting rod is flush with the outer surface of the back wall. An electric socket is placed through the center of the exposed rod and fixed in place with carbon conductive epoxy glue. These connections are wired to a variable DC power source.
Fluid connections: Teflon or stainless steel quick-connections are provided on the bottom of the back wall of the electrode chambers. These outlet or inlets are then connected to volume measuring tubes and pumped via chemical resistant, Teflon tubing. The advantage of the quick connections is that they allow the electrokinetic cell to be detached from the control panel completely while the electrode chambers are still charged with fluid, and that they facilitate fluid sampling at anytime during the experiment.
Gas expulsion or sample extraction/injection ports: These are pressure valves provided at the top of each electrode chamber. These valves have metal surfaces which are coated to control any deterioration by electrochemical reactions or metal ion deposition on them. Sample extractions or fluid injections can be accomplished using a volumetric syringe which allows for accurate control of quantities of fluids.

B. The control panel, shown in Figure 3.2, has the following components:
Burettes: 25 cc-glass burettes of are used to measure inflow, normally to the anode (positive electrode) chamber, and outflow , normally from the cathode (negative electrode) chamber to an accuracy of 0.1 cc.
Vent-pressure valves: Vented pressure valves exist at the top of each burette to provide gas expulsion. They are also linked to an air-pressure line via a regulator mounted on the panel which can facilitate the application of hydraulic gradient.
Water connection from cell: Water ports are provided from the control panel to the cell. They are made of chemical resistant flexible teflon tubes of 0.16 cm ID.
Water fill/drain valves: These are three way valves.
Pump: 30 ml/min. capacity flushing pumps are used to fill burettes and chambers with water.

Dedicated electrical units for each E-K cell consist of variable Direct Current (DC) power supply capable of applying either constant voltage (0 to 30 volt) , or constant current (0 to 1500 mA). These units also house analog meters for voltage and current readings.

3.3 Materials

The soil used to prepare the samples in this study was Georgia Kaolinite clay. The organic TCE (trichloroethylene) used to contaminate the clay slurry was in the liquid form and purchased from Fisher Scientific.

3.4 Experimental

3.4.1 Sample Preparation

The soil slurry is prepared at approximately 100 percent water content. It is then transferred to a glass jar with an air tight lid. A measured amount of the liquid organic is added directly into the slurry to acquire contamination at 1000 ppm initially. The filled jar is then shaken rigorously to obtain a homogeneous mixing of the contaminant .

The sample tube and guide tube are assembled on the base of the consolidation apparatus and filled about 3/4 of the way with slurry. After the removal of air bubbles, the piston is lowered into the guide tube to the top of the slurry column and the apparatus is assembled. A setting load of 2 psi is applied to overcome mechanical friction. Samples are consolidated to about 50 percent water content under a final pressure of 30 psi (200 kPa). Calibration of the instrument determined that, for a factor of safety of two, consolidation be conducted for 24 hours at increments given in Table 3.1.

The last column in this table accounts for the ratio of diameter (0.7) between the piston and the piston end cap. The pressure delivered by the piston is distributed uniformly over the larger area of the end cap, resulting in a reduced pressure than desired on the slurry column. This was asjusted by dividing desired pressures by 0.7 and applying the result.

Table 3.1: Consolidation Guide

Cumulative Time(hr.)	Actual Pressure (psi)	Applied Pressure (psi)
2	5	7
4	10	14
14	15	21
20	20	28
22	25	35
24	30	42

After consolidation, the sample tube is removed from the consolidation apparatus and any soil extruding from the top end is trimmed. Porous stones and o-rings are attached to each end with silicone glue. After applying high vacuum grease to the inner circular openings of the chambers, the sample tube is weighed and mounted between the chambers. This is achieved by removing one chamber of the E-K unit, positioning the sample, and reassembling the cell. Three auxiliary secondary probes are then inserted through holes pre-drilled at equal lengths across the soil sample.

The end plates of the electrode chambers are attached with a rubber gasket to ensure water and air tightness. The chambers are then pumped full with the chosen fluid. The cell is connected to the control panel by the fluid and power lines. With the drain valves closed, fluid is pumped into the burettes. Following this step all gas within the electrode chambers must be removed through the gas expulsion ports; this will cause fluid to drain from the burettes into the chambers, completely filling the electrode chambers. After the gas removal, fluid levels in the burettes are adjusted. The cell is now ready for an experiment. However, it is a good precautionary practice to allow the cell sit for about 10-15 minutes while checking for water leaks before the experiment is initiated.

3.4.2 Electrokinetic Testing

In all the E-K experiments, 30 volts DC was applied across the electrodes. The actual voltage gradient in soil varied in time and space as a result of variations in resistivity of the soil.and.

3.4.3 Measurements and Methods of Analysis

The data recorded before, during, and, after the E-K test is as follows:

<u>During consolidation</u>: Water content, pH, and quantitative chemical analysis sampling is done on the slurry. The volumes of the top and bottom waters extracted during consolidation are measured and analyzed for chemical concentration.

<u>During sample preparation</u>: A portion of the trimmings from the consolidated sample is analyzed for water and chemical content. This measurement provides an "initial" concentration of contaminant in the sample before E-K treatment and allows for normalization of concentrations obtained after the E-K test.

During the E-K test: Volumetric electroosmotic inflow and outflow readings are taken from the burettes. The system is checked to ensure that it is delivering 30 volts, and the corresponding current is recorded. Voltage readings through the anode and cathode chambers are taken via the power connections, and voltage drops across the soils are taken via the secondary electrodes. Readings were generally taken at zero, 15, and 30 minutes and one and two hours at the start of the test. Readings were taken at every two-hour intervals thereafter.

After the E-K test: During cell disassembly, the pH of the anode and cathode waters is recorded and the water samples are stored for chemical analysis. Because the cathode water is generally basic and may contain chemical that has precipitated out of solution, it is acidified with the addition of diluted HCl before chemical analysis to provide a more accurate chemical content. Basic observations like the color and turbidity of the water, the color of the soil, and fissures, discontinuities formed in the soil are recorded. The soil is then extruded from it's tube and measured at the center of the soil cross-section at 5 evenly spaced points along its length for pH, water content. Soil samples at the anode, center, and the cathode are collected for the analysis of chemical concentrations retained in the soil after E-K test.

Water content samples were dried for at least 24 hours in an oven at about 100°F, according to ASTM D4959. The pH of water was measured using a Beckman digital pH meter and standard bulb probe. A flat probe, Orion #913600, was used for the soil pH readings.

The quantitative chemical analysis for the organics was performed using a Hewlett Packard 5880A Series Gas Chromatography (G.C.), equipped with a 5880A Series G.C. Terminal(level four), with a Restek Crossbonded 100% Dimethyl Polysiloxane capillary column(30 m. length; .053 mm.ID; 5 μm. df). The extracted samples were evaluated at Lehigh University's Seeley G. Mudd facility. The chemical analysis for the TCE contaminants were performed following the APHA-AWWA-WPCF standard methods. Organic compound/extraction solvent solubilities, as referenced in the CRC Handbook of Chemistry and Physics, were evaluated for maximum soil desorption. The following extraction method was used based on the information provided in the referenced documents: Two-gram soil samples were combined with 15 ml. of acetone. The mixture was sonicated and the subsequent suspension was allowed to settle. The resultant supernatant was then analyzed for the TCE organic compound.

Chapter 4

Methodology and Approach-Enhanced Electrokinetic Testing

4.1 Introduction

In order to investigate the enhanced electrokinetic process, two new experimental units were developed. The original cells described in Chapter 3 were modified and employed by each one of these new units together with other system features which would facilitate the associated physical enhancement.

The two physical enhancements investigated are: i)increasing the temperature to increase the migration potential; ii)applying low amplitude-high frequency shear waves through the soil. In the following sections the experimental implications and the theoretical approach will be given for these enhancement methods.

4.2 Thermal Enhancement

It was anticipated that increased temperature in soil would develop significant pore water pressure increasing the tendency for the water to flow out of the soil pores. Thus, simultaneous application was expected to cause enhanced flow rate, therefore, increase the flushing of contaminants. The experimental set-up was developed based on this coupled effect.

4.2.1 Facilities and Equipment

A schematic diagram of a thermally enhanced electrokinetic experiment set-up is shown in Figure 4.1. The set-up incorporated three units: a-the modified electrokinetic cell and control panel; b-multipoint temperature recorder; c-temperature controlling device and power attenuator.

a-The soil sample assembled in the original electrokinetic cell and wrapped circumferentially with Glas-Col heating and insulating tapes. The maximum temperature output of these heating tapes are 250°C. Therefore, operation of the tapes was done through

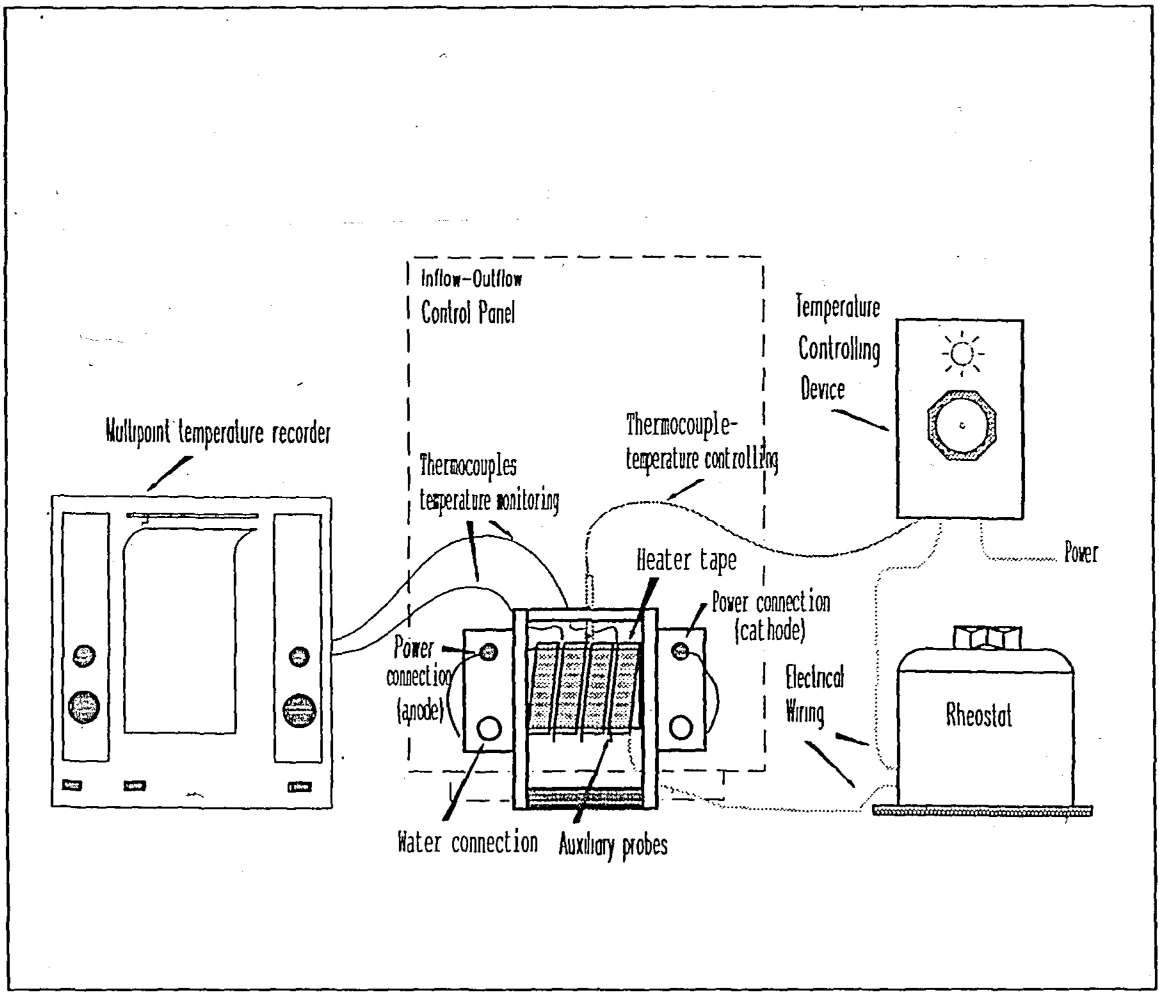

Figure 4.1 Schematic Diagram of Thermally Enhanced Electrokinetic Experimental Set-up

a power attenuator. Temperature control and monitoring are done through three thermocouples mounted into the soil sample through the acrylic sample tube. Two K-type ready-made thermocouples placed in teflon casing, being exposed to soil only at the welded-junction were mounted closest to either one of the soil chamber ends and used for monitoring. The temperature probe placed in the middle was for maintaining the desired constant temperature in the soil in conjunction with a power attenuator and a temperature controller. The cell was connected to the same control panel used for background testing through water and electrical connections.

b-A Model L1124S Speed Servo II Multipoint Recorder was used to monitor the temperature of the soil sample during the enhanced electrokinetic test through the K-type ready-made thermocouples. The temperature data was recorded on thermally-sensitive chart paper. Calibration of the instrument was checked against water at known temperatures before each experiment.

c-An Athena 11 Temperature controller was used to maintain the desired constant soil temperature by adjusting the knob on its front panel. Input to the controller was through its temperature probe mounted to the soil chamber. Responding to the signals through its probe, the controller operates the voltage attenuator intermittantly and the voltage attenuator supplies power to the heating tape.

4.2.2 About The Experimental Procedures

Experimental procedures and data gathering are as given in section 3.4. with the following exceptions:

1)- Three more holes other than that of the auxiliary voltage probes were drilled through the sample tube to mount the thermocouples. Special care was taken while mounting the thermocouples to the soil sample. Adhesive silicon glue was used to seal the thermocouple holes and the samples were allowed to stay long enough to make sure that the glue was set and the system was water tight. Sealing the system against water leakage has gained more importance in thermally enhanced experiments because increased temperature speeded up evaporation of water and thus, monitroing possible water losses through leakage and taking precautions against them became more difficult.

2)- After the electrokinetic cell assembly and the installation of thermocouples, the sample was wrapped with heating tape and also insulating tape to lessen heat loss to the environment once the desired temperature was maintained.

3)- In order to prevent overheating the soil chamber, sample was heated up to the desired temperature gradually. Adjusting the temperature controller to the target temperature in the first place would cause the controller keep the circuit closed providing continuous power to the heating tape until the elevated temperature is reached within the soil. The heating tape would in this case exceed the desired soil temperature before the temperature was reached in the soil. Therefore temperature of the sample was elevated gradually to prevent damaging the acrylic sample tube due to heat.

4)- Temperature data was monitored and recorded continuously on a thermal-sensitive chart paper. All the other data was collected in the same way as described in section 3.4.3.

4.3 Enhancement with Shear Wave Application

The experiment set-up is based on the phenomenon of seismic waves causing temporary instability condition in the ground by increasing pore water pressures progressively.

Shear waves vibrate particles perpendicular to the direction of the wave propagation. Since the soil is confined with no deformation allowed, the vibratory or cyclic strains cause a progressive increase in the pore water pressure in the soil. This is phenomenon most observed in saturated, loose soil deposits (Seed, 1986). When loose, saturated soils are subject to strains and shocks, there is a tendency for the soil to decrease in volume. This tendency causes a positive increase in pore pressure which result in a decrease in effective stress within the soil mass.

In this study, it is anticipated that the progressive increase in the pore water pressures (the level of which is dependent on frequency, amplitude, and duration of vibration,and also soil physical properties) would cause an increased tendency for the water to flow out of the soil pores. Thus, simultaneous application of the electrical potential is expected to cause enhanced flow rate, and therefore, increase the flushing of the contaminants. Another result of shear wave propagation is expected to be the release of loosely held contaminants on clay surfaces and also the promotion of emulsification of same organic contaminants, such as hydrocarbons. It is anticipated that the physical vibration might promote the migration of some organic molecules into the free water in the soil pores. Similarly the vibration may cause emulsification of some relatively large droplets of hydrocarbon fluids in the pore water. Subsequently, these particles may be flushed out of the soil with increased flow under the effect of the induced pore water pressures and the applied electrical potential.

4.3.1 Facilities and Equipment

A schematic diagram of the experimental set-up to investigate this simultaneous application of electric potential and shear waves is given in Figure 4.2. The set-up employed: a-modified electrokinetic cell for shear wave application, b-A computer with a data acquisition board connected to the set-up via a voltage attenuation box, c-Wave generating and monitoring units, and d-the same power unit and control panel used in background electrokinetic testing.

a-The modified electrokinetic cell has the following components:

<u>Piezoelectric Bender Elements:</u> The application of shear waves through the soil is facilitated with piezoceramic bender elements placed at each end of the soil sample tube(Dyvik and Madshus, 1986). The idea of using piezoceramic bender elements is developed from the use of such elements in a variety of standard geotechnical laboratory testing equipment (e.g., triaxial, direct simple shear and oedometer devices). Equipment for generating compression

waves especially through rock cores by piezoelectric elements or similar has also existed for a number of years.

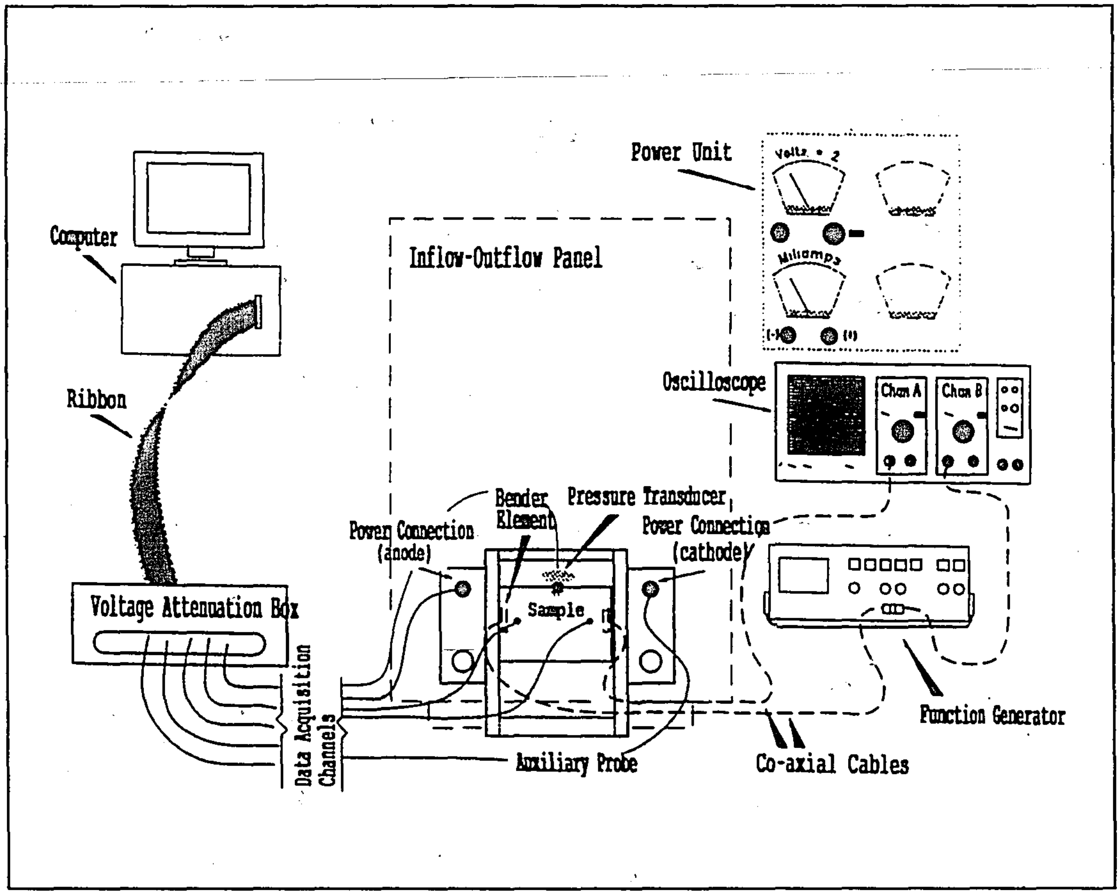

Figure 4.2. A Schematic Diagram of Electrokinetic Experiment Setup with Shear Wave Application

The *piezoelectric bender element* is an electro-mechanical transducer which is capable of converting mechanical energy (movement) either to ~~or~~ from electrical energy. The element itself consists of two thin piezoceramic plates which are rigidly bonded together with conducting surfaces between them and on the outsides (sandwich-type arrangement). The polarization of ceramic metarial in each plate and the electrical connections are such that when a driving voltage is applied to the element, one plate elongates and the other shortens. The net result is a bending displacement which is greater in magnitude than the length change in either of the two layers (plates). On the other hand, when an element is forced to bend, one layer will go into tension and the other into compression. This will result in an electrical signal which can be measured through the wire leads to the element. Figure 4.3 shows the shape of an element before and after a driving voltage is applied. There are two different types of bender elements : *series connected* and *parallel connected.* Standard electrode configurations and electrical connections of bender elements are given in Figure 4.4. A series connected element is twice as effective as a parallel connected element when used as a generator (mechanical to electrical energy). On the other hand, a parallel connected element is twice as effective as a series connected element when used as a motor (electrical to mechanical energy). For these reasons, a parallel connected element is used to generate a shear wave pulse which propagates along the length of the specimen and a series connected one is used to determine the arrival time and traces of the shear waves at the other end of the specimen. The bender element is a high impedance element and can not be exposed to moisture as this will short the transducer. It must therefore be cased in a waterproof material.

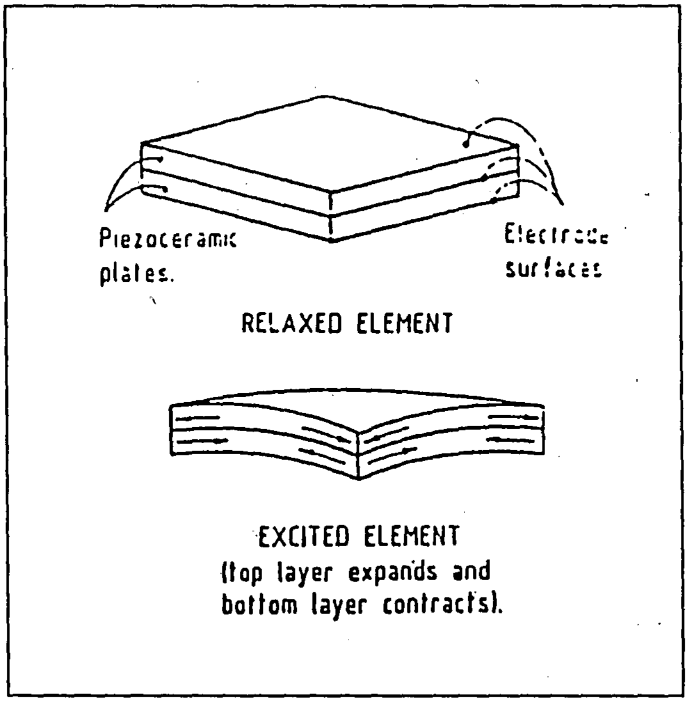

Figure 4.3 Shape of piezoelectric bender elements with and without applied excitation voltage

The modified electrokinetic cell has also two bender elements on either side of the sample tube, placed in porous stones. These elements are mounted normal to the surface of each stone so that they would be imbedded into the soil when assembled. For toughness and durability, a two-component epoxy is the best alternative. Figure 4.5 shows the electrokinetic cell modified with bender elements and the waterproof casing for the bender elements. The shear wave pulses are sent from the anode end in the same direction as electroosmosis to enhance the electroosmotic flow by the help of increased temporary pore water pressure gradients.

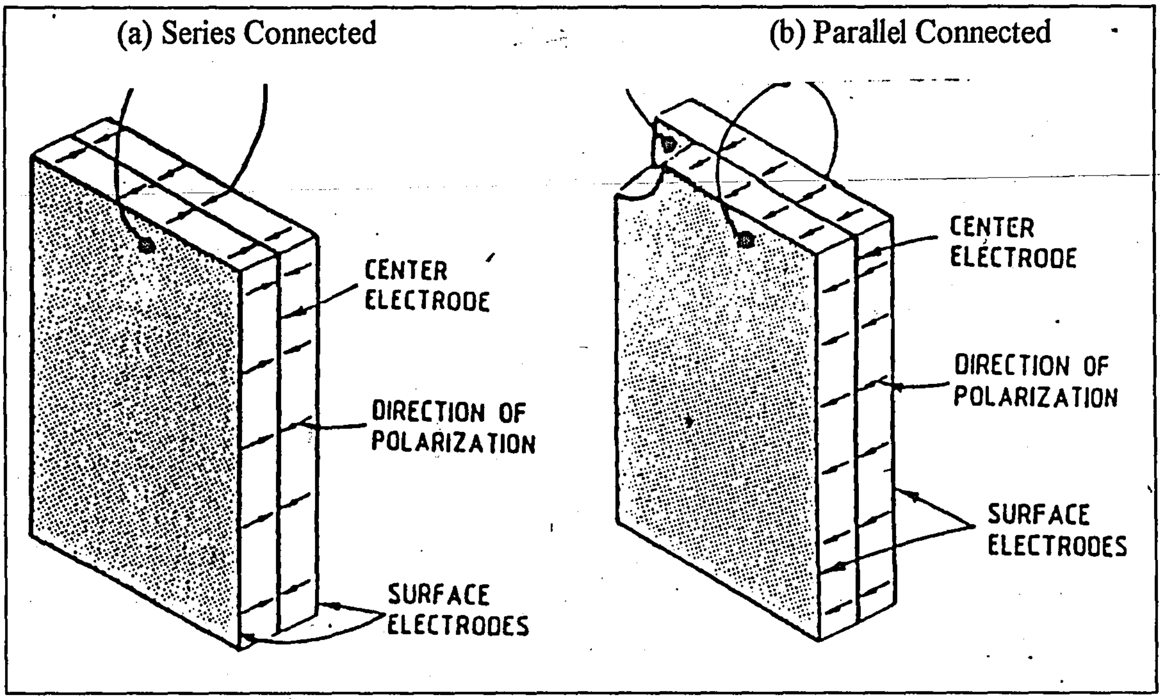

Figure 4.4 Series and parallel connected piezoceramic bender element

The Porewater Pressure Transducer: An Entran EPX-10W-50 Model Miniature Threaded Pressure Transducer is used to monitor the pressure variations within the specimen during the shear wave applicaton, and also during the electrokinetic flow. The transducer is activated by an Entran MM45P-HL-10 Model Power Supply/Digital Meter and the output voltage signals are collected in the computer via a data acquisition board and converted to pressure pressure data by a computer program. This measurement is important because the rate of pore water pressure increase and the rate of subsequent dissipation upon application of electricity helps to estimate the success of the method of increasing electroosmotic flow via increased pore water pressures.

b-The Data Acquisition System has the following components:

The Data Acquisition Board: A Metrabyte DAS-8PGA analog input board which has a Programmable Gain Amplifier is installed in a Gateway 386/Sx Model computer and used for data acquisition via a voltage attenuation box. Five channels are in charge of collecting the the data. A computer program was written in GW Basic Programming Language to operate the analog input board and convert the voltage inputs from the channels into their real values. A copy of the program is given in Appendix C.

The Voltage Attenuation Box: Because the voltage gradients through the soil are at levels too high to be acceptable to an analog input board, they needed to be attenuated first. Therefore, a voltage conditioning apparatus is designed to take a voltage in the range of 10 to 120 volts and attenuate it so that it is at a level acceptable to the analog input board. The attenuated voltage can then be input to a computer for data storage and analysis. Two levels of attenuation can be selected, 10:1 and 100:1. The channels carrying the pore water pressure and ampherage data, however, are directly connected to the computer, because the levels of their voltage inputs are low enough to be managable by the board.

c-Units used to generate and monitor the shear waves are:

The Function Generator: The transmitter bender element is connected to an external function generator to provide continuous frequency output. A Model 3011B 2MHz Digital Display Function General is used. Square wave driving signals of different frequency and amplitude are applied to the bender element via the function generator.

The Oscilloscope: Due to the very short travel time of the shear waves from one end of the soil sample to the the other, an oscilloscope of high resolution and accuracy is needed to record and monitor the resulting wave motion through the soil. A Nicolet NIC-310 Digital Oscilloscope was used in this study. The oscilloscope is connected to both the transmitter and the receiver elements with co-axial cables to monitor the shear wave before and after its travel through the soil sample.

d-The electric potential is applied by the same power unit as in the background electrokinetic testing. The inflow and outflow readings are also done by the same original control panel.

4.3.2 About The Experimental Procedures

The new enhanced set-up with shear wave application provided the ease of data gathering via data acquisition system. Yet, electrokinetic data was also collected manually in order to double check the consistancy and reliability of the system. Comparison of the data collected in either one of the two methods showed the weaknesses of the set-up and also the ways to get rid of these weaknesses.

The following differences in the methodology of enhanced electrokinetic testing should also be noted in addition to section 3.4:

- Since the pressure transducer is designed to measure the water pressures applied on its diaphragm, it needed to be kept away from the touch of soil particles. This was achieved by securing the transducer behind a glass porous stone in a special housing machined from acrylic. Therefore, another hole was drilled through the sample tube for the insertion of the transducer and its casing.

-Special care is taken while porous stones with bender elements mounted at each side are assembled. Extra holes are drilled on electrode compartments on each side and wiring of the bender elements are connected to the oscilloscope and the function generator.

-Five channels are used for data acquisition; three for the voltage drops through the soil, one for the current which is connected to the power unit, and one channel gathering pore water pressure data.

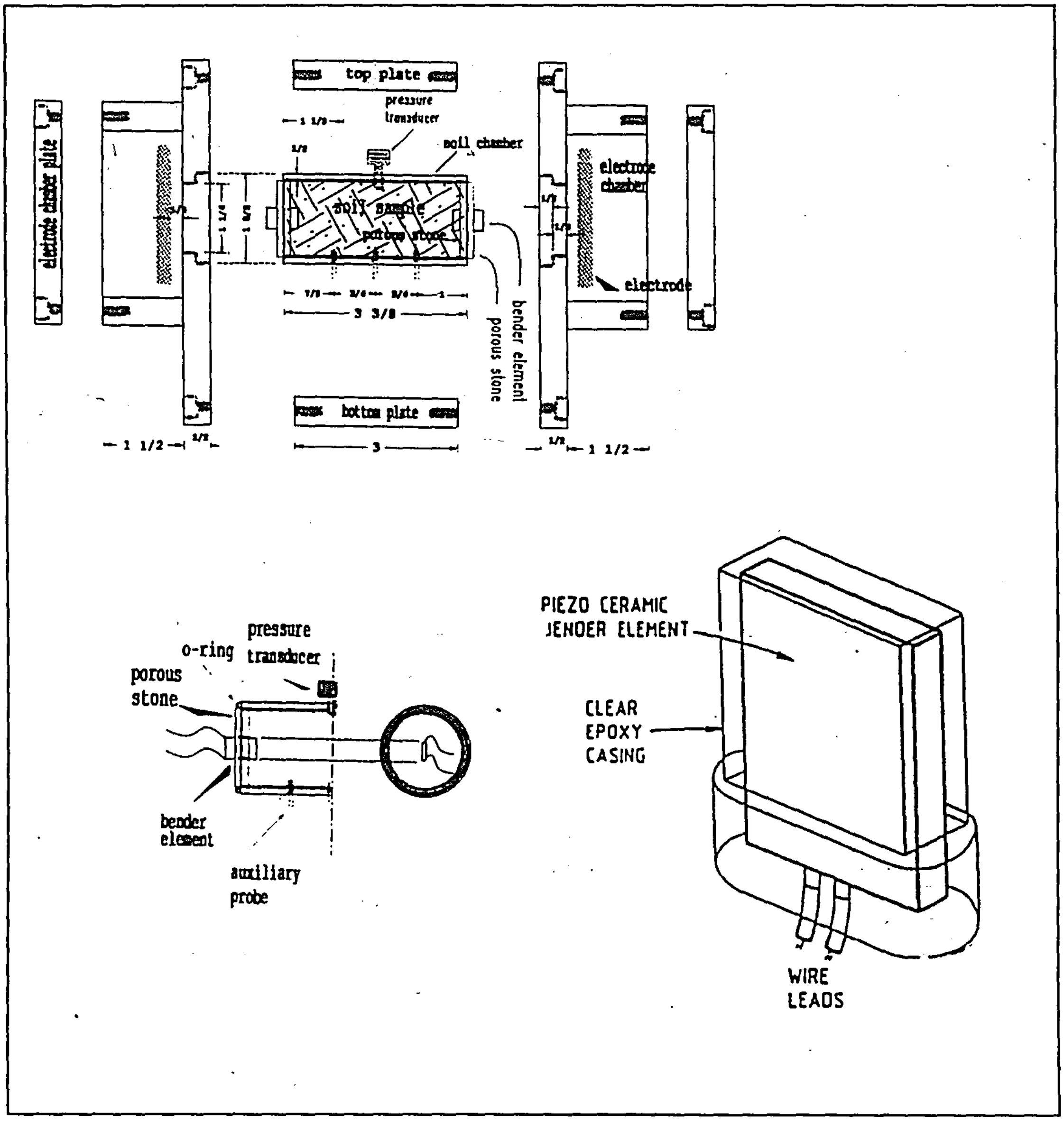

Figure 4.5 General Layout of the E-K Cell with Shear Wave Enhancement and Details of piezoelectric chip placement

Chapter 5

Results and Discussions

5.1 Introduction

The experimental results and discussion on the phenomena are presented in this chapter. The experimental work performed may be divided into two categories according to the apllied enhancement methods which are enhancement with increased temperature and enhancement with shear wave application. Thermal enhancement results will be given in the following section. Results and discussion for enhancement with shear wave appication will be presented afterwards.

5.2 Experiments with Thermal Enhancement

Thermally enhanced electrokinetic tests were conducted on blank and TCE-contaminated samples. Blank samples were run to understand the effects of temperature on electrokinetic phenomena for pure clays. TCE contaminated samples were also run to further investigate the temperature effects on contaminant removal with the simultaneous application of electric potential. The flow and current, and the inflow and current efficiency graphs for both enhanced and unhanced blank samples are presented in Appendix A. The same information for TCE-contaminated samples are presented in Appendix B.

Both enhanced and unenhanced electrokinetic flow data of all experiments was plotted and curve fit. The best seemed to be a straight line fit to the data. Comparison was made to the data of the cases with no enhancement. Plots are given in Figures 5.1 and 5.2.

Figure 5.1 shows the comparison of all thermally enhanced electrokinetic runs of blank kaolinite - distilled water samples to that of the blank samples with no enhancement. Figure 5.2 gives the comparison of all thermally enhanced electrokinetic runs of kaolinite - distilled water - TCE contaminated samples to the same, but unenhanced samples. In all cases of heat enhancement, the current efficiency increased significantly over that of the runs without enhancement, all other conditions being the same.

The electroosmotic flow was seen to increase as high as up to five times in some cases when compared to the ones with no enhancement. The chemical analysis data showed no TCE contaminant left in the soil samples at the end of thermally enhanced electrokinetic runs.

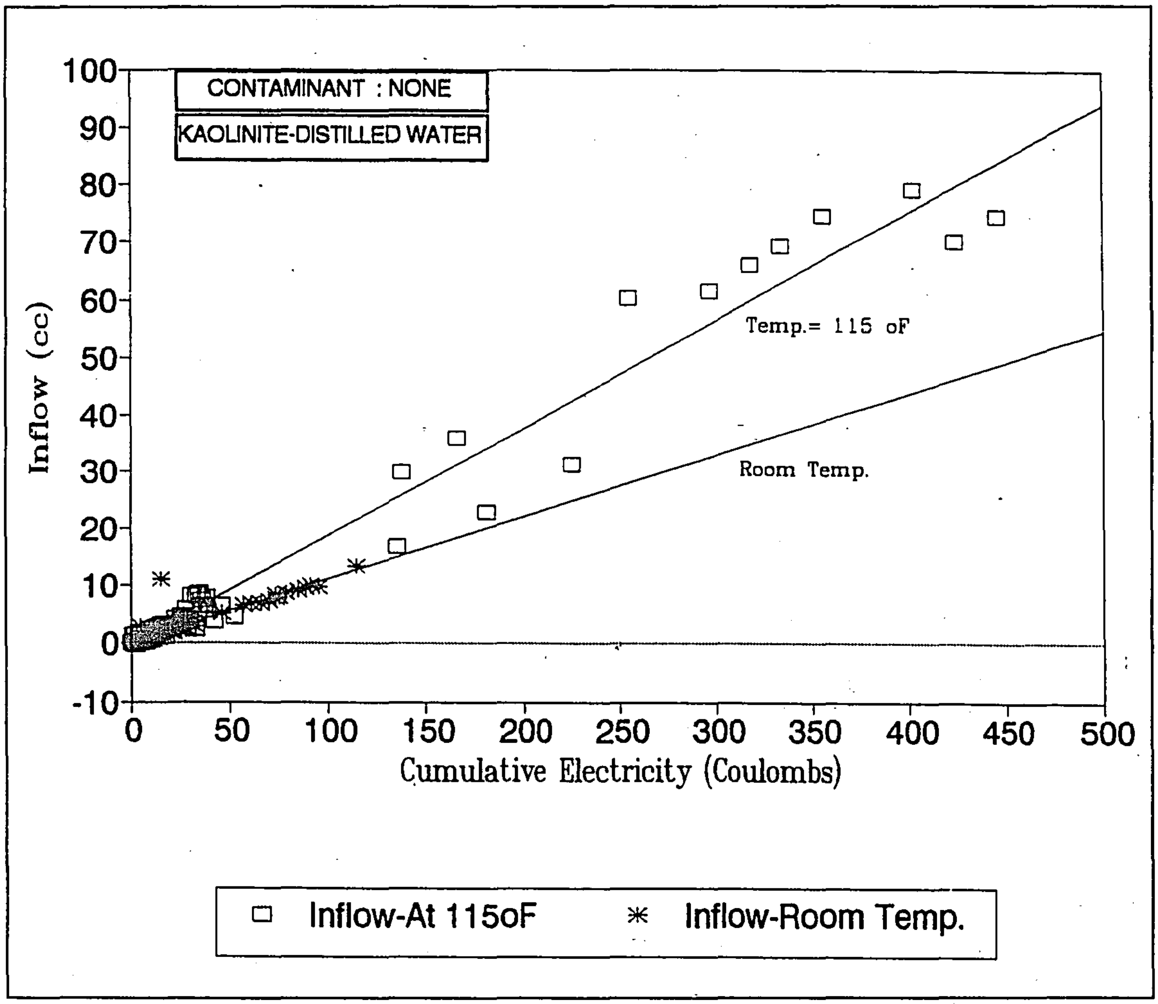

Figure 5.1 : Thermally Enhanced E-K Test Current Effiency Compared to Unenhanced E-K Test Current Efficiency for Blank Kaolinite Soil

5.3 Discussion of The Thermally Enhanced Experiment Results

The interpretatoin of the data shows that temperature increase had a significant positive effect on electrokinetic decontamination. The influence of temperature variations on the engineering properties of soils has been established by a number of studies. Finn (June,1951) and Paaswell (May, 1967), among others, have investigated the effect of temperature on consolidation. Temperature effects on interparticle forces, pore water pressures have been considered by Lambe (1953; 1960; 1961), Ladd (1961), Mitchell (January, 1963), Duncan and Campanella (November, 1965), and others investigated the effects of temperature variations on

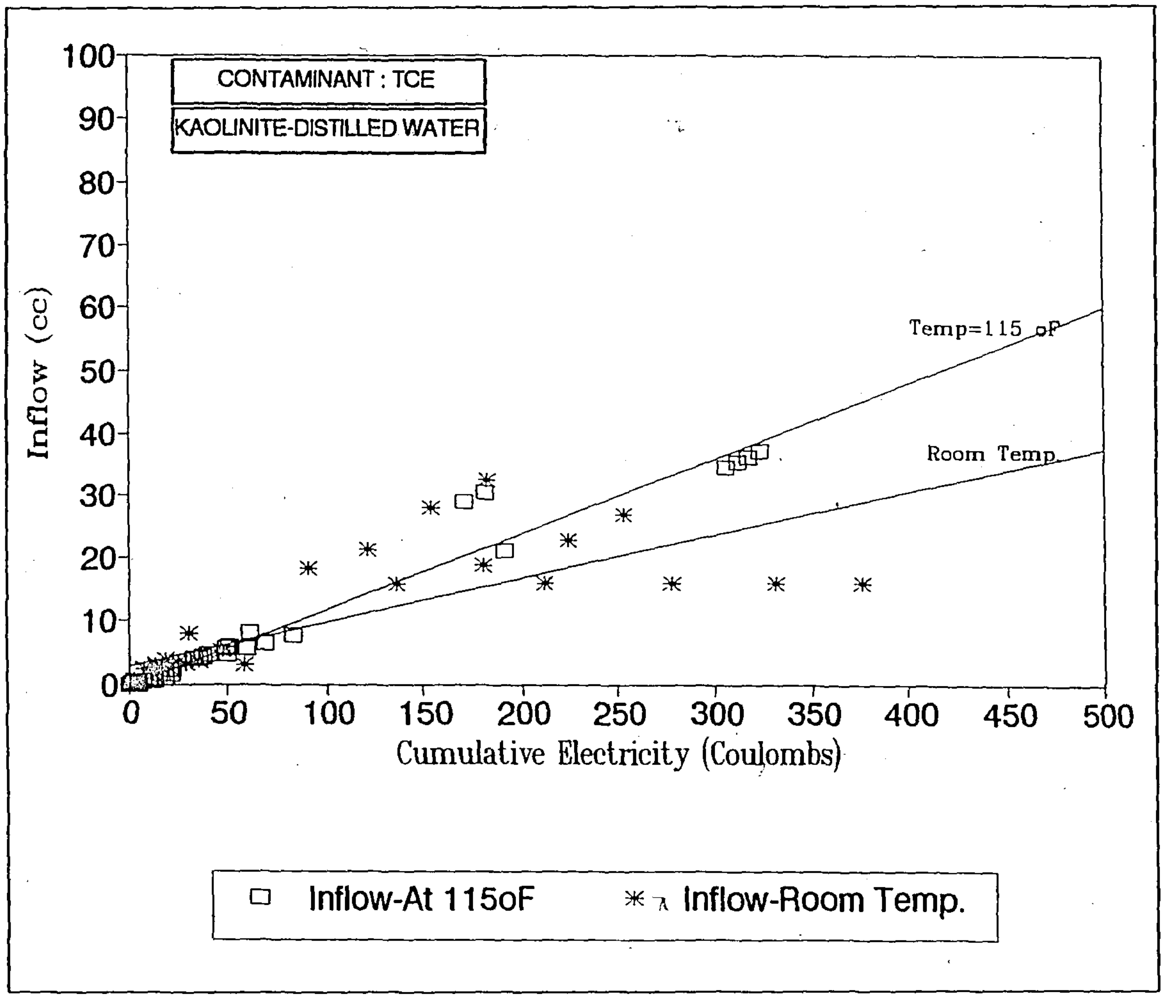

Figure 5.2 : Thermally Enhanced E-K Test Current Effiency Compared to Unenhanced E-K Test Current Efficiency for TCE-Contaminated Kaolinite Soil

soil strength. Pore pressure variations and volume changes associated with temperature changes have been analyzed in several publications (Duncan and Campanella, November 1965; Henkel and Sowa, September 1963; Mitchell and Campanella, September 1963). A study performed by Campanella and Mitchell (1968) seemed to explain the changes due to temperature increase best in our case. T
hey have presented some analyses for the interpretation of volume changes due to the thermal expansion of the soil, compressibility of the soil, and also physico-chemical effects. It was surprisingly found that their saturated specimen were subjected to subsequent temperature increases ranging from 66oF to 140oF. Our samples are also assumed to be saturated and they

are heated up to a constant temperature of 115oF to 120oF which would fall in the range they applied. The dimensions of their cylindrical test specimens (1.4-in. wide by 3.5-in. long) almost matched with ours. The only difference was that they used illite as the clay type istead of kaolinite as in our samples. They have studied the temperature effects on saturated clays for both drained and undrained conditions.

5.3.1 Theoretical Analysis of Temperature Effects on Volume Changes and Pore Pressures in Saturated in Saturated Soils

Volume changes due to temperature variations under conditions of constant effective stress result from the thermal expansion of the mineral solid and the pore water, and any changes in the soil structure resulting from temperature change. The effective stresses are assumed to be constant due to drained conditions. The following explanations is offered for the volume change behavior.

During initial consolidation at constant temperature, the void ratio decreases until sufficient shearing resistance is developed through interparticle bonds to resist the interparticle shear forces resulting from applied boundary normal stresses. When the temperature of a normally consolidated specimen is increased two effects occur. If the increase in temperature is rapid a significant positive pore water pressure may develop, even though the sample is maintained under fully drained conditions. This excess pore pressure results primarily from a greater volumetric expansion of the pore water than of the mineral solids. The lower the permeability of the soil, the longer the period required for this pressure to dissipate. The second effect relates to the influence of increased temperature on the strength of the soil structure. An increase in temperature causes a decrease in the shearing strength of individual interparticle contacts. This decrease in the interparticle bond strength may be considered to result from the increase in thermal energy which acts in conjunction with the shear force at interparticle contacts to increase the probability of bond slippage or failure. As a consequence, there is a partial collapse of the soil structure, and a decrease in void ratio until a sufficient number of bonds are formed to enable the soil to carry the stress at the higher temperature. This effect depends only on properties of soil structure, and its rate is independent of pore watter pressure considerations. It is analogous to secondary compression under a stress increase.

5.3.2 Amount of Volume Changes

The increased flow results presented here also agree with their findings. It is apparent that the amount of water transported under the electric potential was increased with the simultaneous application of heat. However, comparison of the volumes of the water drained in the experiments performed by Campanella and Mitchell (1968) with that in our experiments showed that the excess water transported during the thermally enhanced electrokinetic tests over the ones with no enhancement amounted more than an elevated temperature of 115oF would solely cause. Therefore, simultaneous application of the electric potential and heat resulted in higher water flow rates than it could be expected by considering the electrokinetic and temperature effects on soils independent of each other.

The increase in the current efficiency can be explained by the decrease in the stability of the molecules in the double layer resulting in less frictional forces against the plug flow of electroosmosis. In addition larger pore volumes would favor electroosmotic flow.

The increased transport of TCE is also attributed to heating which probably promoted the migration of the contaminant into the pore fluid environment away from the clay surfaces by way of: 1) dissolution and 2) increased flow rate due to the increased water pressures.

5.4 Experiments Enhanced with Shear Wave Application and Discussion of Results

0.240" x .240" x .023" piezoelectric bender elements were soldered to electrical wiring in series placed in an approximate area of .25" x .50" at the center of the porous stones. Therefore the flow area on the porous stone was decreased by 15 percent. This difference was evidenced by a slight decrease in water inflow during the electrokinetic runs with the bender element mounted-porous stones at the ends of the soil sample, but with no shear wave application yet. The blank and contaminated (TCE) kaolinite soil samples were subjected to E-K treatment with shear wave enhancement at two different frequencies, 1500 Hz and 4000 Hz. The duration of these tests were again 24 hours or less.

The results of these tests showed no appreciable improvement over current efficiency or contaminant removal over the duration and frequencies of shear wave enhancement applied. Since the level of increased pore water pressures is dependent on frequency, amplitude, and duration of vibration, it may be necessary to run more electrokinetic tests with shear wave enhancement for longer terms to find the most effective shear wave frequency and amplitude. Futher observations also showed that the set-up needs changes in the configuration for more reliable results. These possible changes will be mentioned in the next section.

5.5 Recommendations for Future Studies

5.5.1 About Thermal Enhancements

In this study, the experiments were conducted only at one elevated temperature. In order to understand the temperature effects on electrokinetic soil decontamination better, temperature can be chosen as the variable keeping all the other conditions constant, and E-K tests can be run with simultaneous application of heat at different elevated temperatures. Conductivity of soil may also be an important parameter. Therefore, at different elevated temperatures the conductivity measurements can also be done and the temperature dependency of conductivity can be investigated.

The thermally enhanced E-K tests showed significantly increased water flow rates over that of the runs with no enhancement. A better explanation to this phenomenon can be brought by studying further the temperature effects on the double diffuse layer and electroosmosis.

Some organics other than TCE should also be tested and results should be interpreted by taking the partioning coefficients and other pertinent characteristics of organics into consideration.

5.5.2 About Shear Wave Application Enhancement

Since the idea is based on the phenomenon of seismic waves causing temporary instability condition in the soil by increasing pore water pressures progressively, monitoring of pore water pressures could be done during an electrokinetic testing in the absence of seismic wave application to provide a base information for pore water pressure development in the soil due to electroosmosis.

The use of 0.240" x 0.240" x 0.023" piezoelectric bender elements showed the need for bigger rectangular elements. Installation of the bender elements could be made better by keeping the end protruding into the soil longer. In addition, special care should be taken while casing the bender elements with the epoxy glue. The epoxy glue should be relatively thin over the vibrating end in the soil, otherwise the glue after hardening may hinder the vibration of the element considerably.

In this study, wave amplitudes of up to +/- 2 volts were applied. It is suggested that amplitudes of up to +/- 10 volts could give better results. Since the level of increased pore water pressures is dependent on frequency, amplitude, and duration of vibration, it may be necessary to run more electrokinetic tests with shear wave enhancement for longer terms to find the most effective shear wave frequency and amplitude.

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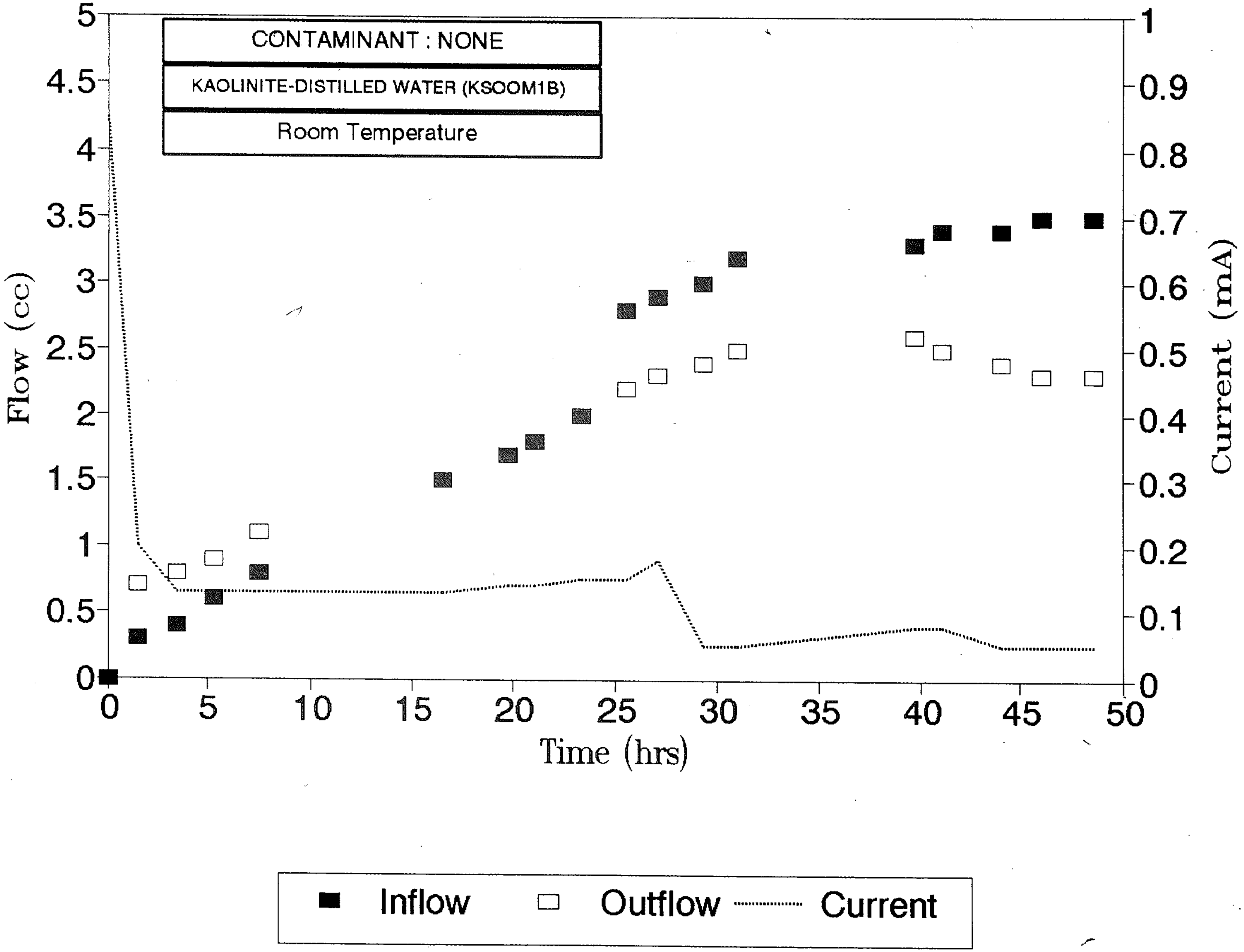
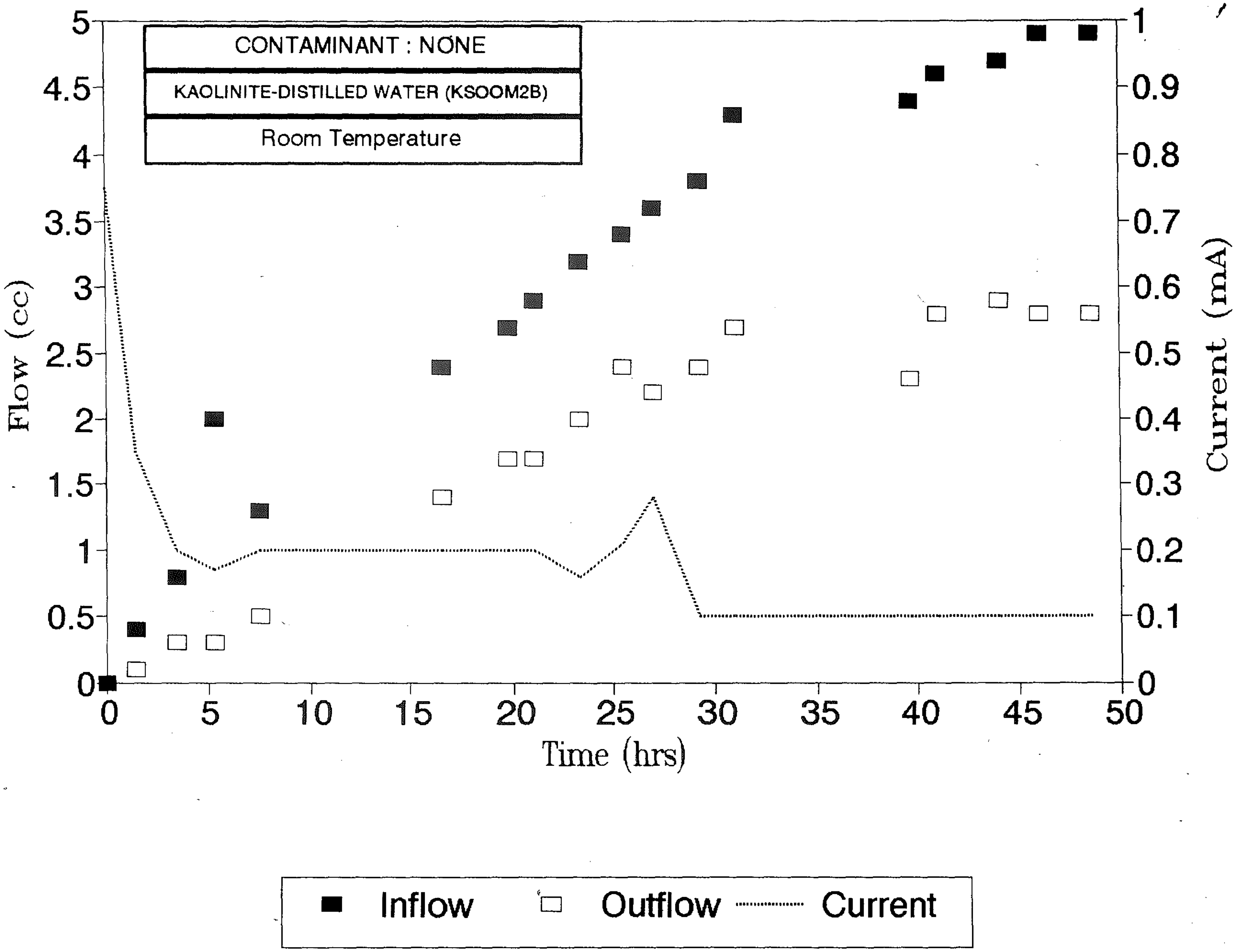
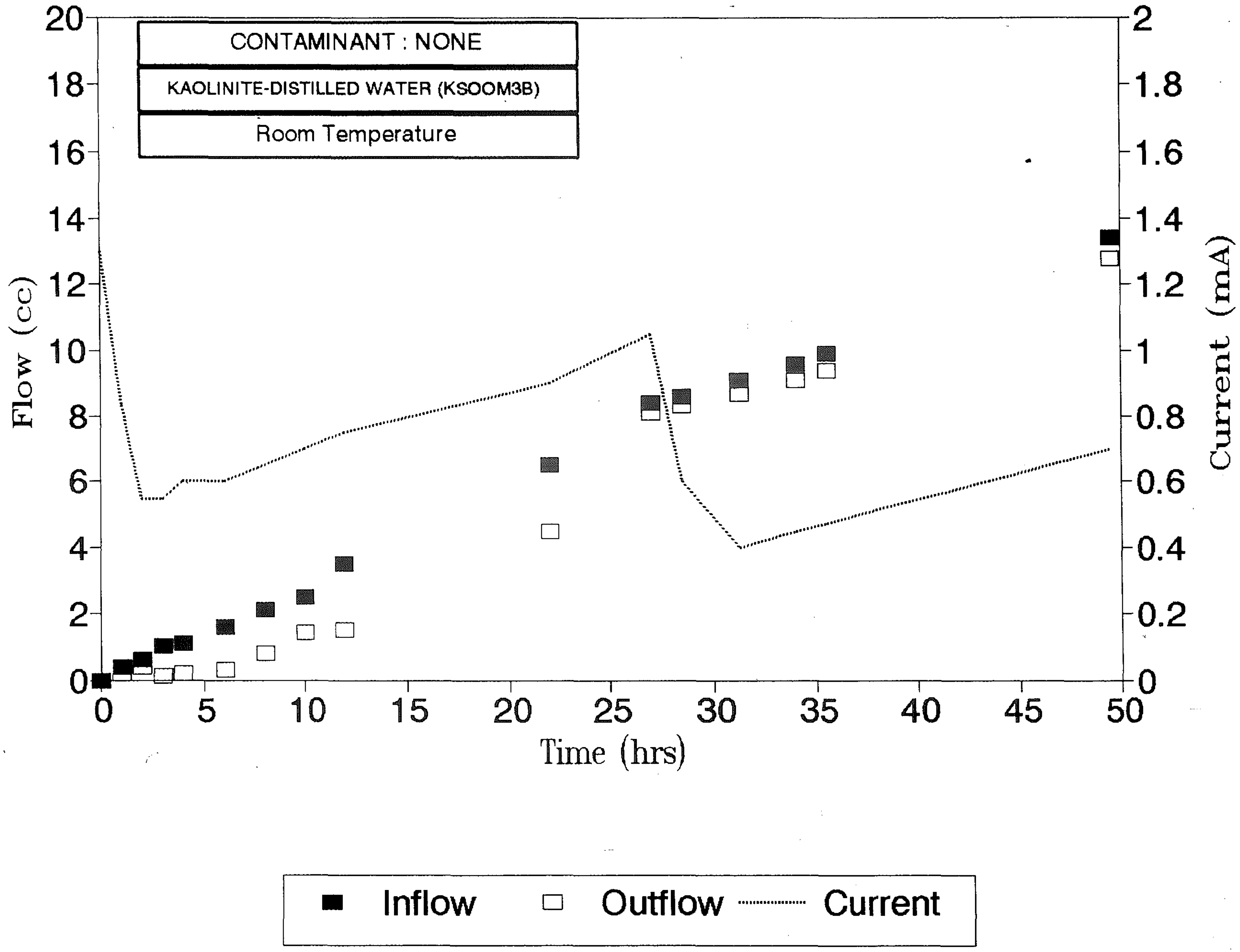
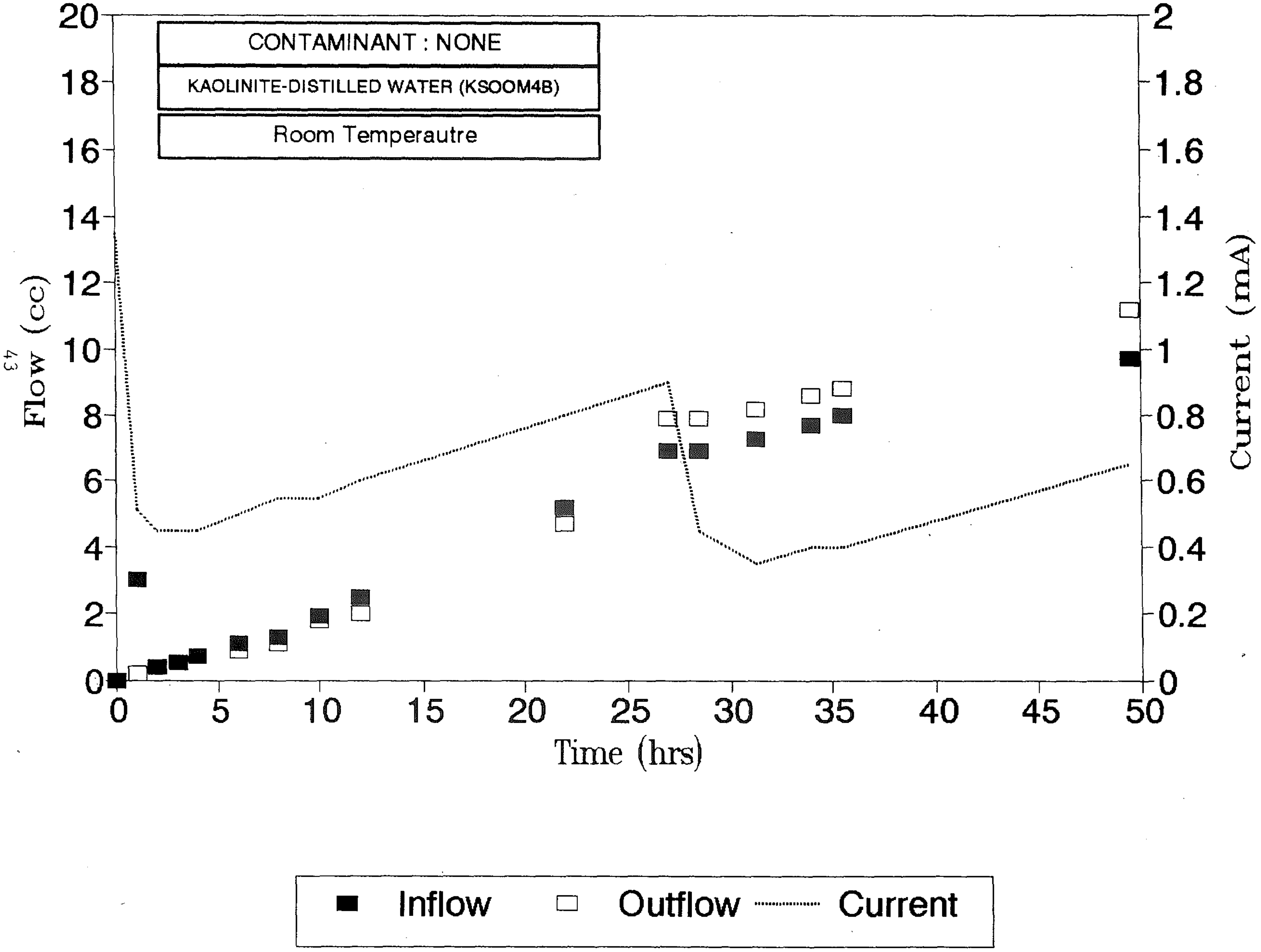
APPENDIX A.

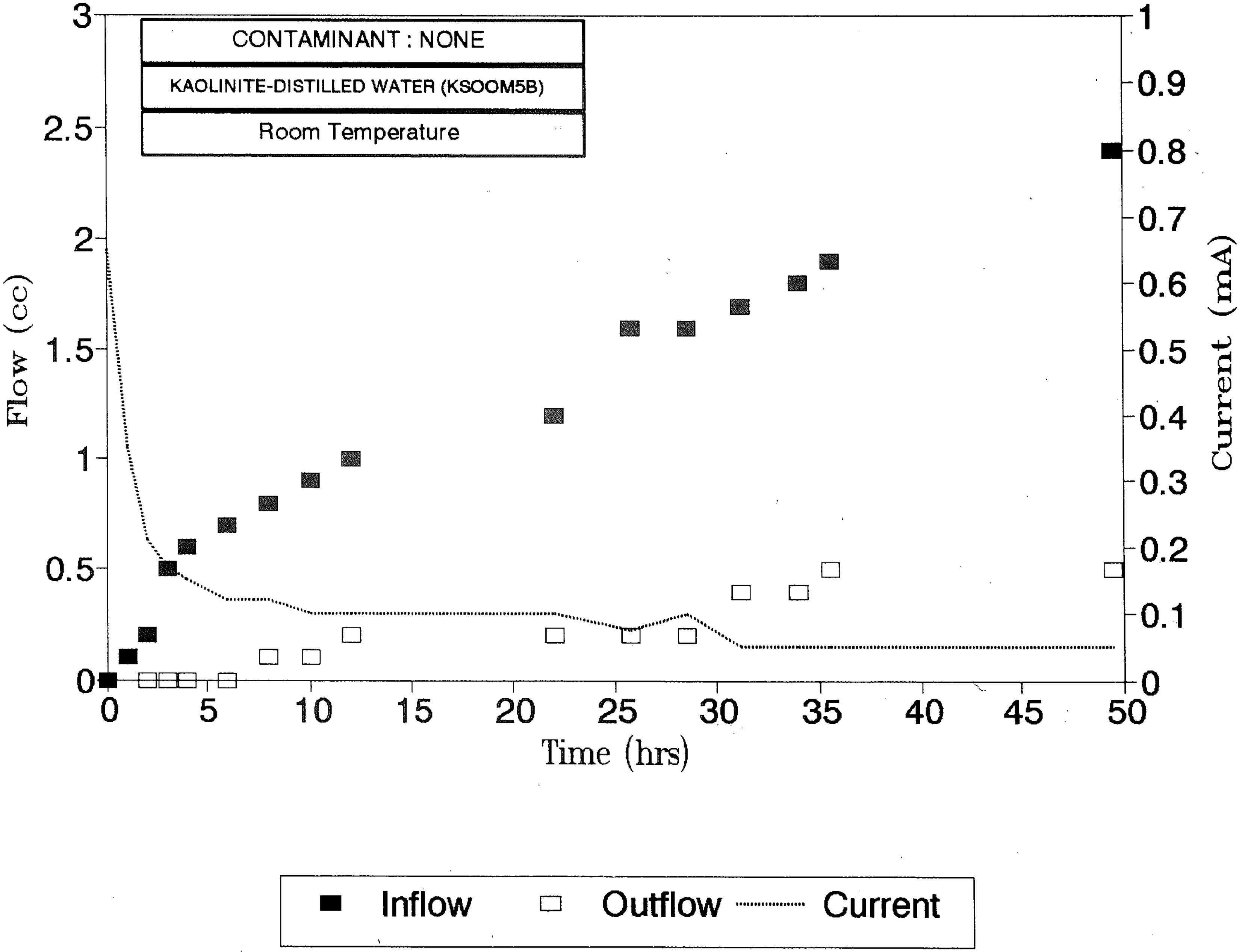
Experimental Data-Background Electrokinetic Testing

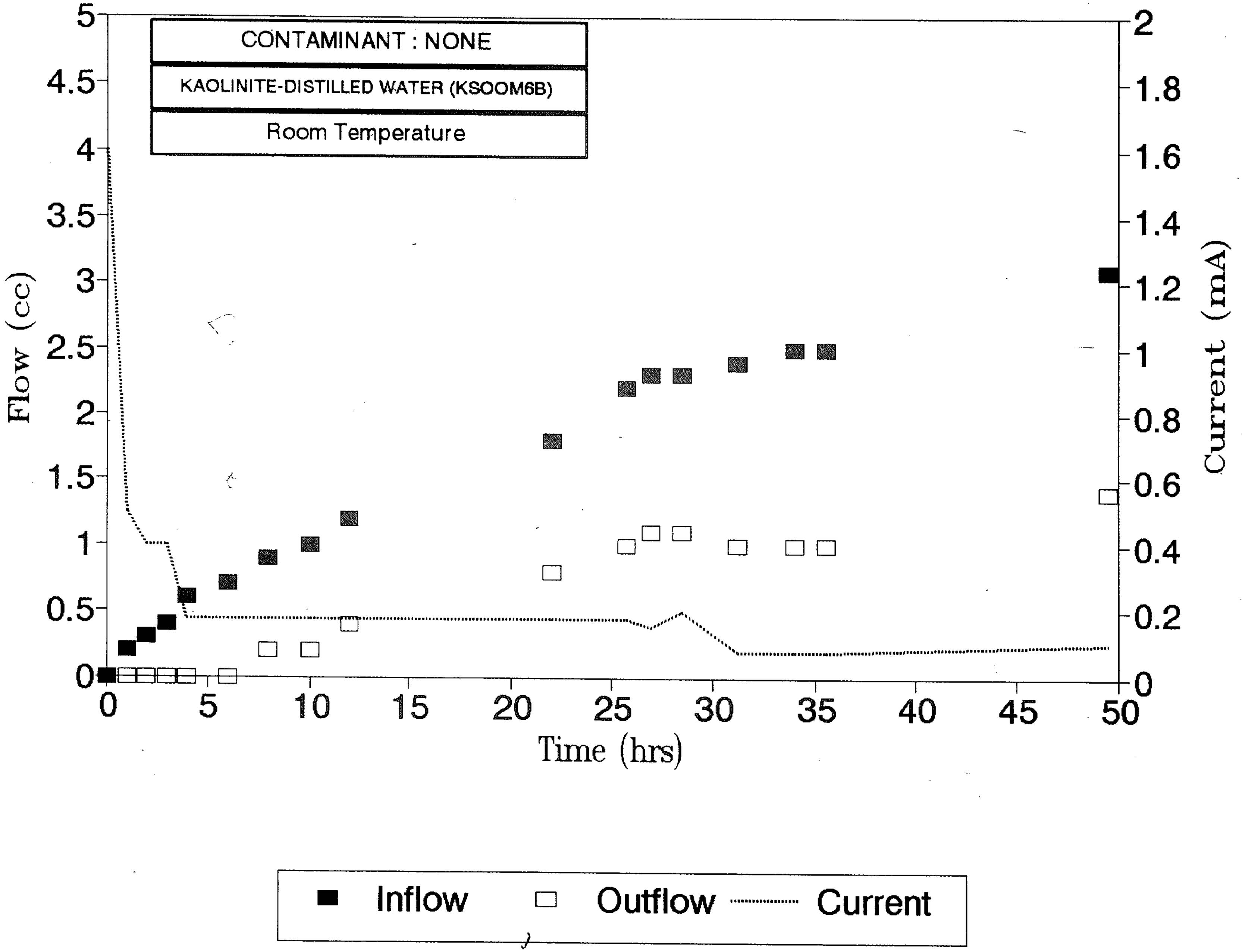

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM1B)
Room Temperature
Flow (cc)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Current (mA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
Inflow
Outflow
Current

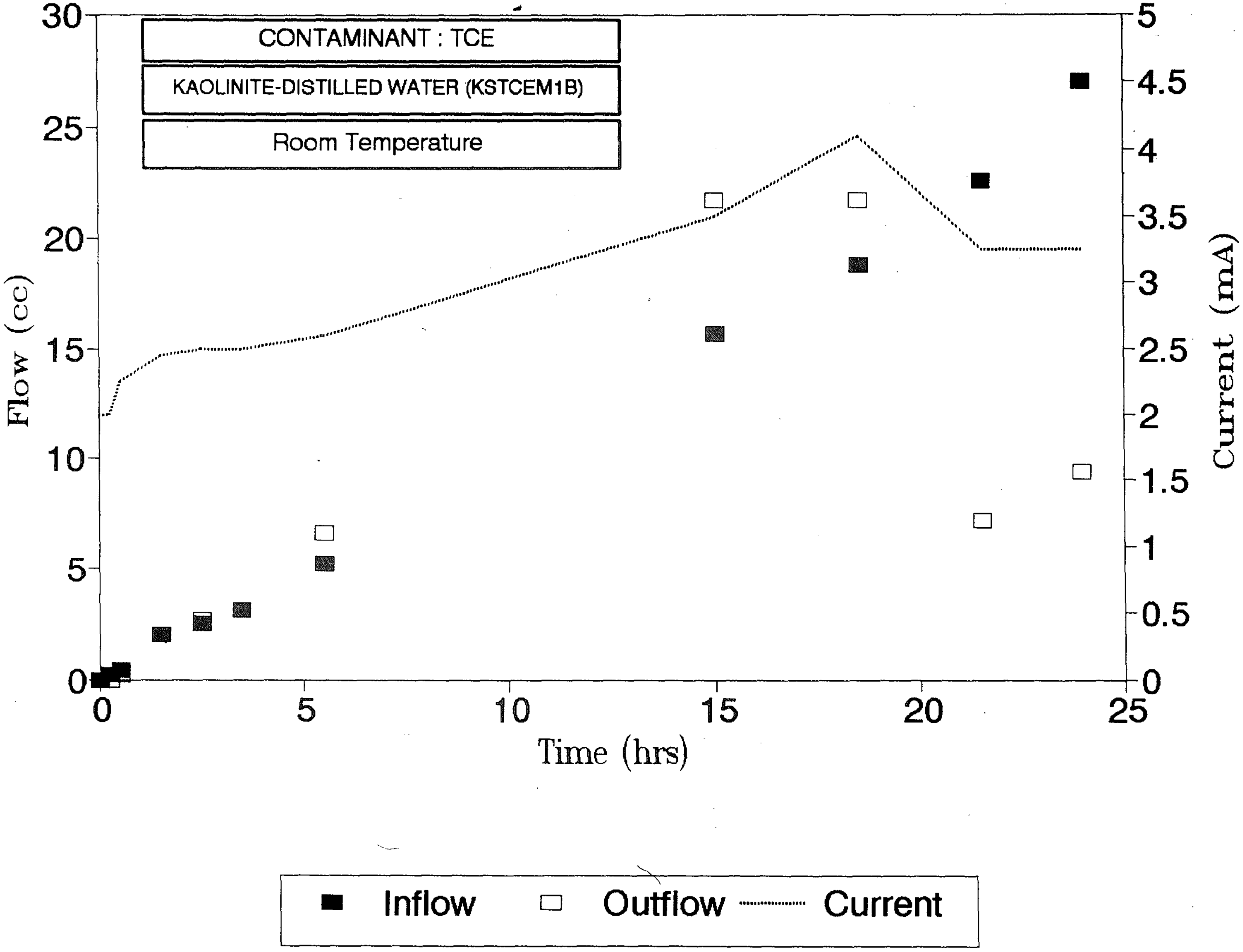

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM2B)
Room Temperature
Flow (cc)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Current (mA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current

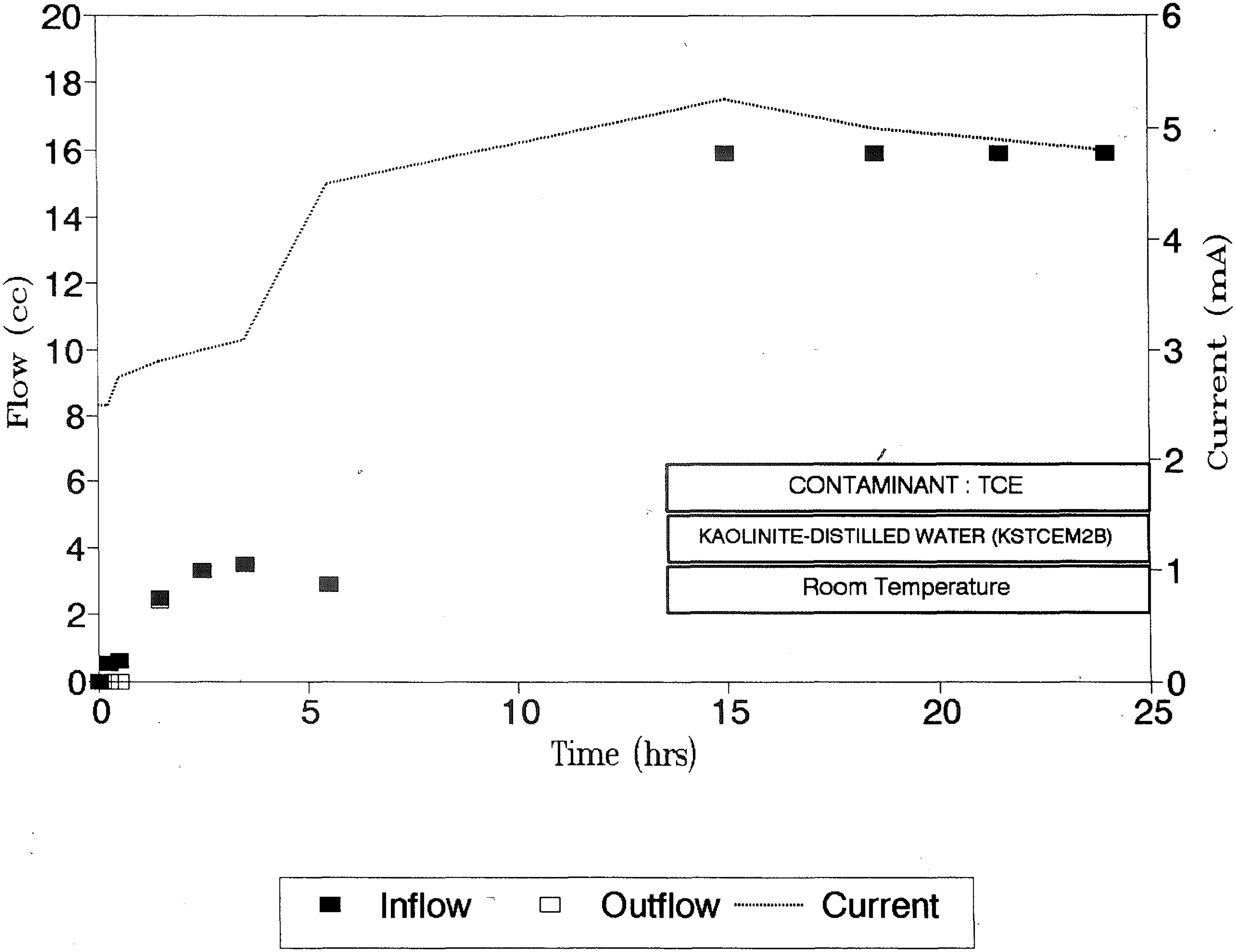

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM3B)
Room Temperature
Flow (cc)
0
2
4
6
8
10
12
14
16
18
20
Current (mA)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current


CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM4B)
Room Temperautre
Flow (cc)
0
2
4
6
8
10
12
14
16
18
20
Current (mA)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current

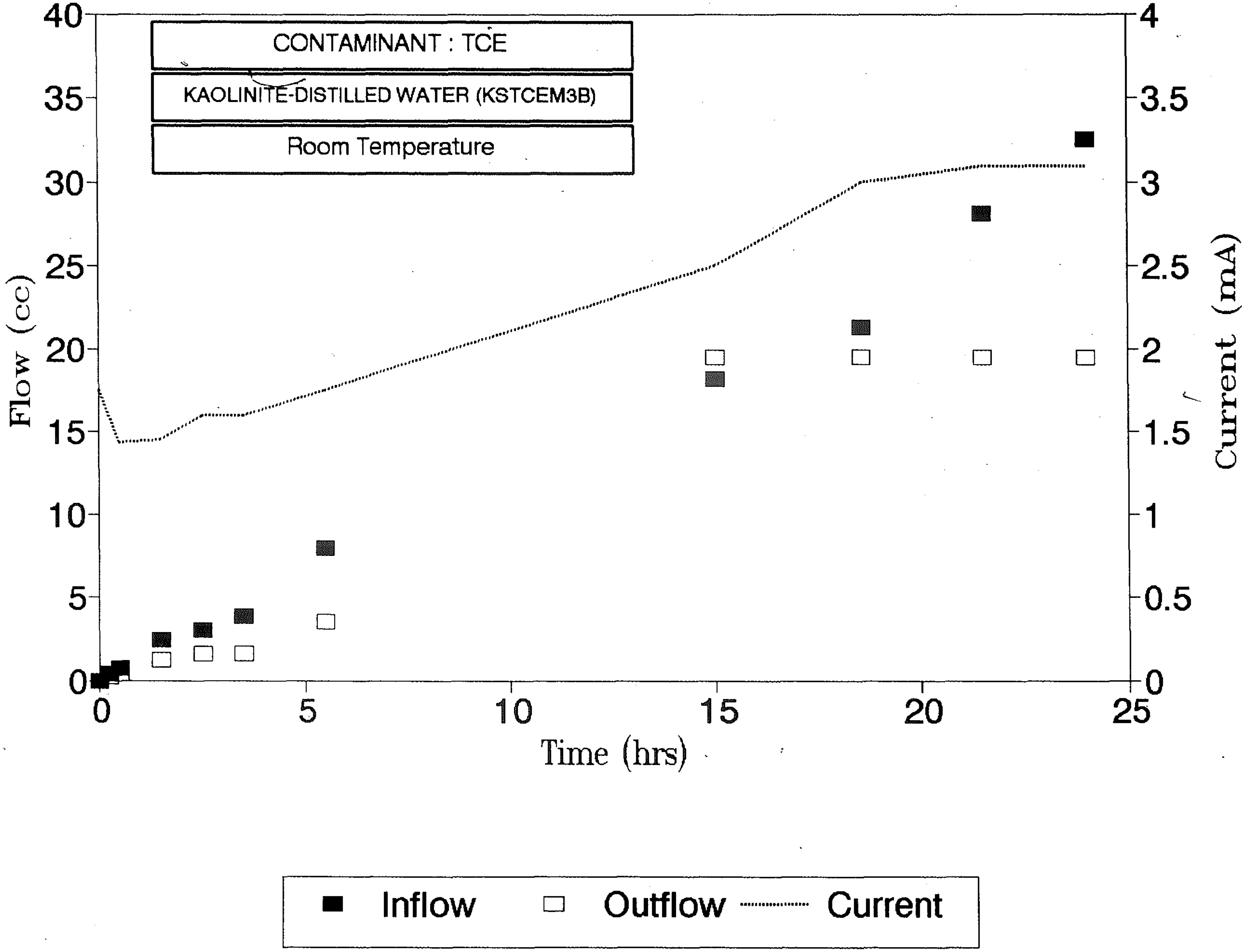

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM5B)
Room Temperature
Flow (cc)
3
2.5
2
1.5
1
0.5
0
Current (mA)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current

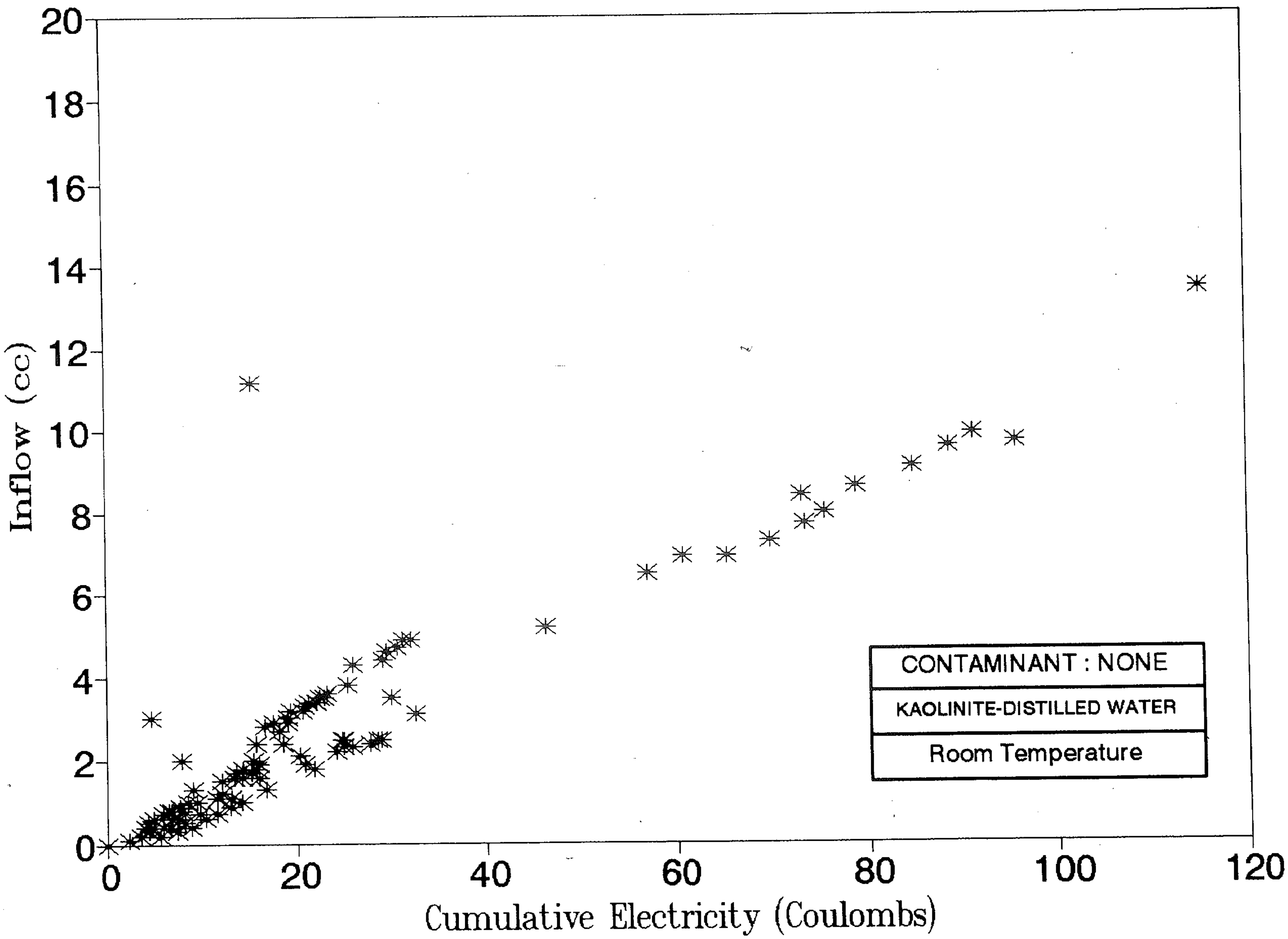

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (KSOOM6B)
Room Temperature
Flow (cc)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Current (mA)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current

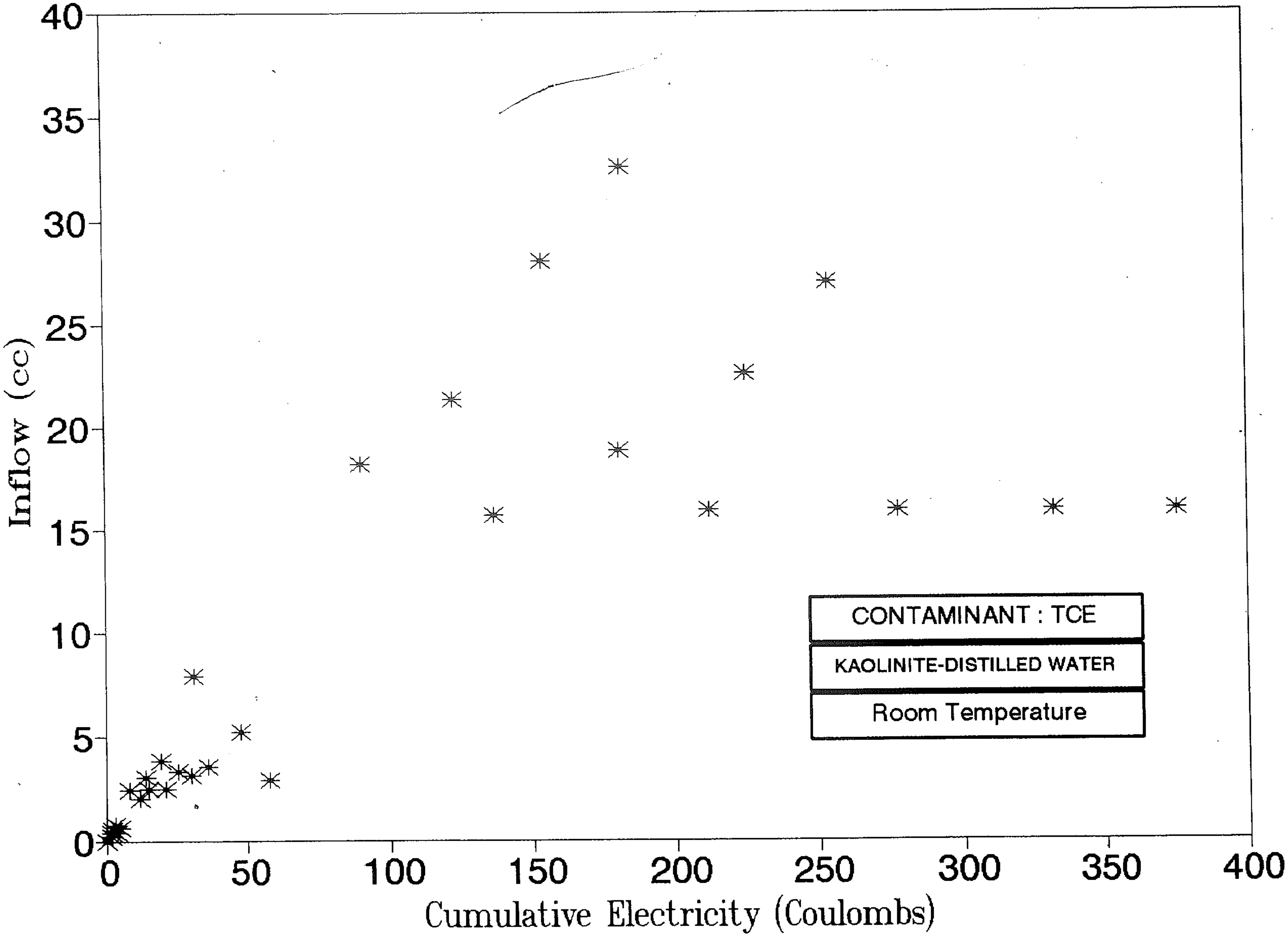

CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (KSTCEM1B)
Room Temperature
Flow (cc)
30
25
20
15
10
5
0
Current (mA)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Time (hrs)
0
5
10
15
20
25
■ Inflow
□ Outflow
······ Current



20
18
16
14
12
10
8
6
4
2
0
Flow (cc)
6
5
4
3
2
1
0
Current (mA)
0
5
10
15
20
25
Time (hrs)
CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (KSTCEM2B)
Room Temperature
■ Inflow
□ Outflow
Current

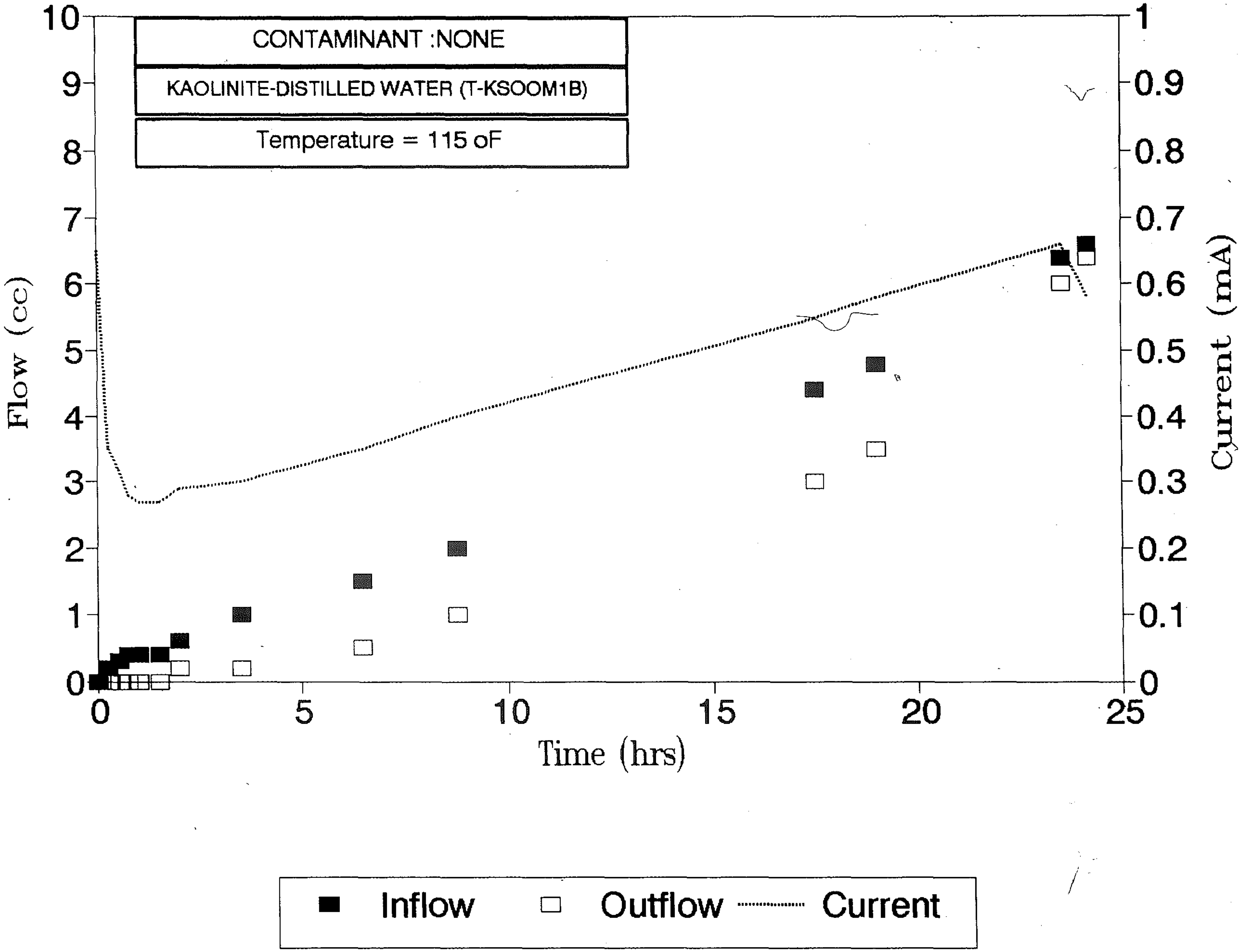

CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (KSTCEM3B)
Room Temperature
Flow (cc)
Current (mA)
Time (hrs)
0
5
10
15
20
25
30
35
40
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
25
■ Inflow
□ Outflow
Current

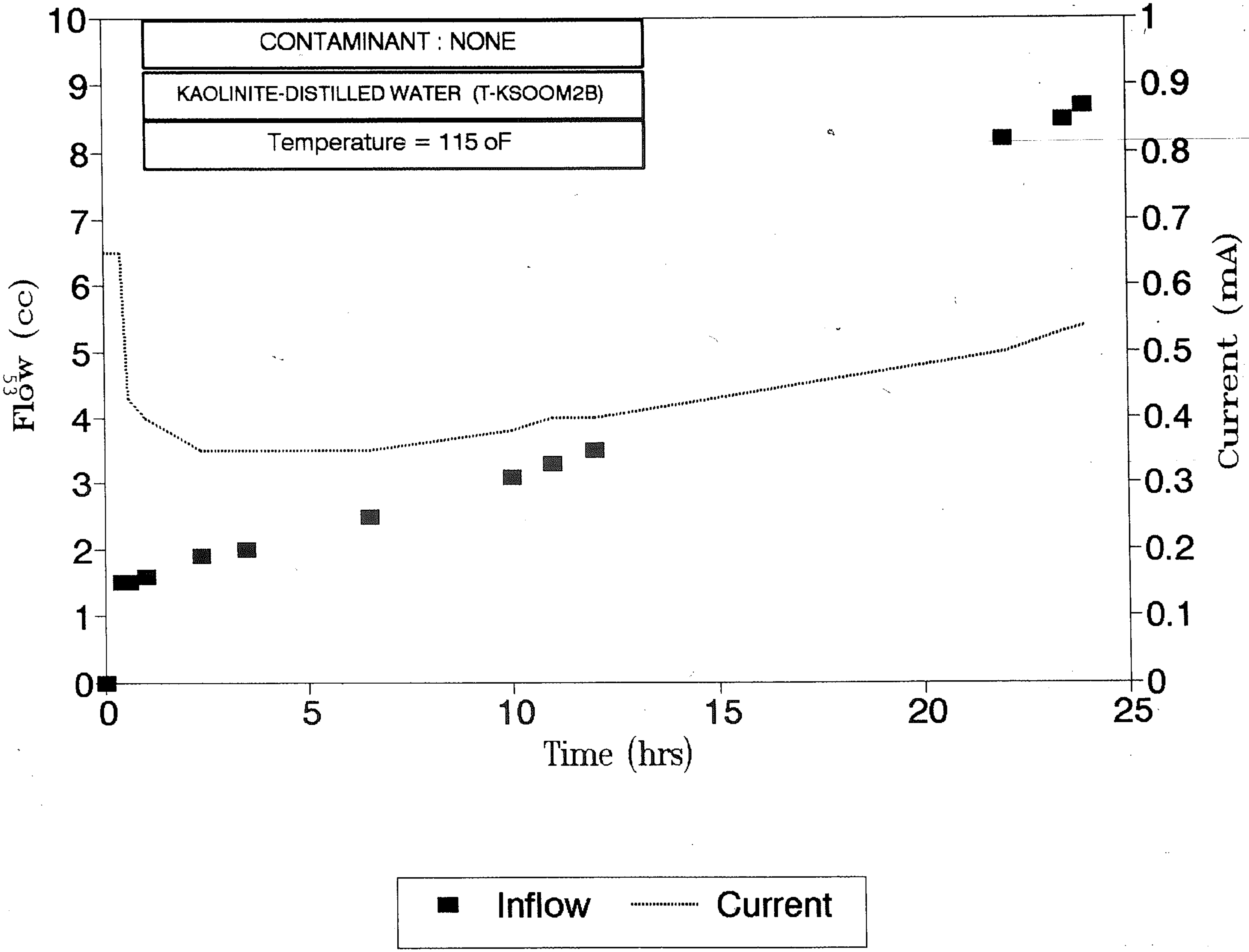

Inflow (cc)
0
2
4
6
8
10
12
14
16
18
20
Cumulative Electricity (Coulombs)
0
20
40
60
80
100
120
CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER
Room Temperature


CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER
Room Temperature
Inflow (cc)
0
5
10
15
20
25
30
35
40
Cumulative Electricity (Coulombs)
0
50
100
150
200
250
300
350
400

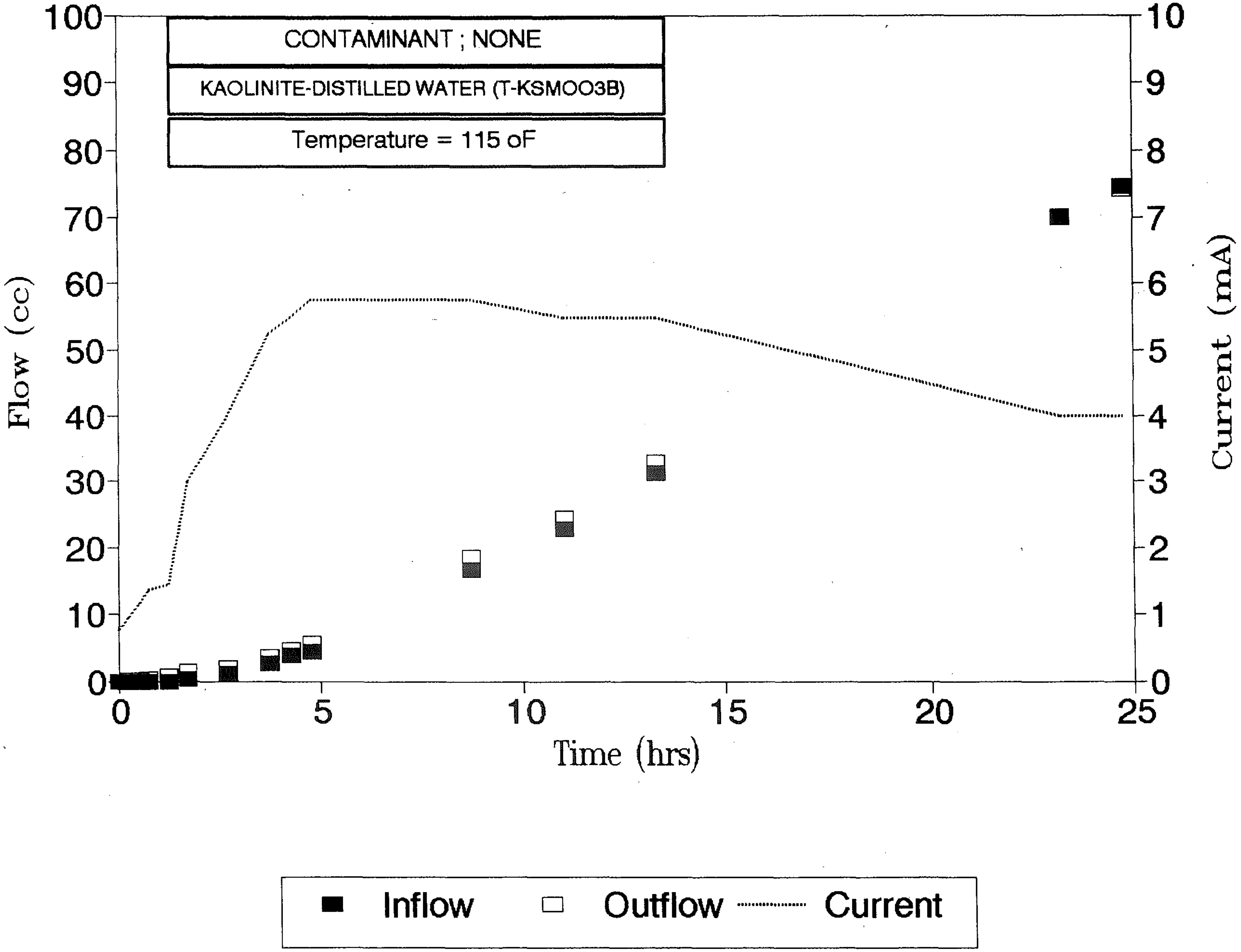
APPENDIX B.

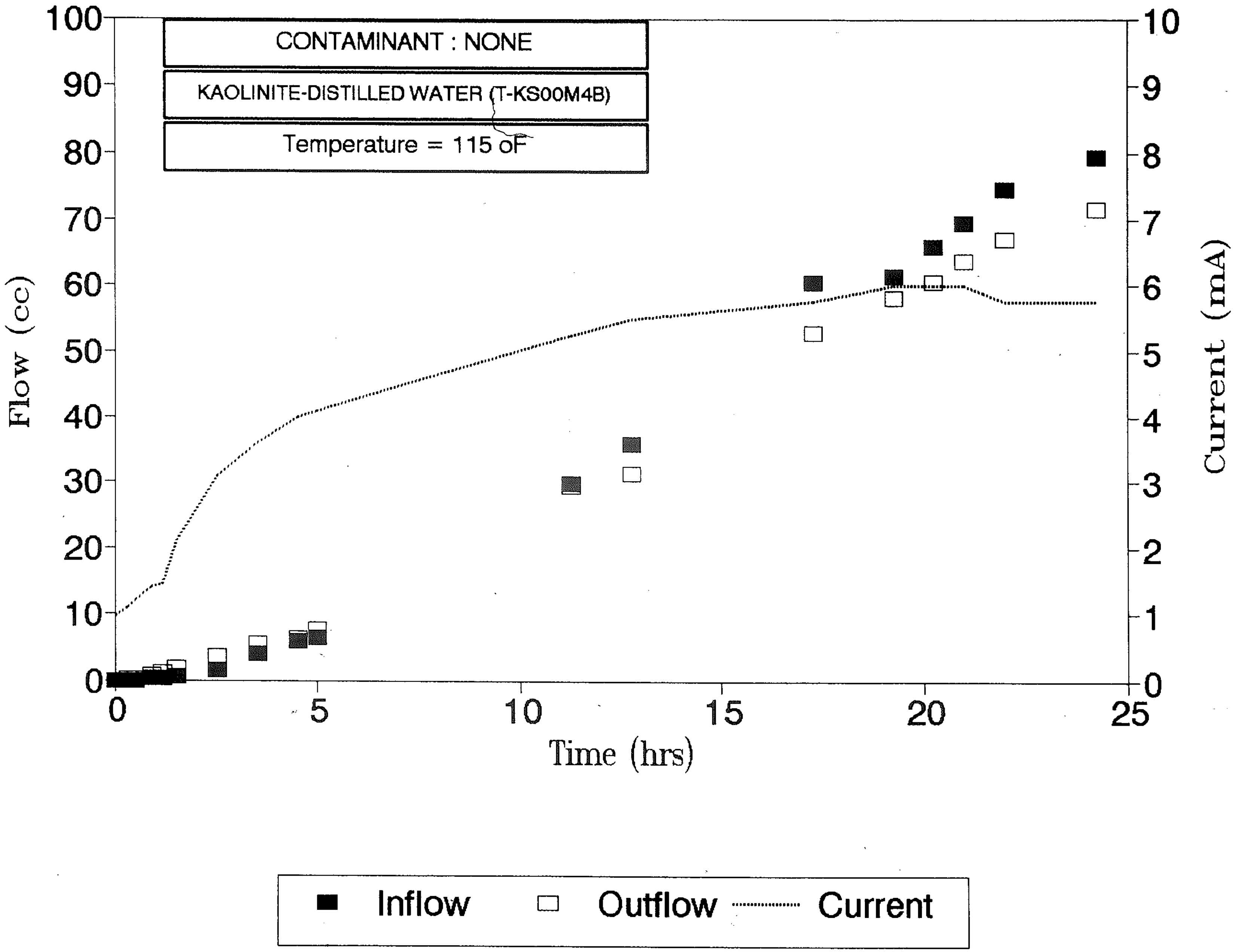
Experimental Data-Enhanced Electrokinetic Testing


CONTAMINANT :NONE
KAOLINITE-DISTILLED WATER (T-KSOOM1B)
Temperature = 115 oF
Flow (cc)
Current (mA)
Time (hrs)
0
1
2
3
4
5
6
7
8
9
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
■ Inflow
□ Outflow
Current



CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (T-KSOOM2B)
Temperature = 115 oF
Flow (cc)
0
1
2
3
4
5
6
7
8
9
10
Current (mA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hrs)
0
5
10
15
20
25
■ Inflow
Current


CONTAMINANT ; NONE
KAOLINITE-DISTILLED WATER (T-KSMOO3B)
Temperature = 115 oF
Flow (cc)
Current (mA)
Time (hrs)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
■ Inflow
□ Outflow
Current


CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (T-KS00M4B)
Temperature = 115 oF
Flow (cc)
100
90
80
70
60
50
40
30
20
10
0
Current (mA)
10
9
8
7
6
5
4
3
2
1
0
Time (hrs)
0
5
10
15
20
25
■ Inflow
□ Outflow
Current

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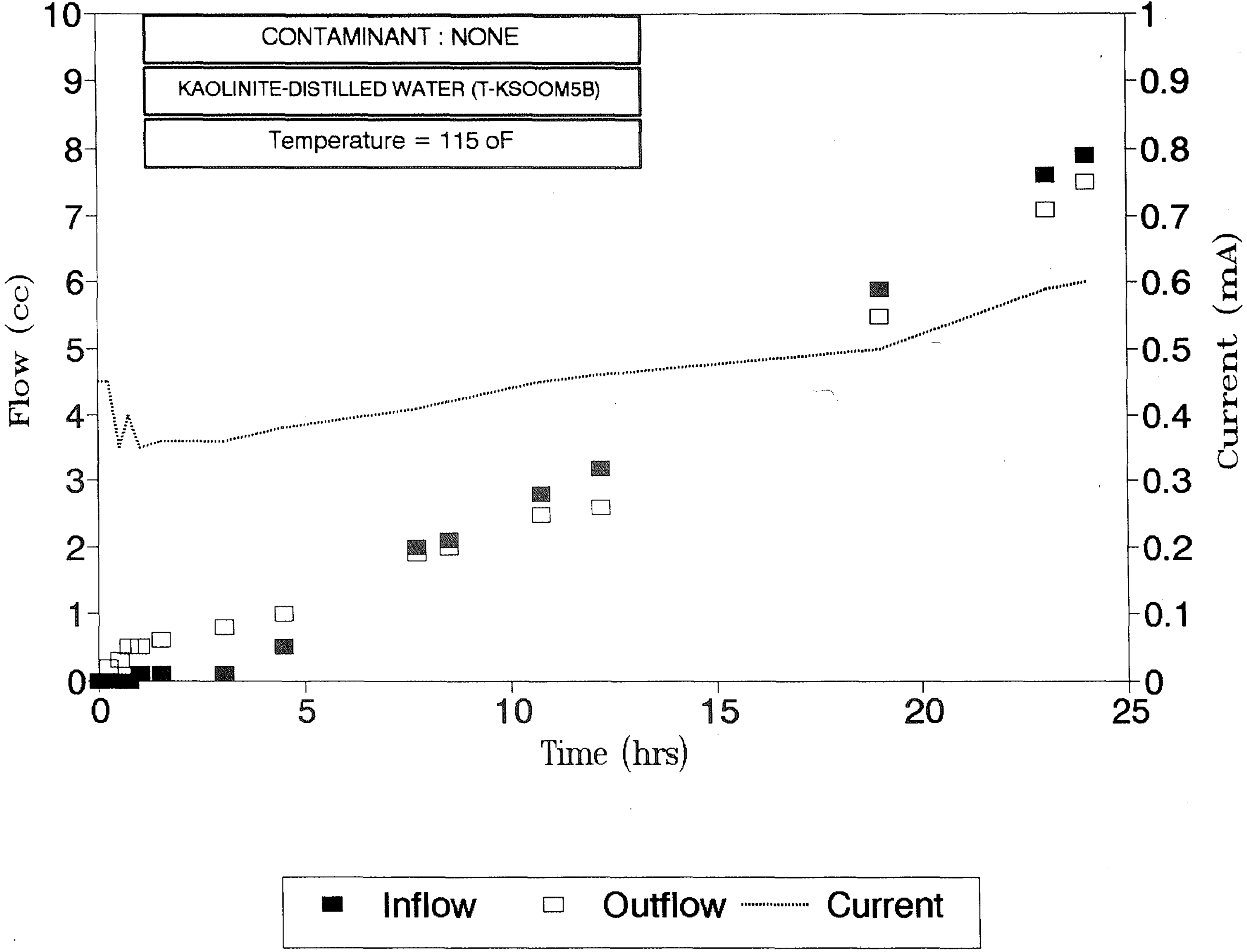
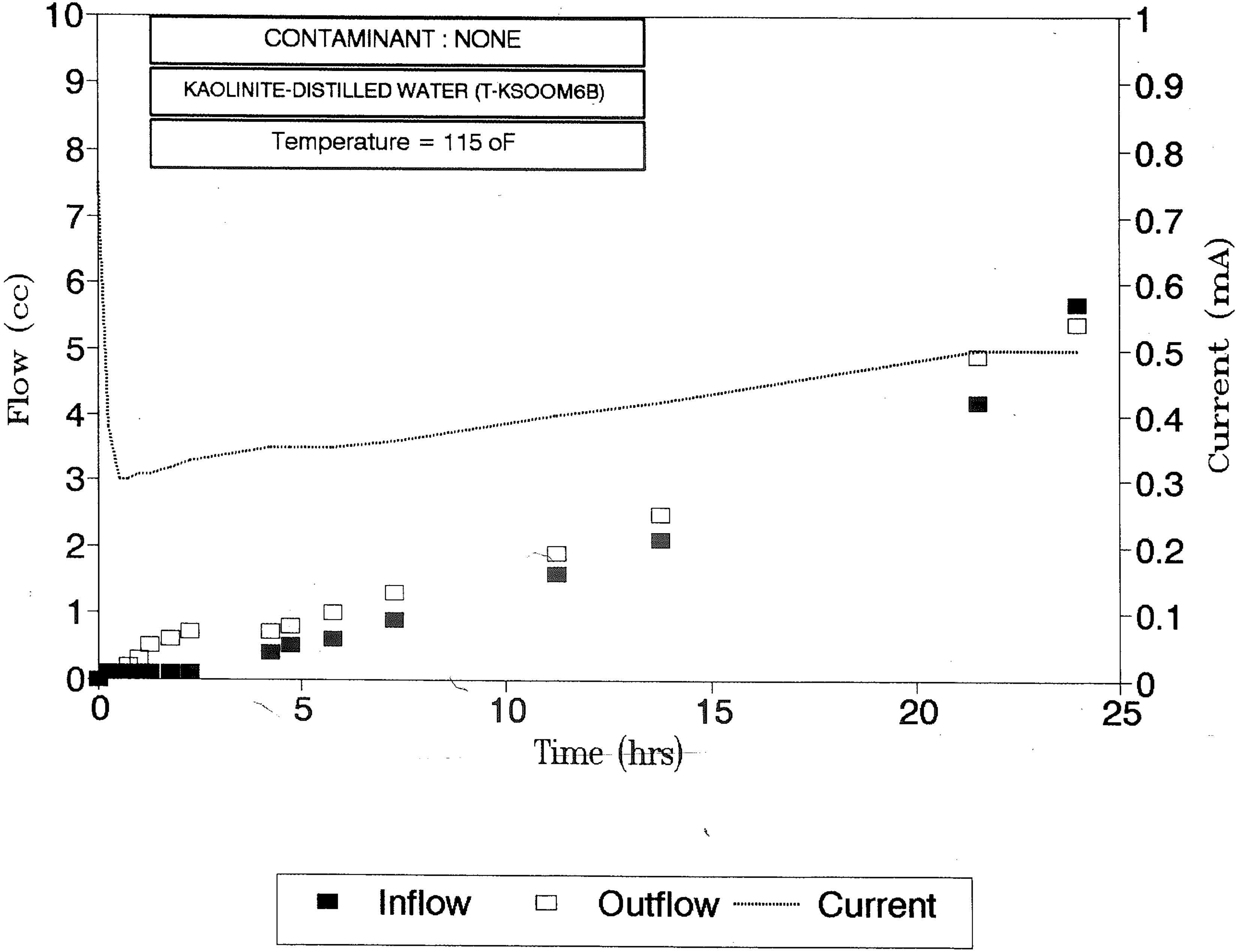
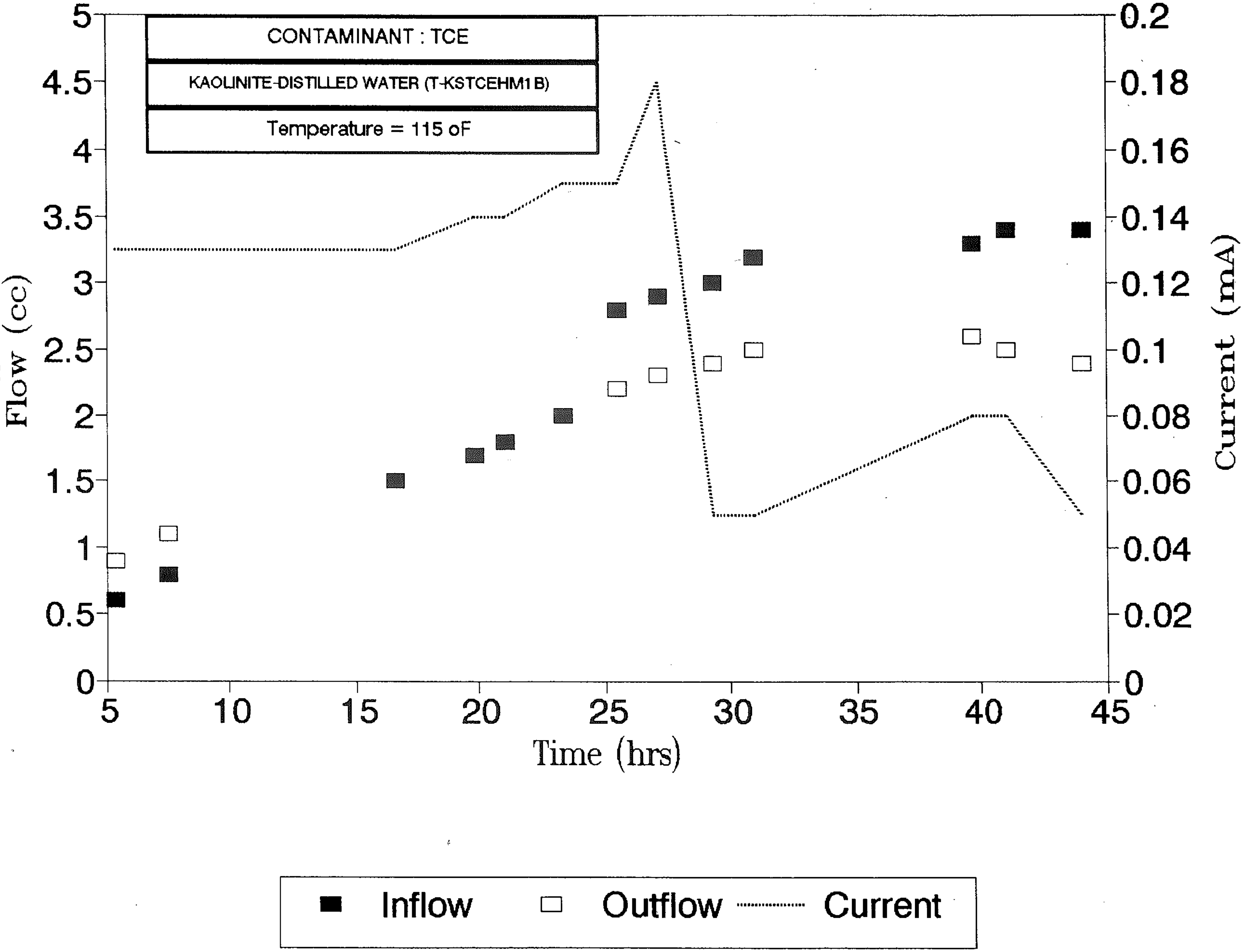
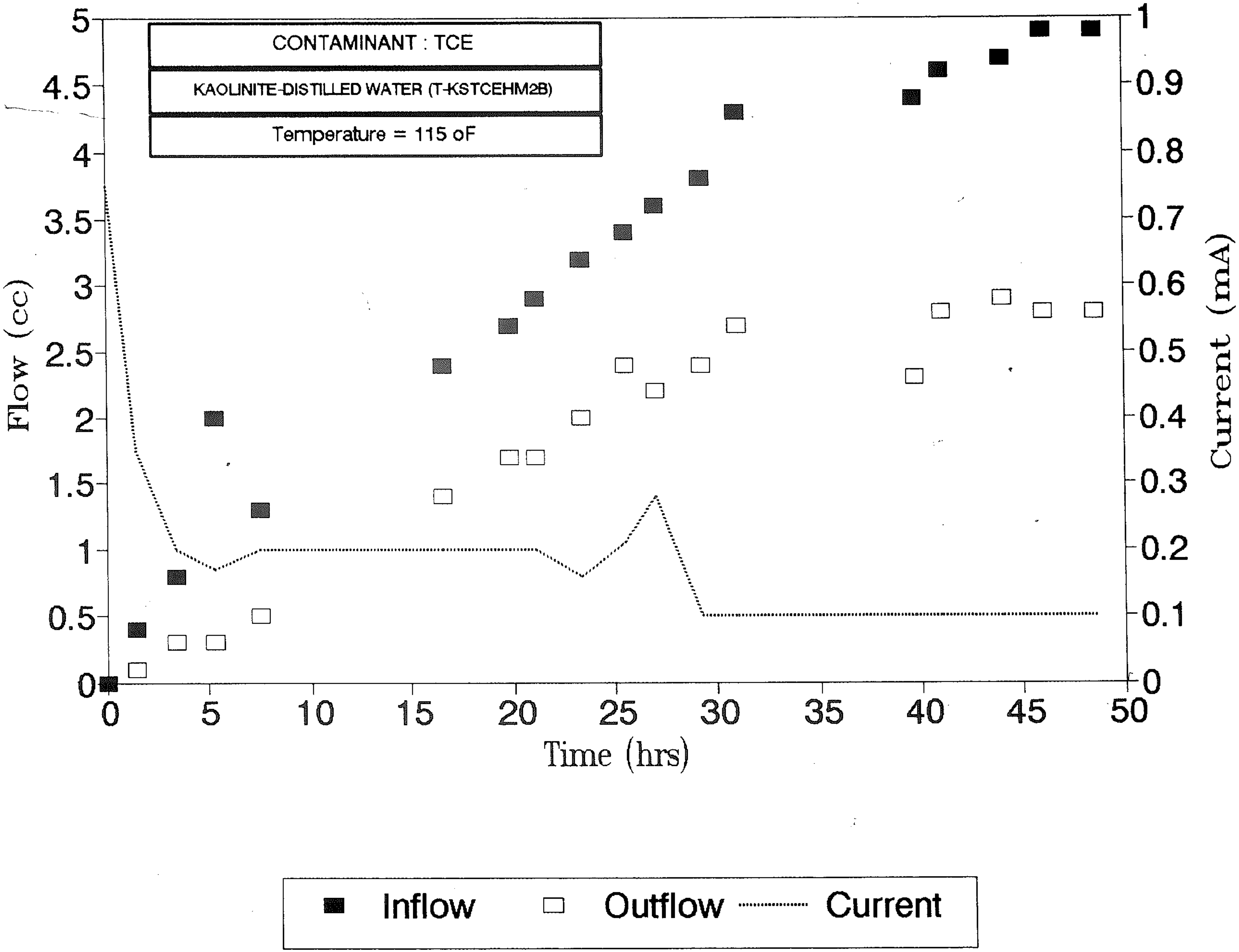
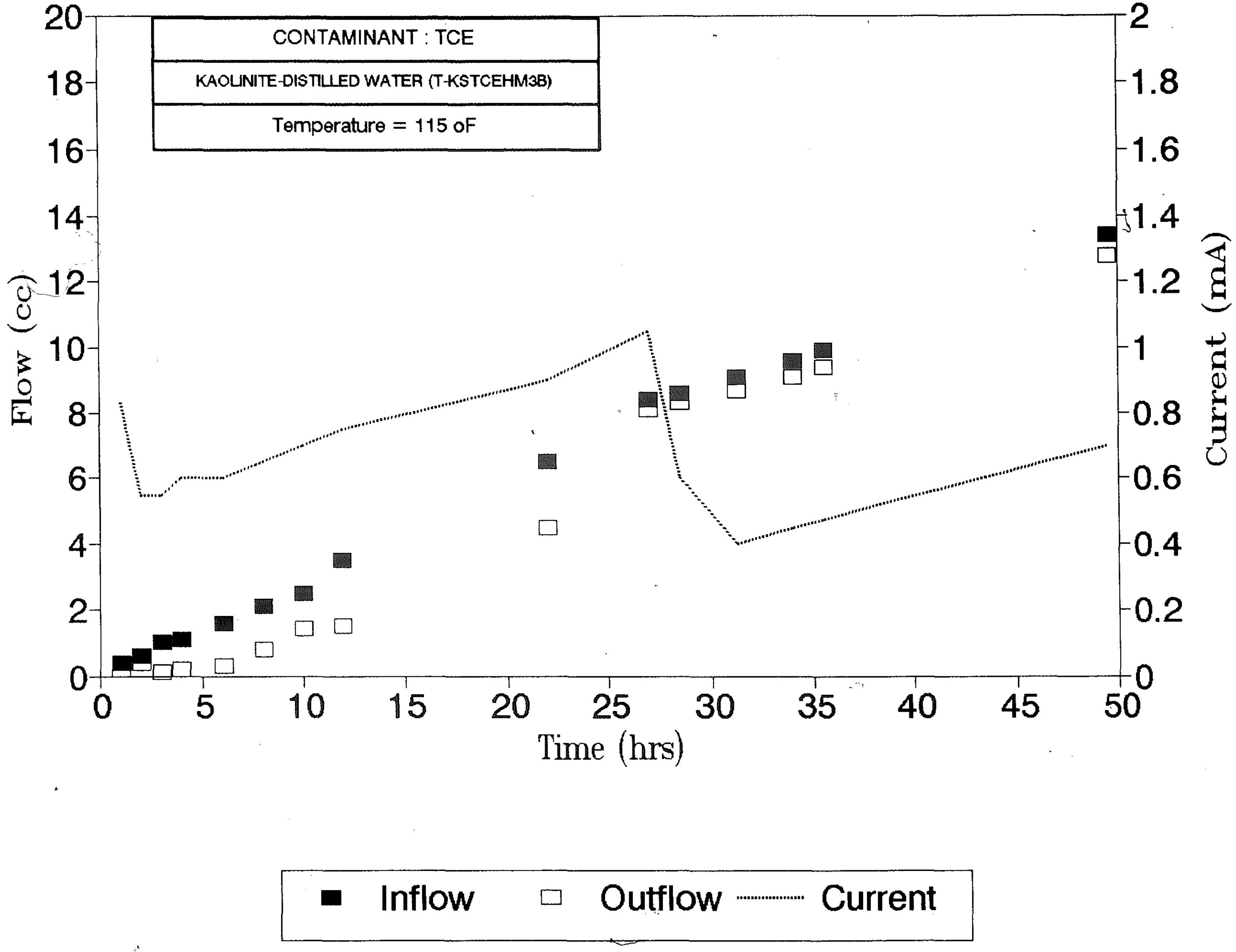


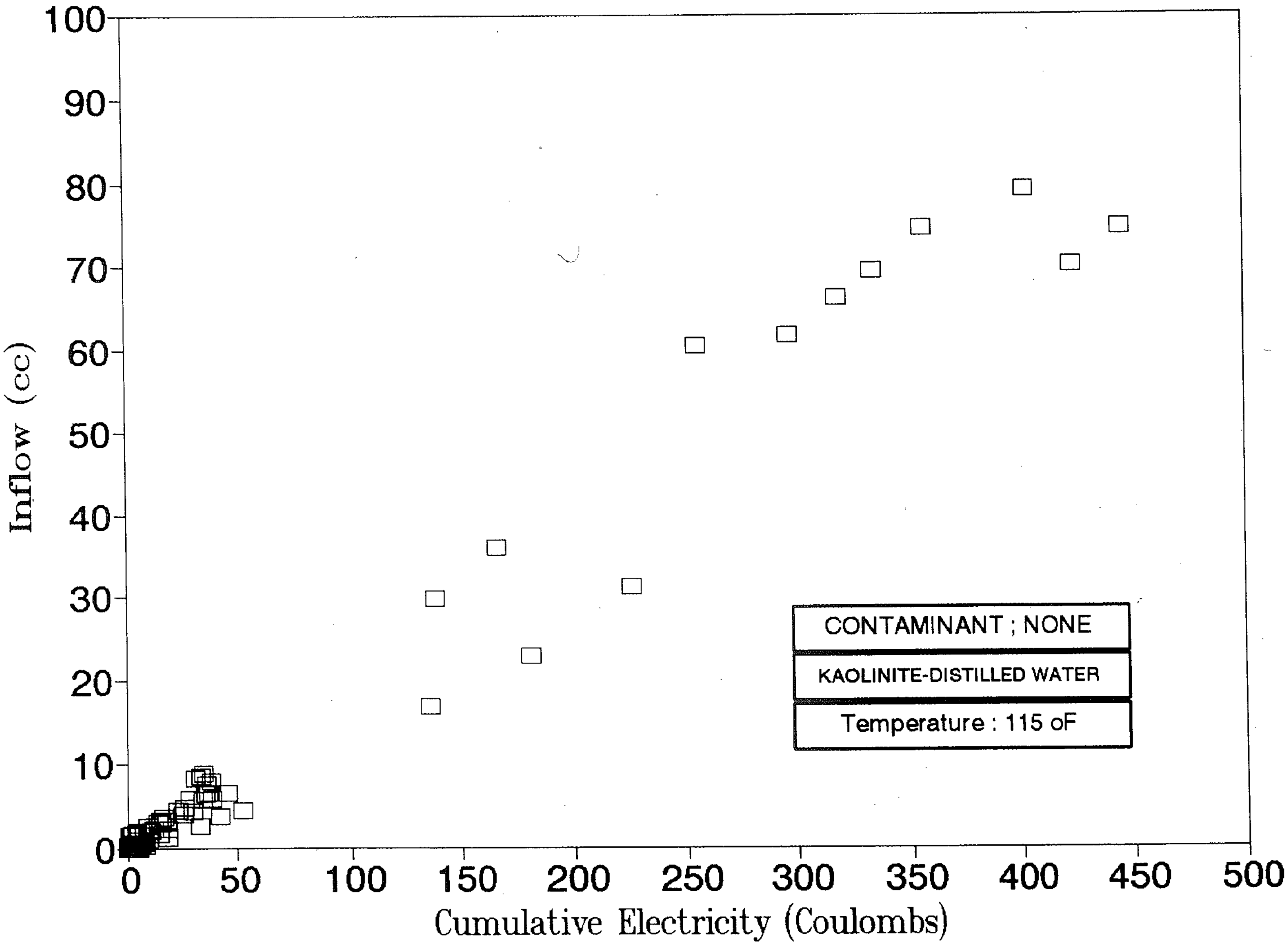
CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (T-KSOOM5B)
Temperature = 115 oF
Flow (cc)
0
1
2
3
4
5
6
7
8
9
10
Current (mA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hrs)
0
5
10
15
20
25
■ Inflow
□ Outflow
Current

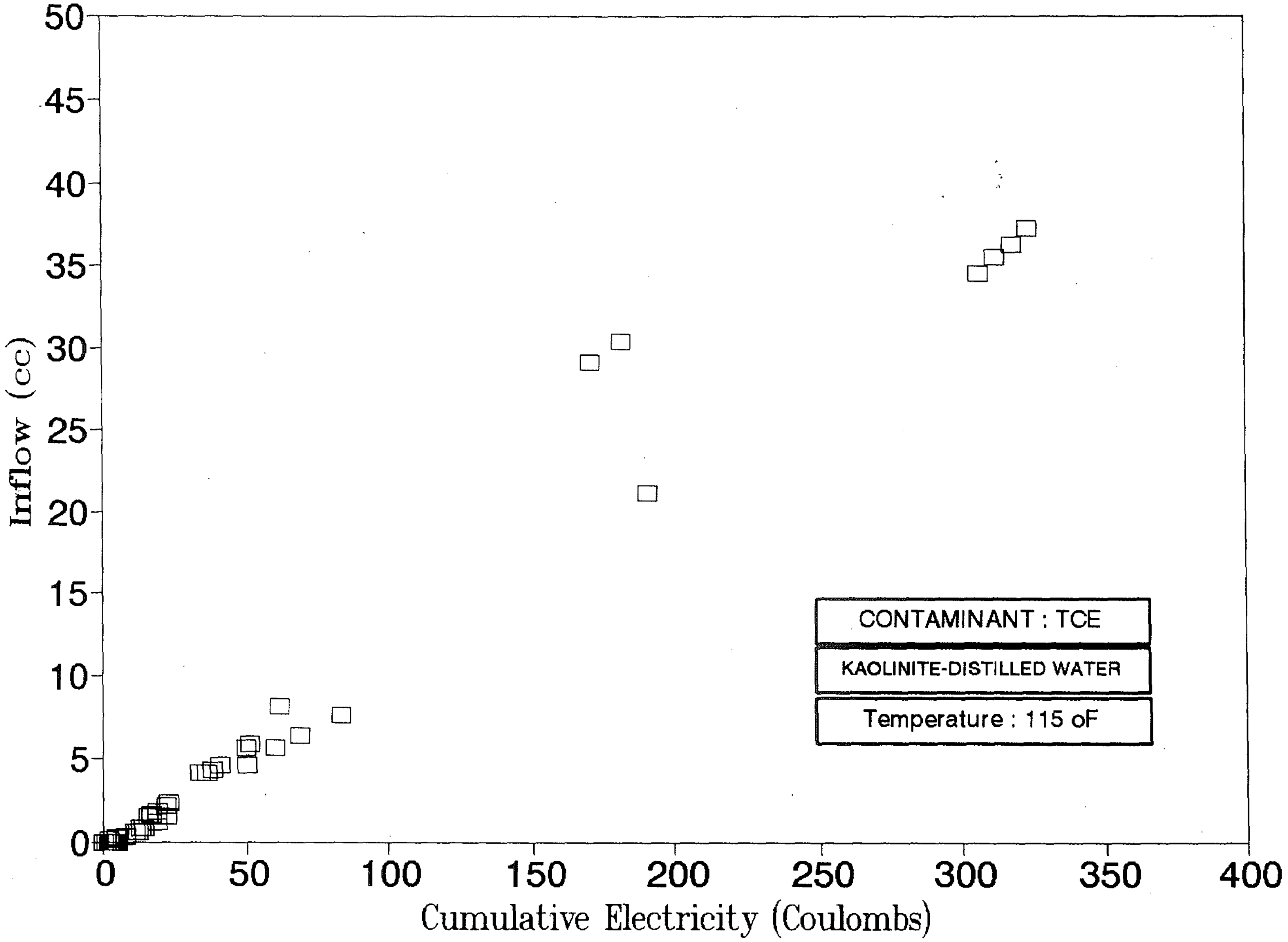

CONTAMINANT : NONE
KAOLINITE-DISTILLED WATER (T-KSOOM6B)
Temperature = 115 oF
Flow (cc)
10
9
8
7
6
5
4
3
2
1
0
Current (mA)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (hrs)
0
5
10
15
20
25
■ Inflow
□ Outflow
Current


CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (T-KSTCEHM1B)
Temperature = 115 oF
Flow (cc)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Current (mA)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
5
10
15
20
25
30
35
40
45
Time (hrs)
■ Inflow
□ Outflow
Current


CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (T-KSTCEHM2B)
Temperature = 115 oF
Flow (cc)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Current (mA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
······· Current


CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER (T-KSTCEHM3B)
Temperature = 115 oF
Flow (cc)
20
18
16
14
12
10
8
6
4
2
0
Current (mA)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
■ Inflow
□ Outflow
Current


Inflow (cc)
0
10
20
30
40
50
60
70
80
90
100
Cumulative Electricity (Coulombs)
0
50
100
150
200
250
300
350
400
450
500
CONTAMINANT ; NONE
KAOLINITE-DISTILLED WATER
Temperature : 115 oF


50
45
40
35
30
25
20
15
10
5
0
Inflow (cc)
0
50
100
150
200
250
300
350
400
Cumulative Electricity (Coulombs)
CONTAMINANT : TCE
KAOLINITE-DISTILLED WATER
Temperature : 115 oF

APPENDIX C.

Computer Program for Data Acquisition

```
100 DELAY1%=1000 : DELAY2%=300
105 SAVEIT%=1
110 INPUT "Enter the Name of the data file:";DFNAME$
115 IF LEN(DFNAME$) = 0  THEN SAVEIT% = 0
120 IF SAVEIT% < 1 THEN  150
125     INPUT "Enter comments:",COMMENT$
130     REM open a file to put the data
135     OPEN "O",#1,DFNAME$
140     PRINT#1,"Starting ";DATE$,TIME$
145     PRINT#1,COMMENT$
150 TIME$="00:00:00"
160 BASADR%=&H300
170 PRINT TIME$
180 ATTEN% = 10
1000 REM program and input from channel 1
1010 REM Channel 1 reads the voltage drop b/w Probe3-Cathode.
1050 MA%=1
1100 OUT BASADR%+2,MA%
1150 REM program for +/- 500mV (10)
1200 GAINVAL%=10
1250 OUT BASADR%+3,GAINVAL%
1300 REM start conversion for the channel
1350 OUT BASADR%+1,0
1400 REM keep checking the status register until end of conversion
1450 IF INP(BASADR% + 2) >= 128 GOTO 1450
1500 REM conversion complete, read the registers
1550 XL%=INP(BASADR%)
1600 XH%=INP(BASADR%+1)
1650 D%=16*XH% + XL%/16
1700 NVOLTS=((D% * 1000)/4096) -500
1750 VOLTS1=NVOLTS * (ATTEN% /1000 )
1800 REM PRINT "read:",D%," Normal:",NVOLTS,","," VOLTS: ",VOLTS1
1850 PRINT "Value read-in from channel 1 is:";VOLTS1;" volts","d%=";D%
2000 REM program and input from channel 2
2010 REM Channel 2 reads the Amphere through the soil.
2050 MA%=2
2100 OUT BASADR%+2,MA%
2150 REM program for +/-500 mV (10)
2200 GAINVAL%=10
2250 OUT BASADR%+3,GAINVAL%
2300 REM start conversion for the channel
2350 OUT BASADR%+1,0
2400 REM keep checking the status register until end of conversion
2450 IF INP(BASADR% + 2) >= 128 GOTO 2450
2500 REM conversion complete, read the registers
2550 XL%=INP(BASADR%)
2600 XH%=INP(BASADR%+1)
2650 D%=16*XH% + XL%/16
2700 NVOLTS=((D% * 1000)/4096) -500
2750 VOLTS2=NVOLTS / 88
2800 REM NO ATTENUATION... this channel bypasses conditioning board
2825 REM The current value needs to be measured and normalized to real ampherage
2830 REM for each step of the amphere knob on the power unit.
2830 REM " 88 " is calculated to be the normalization constant for this test.
2835 REM " 88 " is calculated to be the normalization constant for this test.
2850 REM PRINT "read:",D%," Normal:",NVOLTS,","," VOLTS: ",VOLTS2
2900 PRINT "Value read-in from channel 2 is:";VOLTS2;" milliamps","d%=";D%
3000 REM program and input from channel 3
3010 REM Channel 3 reads the voltage drop b/w Anode-Probe1.
3050 MA%=3
```

```
3100 OUT BASADR%+2,MA%
3150 REM program for +/- 5V (0)
3200 GAINVAL%=0
3250 OUT BASADR%+3,GAINVAL%
3300 REM start conversion for the channel
3350 OUT BASADR%+1,0
3400 REM keep checking the status register until end of conversion
3450 IF INP(BASADR% + 2) >= 128 GOTO 3450
3500 REM conversion complete, read the registers
3550 XL%=INP(BASADR%)
3600 XH%=INP(BASADR%+1)
3650 D%=16*XH% + XL%/16
3700 NVOLTS=((D% * 10)/4096) -5
3750 VOLTS3=NVOLTS * ATTEN%
3800 PRINT "Value read-in from channel 3 is:";VOLTS3;" volts","d%=";D%
4000 REM program and input from channel 4
4010 REM Channel 4 reads the voltage drop b/w Probe1-Probe3.
4050 MA%=4
4100 OUT BASADR%+2,MA%
4150 REM program for +/- 500mV (10)
4200 GAINVAL%=10
4250 OUT BASADR%+3,GAINVAL%
4300 REM start conversion for the channel
4350 OUT BASADR%+1,0
4400 REM keep checking the status register until end of conversion
4450 IF INP(BASADR% + 2) >= 128 GOTO 4450
4500 REM conversion complete, read the registers
4550 XL%=INP(BASADR%)
4600 XH%=INP(BASADR%+1)
4650 D%=16*XH% + XL%/16
4700 NVOLTS=((D% * 1000)/4096) -500
4750 VOLTS4=NVOLTS * ( ATTEN% / 1000 )
4800 PRINT "Value read-in from channel 4 is:";VOLTS4;" volts","d%=";D%
5000 REM program and input from channel 5
5050 REM Channel 5 reads the pore water pressure in the soil(in mV's).
5100 MA%=5
5150 OUT BASADR%+2,MA%
5200 REM program for +/- 500mV (10)
5250 GAINVAL%=10
5300 OUT BASADR%+3,GAINVAL%
5350 REM start conversion for the channel
5400 OUT BASADR%+1,0
5450 REM keep checking the status register until end of conversion
5500 IF INP(BASADR% + 2) >= 128 GOTO 5500
5550 REM conversion complete, read the registers
5600 XL%=INP(BASADR%)
5650 XH%=INP(BASADR%+1)
5700 D%=16*XH% + XL%/16
5750 NVOLTS=((D% * 1000)/4096) -500
5800 VOLTS5=NVOLTS
5850 REM NO ATTENUATION.. this channel is directly connected.
5900 REM PRINT "read:",D%," Normal:",NVOLTS,"," VOLTS: ",VOLTS5
5950 PRINT "Value read-in from channel 5 is:";VOLTS5;" millivolts","d%=";D%
6000 IF SAVEIT% = 0 THEN 6100
6050    PRINT#1,TIME$,VOLTS1,VOLTS2,VOLTS3,VOLTS4,VOLTS5
6100 PRINT "   "
6150 REM delay for a while
6200 FOR I%=1 TO DELAY1% : FOR II%=1 TO DELAY2% : NEXT II% : NEXT I%
6250 GOTO 160
```

VITA

Batu Tarman was born on August 1, 1967, to Serap and Ferruh Tarman of Istanbul, Turkey. He graduated from Kadikoy Anadolu High School in Istanbul, Turkey, in June of 1985 and entered Bogazici University in September of the year. He received his Bachelor of Science degree in Civil Engineering from Bogazici University in January 1990.

In August 1990, he began graduate school at Lehigh University in pursuit of the Master of Science Degree, with special interest in Geotechnical Engineering.

END

OF

TITLE