12-20-2009

Heavy metal removal from bilge water by electrocoagulation treatment

Milton Andrade
University of New Orleans

Recommended Citation

Andrade, Milton, "Heavy metal removal from bilge water by electrocoagulation treatment" (2009). *University of New Orleans Theses and Dissertations*. 1092.
https://scholarworks.uno.edu/td/1092

Heavy metal removal from bilge water by electrocoagulation treatment

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
in
Environmental Engineering

by

Milton Gabriel Andrade

B.S., Civil Engineering
Escuela Superior Politécnica del Litoral
Guayaquil, Ecuador, 2004

December, 2009

Dedication

This thesis is dedicated to:

My parents, Nicolas and Juanita

My brothers, Nicolas, David and Juan

Silvia

Rocky

Mary, in her hands I leave my life

“She did it all”

Acknowledgment

My special thanks go to Dr. Enrique J. La Motta, Ph.D. for his guidance and support throughout this endeavor and for permitting me to pursue this research in his laboratory.

I am grateful to the Faculty and Staff of the Department of Civil and Environmental Engineering of the University of New Orleans.

I would also like to thank Mr. Guillermo Rincón and Mrs. Kathleen McCraven for their technical efforts and suggestions.

My gratitude to Dr. Robert Cangelosi, MD., who made me get my vision back.

Lastly, but in no sense the least, I am thankful to all colleagues and friends who made my stay at the university a memorable and valuable experience.

This research was founded by SPAWAR through eVenture Technologies. Task Order 0099.

Table of Contents

List of Figures

List of Tables

Abstract

The purpose of this research was to observe the removal efficiency for copper (Cu), nickel (Ni), and zinc (Zn) using Electrocoagulation (EC) technique in a continuous flow reactor with a synthetic bilge water emulsion; and additionally, to discuss the operation cost of the treatment.

The optimal configuration for EC treatment used combined electrodes, aluminum and carbon steel; flow rate of 1 L/min; effluent recycling and 7.5 amps; this optimal configuration achieved 99% of zinc removal efficiency, 70% of both, copper and nickel removal efficiency, and low operation costs. The current intensity did not have significance incidence on the removal efficiency.

The analysis of cost per gram of removed contaminant indicated that nickel had an average cost of \$1.95 per gram removed, zinc and copper had \$0.60 and \$0.88 per gram removed, respectively.

To develop additional experiments with the EC reactor are required in order to optimize metal removal efficiency.

Keywords: Electrocoagulation, bilge water, emulsion, nickel, zinc, copper, heavy metal, aluminum electrode, carbon steel electrode, operating cost, specific energy consumption, effluent recycling, tween 40, iron rust.

1 Introduction

1.1 Background: Bilge water, heavy metal production and regulations

In the United States, the bilge water production is estimated in the millions of cubic meters per year (there is not any national report). As a reference, cruise ships operating in Southeast Alaska produce around 5 to 20 m^3 of bilge water every 24 hours, that is 1,800 to 7,200 m^3 per year (Alaska Department of Environmental Conservation 2000).

The Environmental Protection Agency, (EPA) in conjunction with the Department of Defense (DoD), the Secretary of State, the Secretary of Commerce and several Federal Agencies, is developing the Uniform National Discharge Standards (UNDS), organized in three phases, for incidental liquid discharges from vessels of the US Armed Forces. From the Nature of Discharge Report for Surface Vessels Bilge Water, the annual mass loading of heavy metals in bilge water produced by US aircraft carriers is about 116 kg of copper, 57 kg of nickel, 299 kg of zinc, and 160 kg of iron. (EPA 1999)

Even though the discharge of bilge water is strongly regulated both inside and outside the country, the regulations have been focused to control more oil and oily mixture concentrations than heavy metal concentrations. In London in 1973, the International Convention for the Prevention of Pollution from Ships (MARPOL 1973) met and enforced, in 1978, the Regulation 16th which states that any discharge of bilge water (and oily water emulsion) does not have to exceed 15 parts per million (ppm) of oil content, and in function of the weight and kind of ship, the discharge must be at 12 nautical miles from the nearest land.

The Unites States accepted MARPOL Protocol and passed laws to enforce it, such as: the Clear Water Act (CWA 1972; 33 U.S.C. § 1301), that establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters; the National Marine Sanctuaries Act (NMSA 1988; 16 U.S.C. § 1431 et seq.), a law that protects marine resources and ecosystems, such as coral reefs, sunken historical vessels, or unique habitats, from degradation while facilitating public or private uses compatible with resource protection; the Oil Pollution Act (OPA 1990; 33 U.S.C. §

2702 et seq.), that streamlined and strengthened EPA's ability to prevent and respond to catastrophic oil spills; and the Act to Prevent Pollution from Ships (APPS 2000; 33 U.S.C. § 1901 et seq.), federal law that implements those provisions of MARPOL in United States. In addition, the Coast Guard has the primary responsibility to prescribe and enforce the regulation necessary to implement APPS in United States and has regulations pertain to management of the discharge of oil or oily mixtures into the sea from ships. In summary, bilge water discharges are well controlled in oil concentrations but lacking in specific heavy metal concentrations. Since there is no specific regulation for metal pollutants under the bilge water section, reference standards regulating heavy metal concentrations are taken from the ambient water quality criteria to protect aquatic life (65 FR 31682;(EPA 2009)); that is, standards with water body criteria instead of discharge criteria.

1.2 Problem Statement

Since reference regulations are enforcing rigorous standards of heavy metal concentrations, enhanced methods with high removal efficiency, low operation costs, short operation times and reduced use of additional chemical products are required. In the present research, electrocoagulation (EC) is the chosen method to treat bilge water, with a focus on heavy metal removal efficiency for copper, nickel and zinc.

Electrocoagulation technique for wastewater is already used with high efficiency in removing heavy metal pollutants like Cu, Cr, Ni, Zn, Ag, As (Heidmann and Camano 2008, Huhnsom, et al. 2005, Parga, et al. 2005), oily emulsions (Bensadok, et al. 2008, Yang 2007, Ogutveren and Koparal 1997), and organic removals in bilge water (Asselin, et al. 2008).

1.3 Significance

The significance of this research is to demonstrate the heavy metal removal efficiency of EC while removing an emulsified oil suspension, and to provide information on operating parameters for this novel techonology.

1.4 Objective

The main objective of this research is to observe the removal efficiency for copper, nickel, and zinc using EC in a continuous flow reactor with a synthetic bilge water emulsion. The specific objectives are listed below:

- To find relations among EC parameters: current intensity, electrode material, and EC performance efficiency.
- To discuss operation costs of the treatment.

2 Literature Review

2.1 Bilge water

Bilge water is a complex kind of waste water that includes the “mixture of water, oily fluids and lubricants, also cleaning fluids, solid wastes such as rags, metal shavings, paint, glass, and a variety of chemical substances” (U.S. Environmental Protection Agency 2008), accumulated in the lower part of vessels and originating from many sources: leaks, condensation, wash-down, engines, piping, even, in some types of vessels, including gray and black water. When discharged, a small part of the heavy metals are dissolved by the sea water, but large parts go to the sea bed and become aquatic life pollutants. Commonly, bilge area in vessels is located in the lowest part. Figure 2.1 shows where a bilge well is in a general vessel with a bilge water treatment system on board.

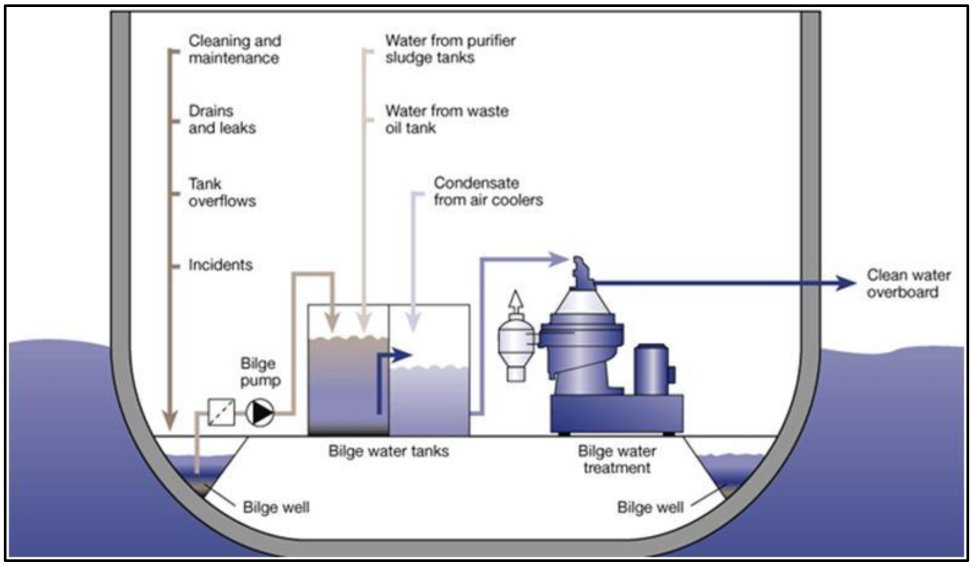
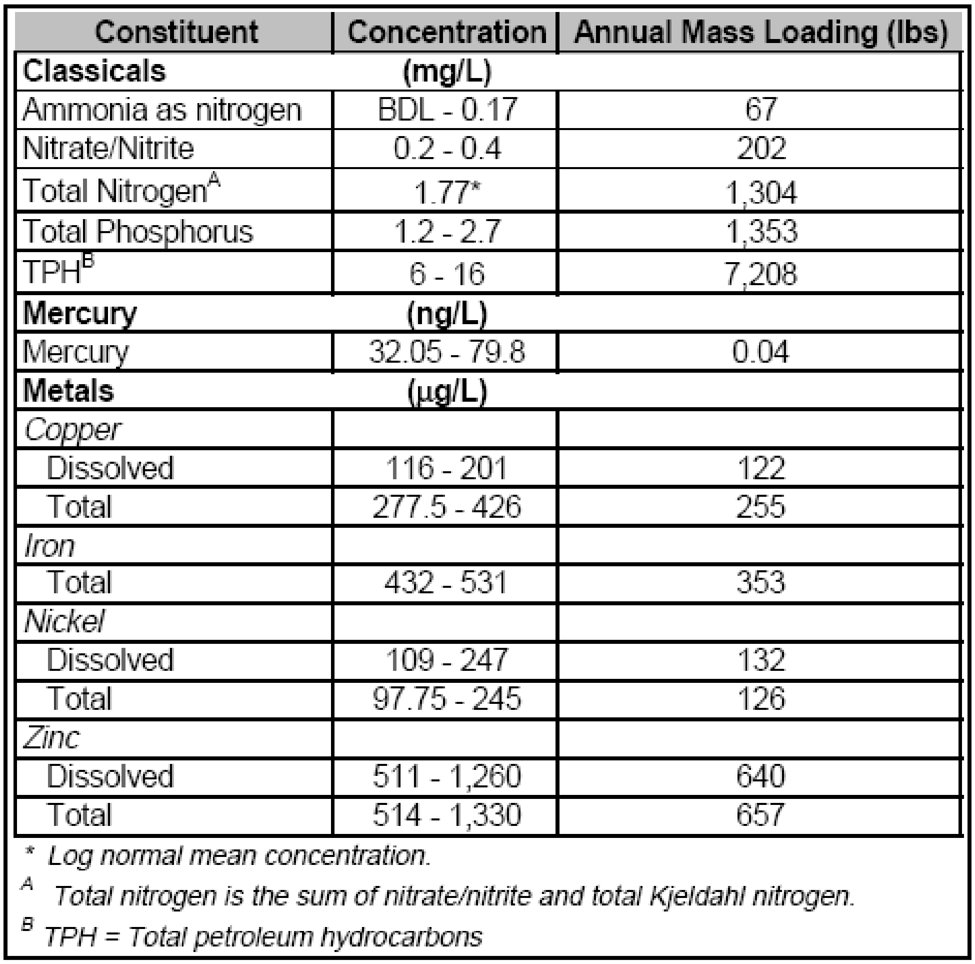


Figure 2.1. Bilge wells location in a general vessel. (Join Systems, Inc 2005)

Bilge water is disposed of in oil-holding tanks on surface vessels, so this water can be treated on board, generally using an oil water separator (OWS), or transferred to a shore treatment plant. As is mentioned in section 1.1, UNDS made preliminary analysis of Oil-Water Separator (OWS) effluents to be discharged from different vessels; the constituents that exceed the water quality criteria are summarized in Table 2.1 in concentration and annual mass loading. Due to the high concentration of heavy metals that exceeds regulations, UNDS has determined the urgent need of a marine pollution control system.

Table 2.1. Constituents in bilge water discharges found in US Aircraft Carriers. (EPA 1999)



Constituent	Concentration	Annual Mass Loading (lbs)
Classicals	**(mg/L)**	
Ammonia as nitrogen	BDL - 0.17	67
Nitrate/Nitrite	0.2 - 0.4	202
Total Nitrogen^{A}	1.77*	1,304
Total Phosphorus	1.2 - 2.7	1,353
TPH^{B}	6 - 16	7,208
Mercury	**(ng/L)**	
Mercury	32.05 - 79.8	0.04
Metals	**(µg/L)**	
Copper		
Dissolved	116 - 201	122
Total	277.5 - 426	255
Iron		
Total	432 - 531	353
Nickel		
Dissolved	109 - 247	132
Total	97.75 - 245	126
Zinc		
Dissolved	511 - 1,260	640
Total	514 - 1,330	657

* *Log normal mean concentration.*

^{A} *Total nitrogen is the sum of nitrate/nitrite and total Kjeldahl nitrogen.*

^{B} *TPH = Total petroleum hydrocarbons*

2.2 Electrocoagulation (EC) process

EC is the process of destabilizing suspended, emulsified, or dissolved contaminants in an aqueous medium by introducing an electric current into the medium for short time, then transferring the stream to a clarifier system where the mixture of water and pollutants is almost totally separated. It forms three layers: floating sludge layer, clean water, and sediment layer.

2.2.1 Theory of Electrocoagulation

The EC process involves many chemicals and physical factors, where electrical current is applied to consumable electrodes that generate, in the primary stage, coagulants due to electrolytic oxidation of the electrode. Immediately after this is the secondary stage, in which contaminant destabilization, particulate suspension, and breaking of emulsions are produced; after that, the ultimate stage, in which the formation of flocs takes place due to the aggregation of destabilized phases (Mollah, Morkovsky, et al. 2004). EC stages are detailed as follows (Chen, Chen and Yue 2000, Kobya, Taner Can and Bayramoglu 2003, G. Chen 2004, Mollah, Morkovsky, et al. 2004, Heidmann and Camano 2008, Merzouk, et al. 2009, Khella, et al. 2008):

- ✓ **Generation of metal ions:**

At the carbon steel anode:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-} \qquad (1)$$

$$Fe_{(s)} \rightarrow Fe^{3+}_{(aq)} + 3e^{-} \qquad (2)$$

At the aluminum anode:

$$Al_{(s)} \rightarrow Al^{2+}_{(aq)} + 2e^{-} \qquad (3)$$

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^{-} \qquad (4)$$

- ✓ **Generation of hydroxides and polyhydroxides:** Metal ions are hydrolyzed forming hydroxides like $Al(H_2O)_6{}^{3+}$, $Al(H_2O)_5OH^{2+}$, $Al(H_2O)_4OH^{2+}$, $Fe(OH)_3$ and these hydrolysis products can produce $Al(OH)^{2+}$, $Al(OH)_2{}^{+}$, $Al_2(OH)_2{}^{4+}$, $Al(OH)_4{}^{-}$, $Al_6(OH)_{15}{}^{3+}$, $Al_7(OH)_{17}{}^{4+}$, $Al_8(OH)_{20}{}^{4+}$, $Al_{13}O_4(OH)_{24}{}^{7+}$, $Al_{13}(OH)_{34}{}^{5+}$, $Fe(H_2O)_6{}^{3+}$, $Fe(H_2O)_5(OH)^{2+}$, $Fe(H_2O)_4(OH)_2{}^{+}$, $Fe_2(H_2O)_8(OH)_2{}^{4+}$, $Fe_2(H_2O)_6(OH)_4{}^{4+}$.

- ✓ **Water stream electrolysis:** Due to salinity in the water stream, chlorine is released. Many authors include the evolution of oxygen at the anode. Moreno et al reported that when iron electrodes are used there is no formation of oxygen during EC even though the presence of magnetite (Fe_2O_4) and maghemite (Fe_2O_3) in EC sludge could suggest it; these iron oxides are formed through dehydration of iron hydroxides. In some cases, iron oxides can occur during the analysis of the flocs by filtration and sample preparation. (Moreno, et al. 2009)

At the anode:

$$2H_2O_{(l)} \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^- \quad (5)$$

$$2Cl^- \rightarrow Cl_2 + 2e \quad (6)$$

At the cathode:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^- \quad (7)$$

$$2H^+ + 2e^- \rightarrow H_{2(g)} \uparrow \quad (8)$$

- ✓ **Wastewater destabilization and aggregation:** In this stage, the destabilization of contaminants, breaking of emulsion, particulate suspension and formation of flocs take place; also, the diffuse double layer is compressed, and ionic species are neutralized. Small flocs trap contaminants and are carried to the surface by hydrogen bubbles when the bubbles emerge from the reactor; hence, the sludge layer is formed at the surface. The smaller the hydrogen bubble size, the more surface area provided to trap flocs and the more effective separation of contaminants from water (Chen, Chen and Yue 2000). Even during the flotation process, there are heavy stable flocs that go downward, creating a sediment layer.

Moreno also describes as an ultimate stage the physiochemical reaction, in which several processes occur such as chemical reaction and precipitation of metal hydroxide with pollutants, cathodic reduction of impurities or metal ions present, electrophoretic migration of ions, oxidation of pollutants to less toxic species, and more electrochemical processes (Moreno, et al. 2009). A schematic view about main reactions into a basic electrochemical cell is shown in Figure 2.2.

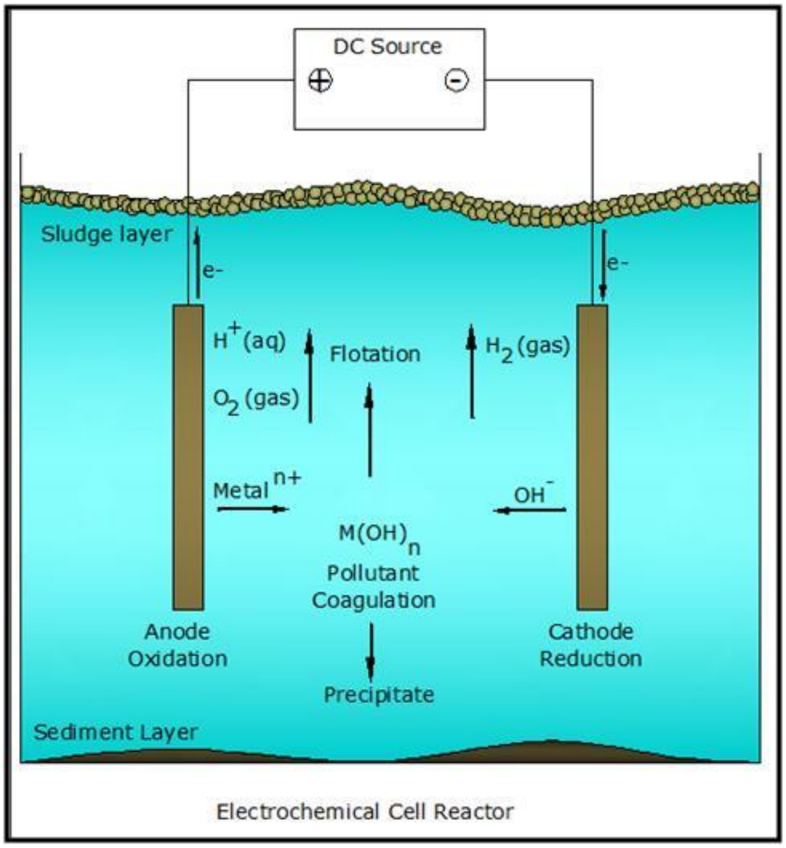


Figure 2.2. Schematic view of electrochemical reactions in a batch reactor adapted by the author from (Mollah, Morkovsky, et al. 2004).

2.2.2 Main parameters

EC is a process that involves chemical, electrical, and mechanical concepts; therefore, there are parameters that apply to each area or all of them, resulting in complex and interesting research. Parameters fixed in the present study were electrode material, current type and intensity, and passivation prevention, all of which are concerned directly with the EC process. Other parameters that affect the EC process are overpotential: ohmic or IR-Drop, kinetic or activation, concentration or mass transport; pH, conductivity, and size of bubbles.

2.2.2.1 Overpotential

Overpotential or overvoltage is a consequence of the shift in polarization, or the shift in the potential difference across a cell caused by the flow of current. This overpotential (η) is required to be minimum for lower costs of the process and has three distinct causes: ohmic polarization, activation polarization, and concentration polarization (η_{Conc} or η_{MT}). Each overpotential has the same sign as the current that causes it, as shown in Figure 2.3.

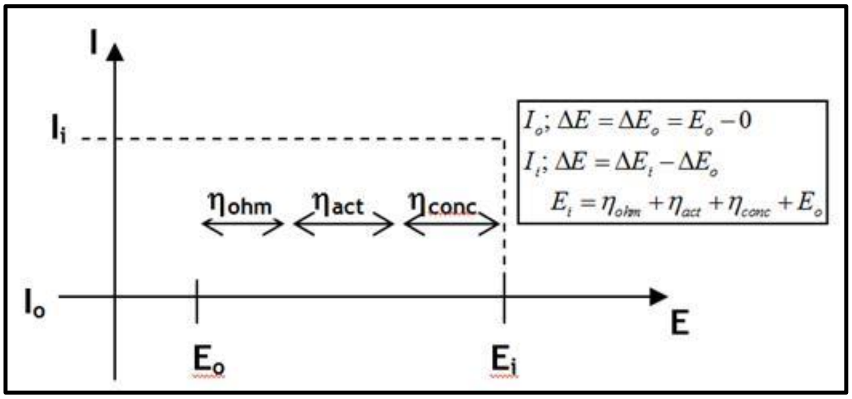


Figure 2.3. Potential in function of overpotential

The ohmic overpotential (η_{ohm} or η_{IR}), is given by the potential gradient across the cell that promotes the motion of the ions through the electric field; it is a function of the current to flow and the respective resistance of the solution between two electrodes, because this is often called "IR drop". The resistance of any solution is related to the distance (L) between two electrodes, the cross-sectional area (A) of the intervening solution, and the conductivity (κ). In the research, because L and A are constants, in order to minimize the IR drop, the current (I) was varied and the conductivity K was increased.

$$\eta_{ohm} = IR = I \times \frac{L}{A\kappa} \tag{9}$$

The activation overpotential (η_{act} or η_K), is related directly to the rate or kinetics of the reaction, so this is often called kinetic overpotential; the rate of the reaction is a function of the potential E and the current I, as will be demonstrated. In an electrochemical cell where oxidation and reduction occur, there are involved electrode reaction rates r_O and r_R, mass concentrations, c_O and c_R, and chemical activities, γ_R and γ_O, where the subscripts "O" and "R" reference if they occur in the oxidation or reduction reaction. The Nernst equation describes the potential as a function of the mass concentration and chemical activities,

$$\begin{aligned} E_{null} &= E^{o'} - \frac{RT}{nF}\ln\frac{c_R}{c_O} \\ where\ E^{o'} &= E^{o} - \frac{RT}{nF}\ln\frac{\gamma_R}{\gamma_O} \end{aligned} \tag{10}$$

Where R, T and n conform to the ideal gas law; F is the Faraday constant, $E^{o'}$ is called the conditional potential and is considered as a constant, but it depends on the activity of each ion and the standard potential. The convenience to work with $E^{o'}$ is first to not work with activitiy coefficients that become almost constant for solutions with high ionic strength, and second to not work with the speciation of the reaction that will be too complex. The net reaction r_{net} is expressed in the following equation,

$$r_{net} = r_O - r_d = \frac{I}{nAF} \tag{11}$$

The rate of electrode reaction r_O and r_R can be equal only at the electrode's null potential and are proportional to the concentration with the potential-dependent rate constant *K*, called oxidative or reductive rate constant for oxidation or reduction reactions respectively,

$$r_O = k_o\left(E\right)c_R \tag{12}$$

$$r_R = k_R\left(E\right)c_O \tag{13}$$

The rate constants depend on the differences of potential E, as can be seen in the following set of equations,

$$\begin{aligned}
&r_O = r_R \\
&k_o\left(E_{null}\right)c_R = k_R\left(E_{null}\right)c_O \\
&\frac{k_o\left(E_{null}\right)}{k_R\left(E_{null}\right)} = \frac{c_O}{c_R};\quad \ln\frac{k_o\left(E_{null}\right)}{k_R\left(E_{null}\right)} = \ln\frac{c_O}{c_R} \\
&\left(E - E^{o'}\right)\frac{F}{RT} = \ln k_o\left(E\right) + \ln\frac{1}{k_R\left(E\right)} \\
&\frac{RT}{F}\frac{d}{dE}\ln k_o\left(E\right) + \frac{RT}{F}\frac{d}{dE}\ln\frac{1}{k_R\left(E\right)} = 1
\end{aligned} \tag{14}$$

Manipulating the equations, the rate constants can be expressed as,

$$\begin{aligned}
&k_R(E) = k_R\left(E^{o'}\right)e^{\left[\frac{-\alpha F\left(E-E^{o'}\right)}{RT}\right]} \\
&k_O(E) = k_O\left(E^{o'}\right)e^{\left[\frac{(1-\alpha)F\left(E-E^{o'}\right)}{RT}\right]} \\
&\textit{where,} \\
&\alpha = \frac{RT}{F}\frac{d}{dE}\ln\frac{1}{k_R(E)}
\end{aligned} \tag{15}$$

Then, equation (11) is rearranged like,

$$\frac{I}{A} = nFk^{o'}{c_O}^{\alpha}{c_R}^{(1-\alpha)}\left\{e^{\left[\frac{(1-\alpha)nF\eta_{act}}{RT}\right]} - e^{\left[\frac{-\alpha nF\eta_{act}}{RT}\right]}\right\} \tag{16}$$

Where $\eta_{act} = \left(E - E^{o'}\right)$. For this relation, when the current increase, the η_{act} tends to increase. More information about the kinetics of electron transfer is provided by Oldhman and Myland. (1994)

The concentration overpotential (η_{conc} or η_M), is related to the surface and bulk concentrations, c^s and c^b, each one for oxidation and reduction. Nernst's law can be applied when the electrode reaction is so fast that the activation overpotential is absent; also, Nernst's law is applied when the equilibrium prevails, the surface concentrations acquire their bulk values,

$$E = E^{o'} - \frac{RT}{nF} \ln \frac{c^s{}_R}{c^s{}_O} \tag{17}$$

$$E_{null} = E^{o'} - \frac{RT}{nF} \ln \frac{c^b{}_R}{c^b{}_O} \tag{18}$$

Assuming only concentration overpontential is present in the reaction, $\eta_{conc} = \left(E - E_{null}\right)$ can be expressed as,

$$\eta_{conc} = E - E_{null} = \frac{RT}{nF} \ln \left\{ \frac{c_R^b c_O^s}{c_R^s c_O^b} \right\} \tag{19}$$

2.2.2.2 pH

This parameter relates to the EC efficiency. EC can work effectively over a wider range of pH because EC has the ability to neutralize wastewater pH: when influent pH is acidic, effluent pH value rises, and when influent pH is alkaline, effluent pH drops (Chen, Chen and Yue 2000). Some authors have noted an imperceptible incidence over EC efficiency between pH ranges from 4 to 9, out of these limits, the efficiency varies linearly with pH, probably due to the few coagulant produced in that outrange.

Initial pH of 6 was found optimal for more than 90% arsenic removal (Gomes, et al. 2007); initial pH of 7 and 8 achieved higher removal efficiency for zinc (90% at 40 min) and nickel (90% at 100 min) than an initial pH of 3 (zinc= 60% at 40 min; nickel= 70% at 100 min); for TOC removal, variations in initial pH did not make any difference (Kabdaşli, et al. 2009). The influent pH did not affect the removal efficiency significantly over a wide range. A slight drop of COD removal of 60% was observed for pH<4 or pH>9 compared with 70% COD removal at pHs 4-9, for suspended solids, a low efficiency of 40% at pH 3 compared with 90% at pH 5 (Chen, Chen and Yue 2000).

The removal efficiency for iron was increased with increasing pH, and the maximum removal efficiency of 98.8% was obtained at pH 6.5, the minimum was 60% at pH 10, considering the presence of soluble cations Al^{+3} at acidic pHs and the presence of monomeric anions $Al(OH)^{4-}$ at alkaline pHs. (Vasudevan, et al. 2009). Over the electrolysis voltage, the effect of pH was found insignificant for both new and passivated electrodes; for new electrodes, an increase of pH from 3.75 to 10.41 resulted in only an increase from 13.2 to 13.8 V. (Chen, Chen and Yue 2000)

2.2.2.3 Conductivity

Electrical conductivity is the ability of the media to conduct electrical current between two electrodes. This electrical conductivity seems to affect more directly the voltage or the current intensity than the removal efficiency. In restaurant wastewater, the removal efficiency for oil and grease, COD and suspended solids was not significantly affected by variation in conductivity, but in electrolysis voltage, the higher the conductivity, the lower the electrolysis voltage. With conductivity values from 1000 to 4000 μS/cm, the voltage between electrodes decreased from 4 to 2 V. (Chen, Chen and Yue 2000); this feature of the conductivity is used to lower the power used in the treatment, and consequently, to lower the operation costs.

Sodium chloride is commonly used as an electrolyte to increase conductivity, in the treatment of orange II dye. The percent of removal efficiency increased from 93 to 98% when the electrolyte concentration was increased from 0.034 to 0.102 M. (Mollah, Pathak, et al. 2004); turbidity removal efficiency remains almost unchanged 80 to 90% between the conductivity range of 2100 and 3000 μS/cm, reported in research of heavy metal removal. (Merzouk, et al. 2009)

2.2.2.4 Passivation

Passivity is caused by an impermeable oxide layer on the surface of the electrode, which protects the underlying metal from oxidation. The oxide is an electronic, but not an ionic, conductor. This passivation becomes an additional overpotential that is related to many factors, such as pH, conductivity and current density, but close to the anode, the pH is always acidic thus the passivation overpotential (hpass) depends on the conductivity (k) and current density (i).

$$\eta_{pass} = K_{pass} \frac{i^m}{\kappa^n} \tag{20}$$

Electrodes that are passivated show a rough surface; this roughness causes an insignificant effect in the flow rate of turbulence (Chen, Chen and Yue 2000). To avoid the passivation, it is believed that a shift in polarization could be useful; this shift causes the electrode to have a self-cleaning in its surface due to the particle repulsion by its charge. The efficiency of the method depends on the rate of oxidation of the electrode and the grade of passivation the electrode has suffered before the shift. The time given for this layer release significantly affects the EC performance, decrease in efficiency, and increase in power consumption.

2.2.2.5 Current

This parameter directly affects the EC process performance and operating cost. In most cases, it is expressed as current density (i) which represents the current flow through at right angles into a cross-sectional area; the units are Amps/m^2 or mAmps/cm^2.

It is known that in EC the removal efficiency is proportional to the amount of hydrous oxides (coagulant) generated by the electrode in the solution; this amount (m) can be related to the current by the Faraday's law,

$$m = \frac{M_W}{ZF}\frac{I}{A}t \tag{21}$$

where M_W is the molecular weight of the electrode material, Z the number of electrons involved in the reaction, F is the Faraday's constant, I current intensity, A cross-sectional area, t is the time of the current application. As *m* is proportional to *I* and *t*, increasing current intensity will increase removal efficiency during a time t but will also increase the power required to achieve the removal efficiency.

In metal plating effluent, 60% of TOC was removed after 150 min at 9 mA/cm^2. The same removal efficiency was obtained in 45 min at 45 mA/cm^2, zinc was 90% removed with current densities higher than 9 mA/cm^2 with 25 min of application (Kabdaşli, et al. 2009). Removal efficiencies of 58.1, 88.6, 99.3 and 100% were achieved for arsenic (III) at current intensity values of 25, 50, 75 and 100 A/m^2 respectively for 30 min of process; and 81.9, 99.2 and 100% of chromium (VI) removal efficiency was found with 25, 50 and 75 A/m^2, respectively during 30 min. (Thella, et al. 2008).

2.2.2.6 Electrode material

According to the mechanism of EC process, the formation of hydroxides due to the oxidation of the electrode promotes the sorption of the contaminants in the stream and produces coagulation or flocculation; hence, the electrode material is directly proportional to the efficiency performance of the EC. Commonly, carbon steel or iron and aluminum electrodes are chosen for EC. Carbon steel electrodes have low cost and can be easily oxidized; this characteristic could be useful when more iron can be released to react with the solution and to form coagulants; this also means iron electrodes have a low operation life. Iron electrodes can form rust easily in open environments. This rust produces a passive layer over the electrode's surface that can be released during the EC process but does not form effective coagulants, so the removal efficiency decreases significantly. Also, the voltage increases due to the passivation overpotential originating a waste of power. Figure 2.4 shows the passive layer over an iron electrode surface after EC process; the experiment had low removal efficiency.

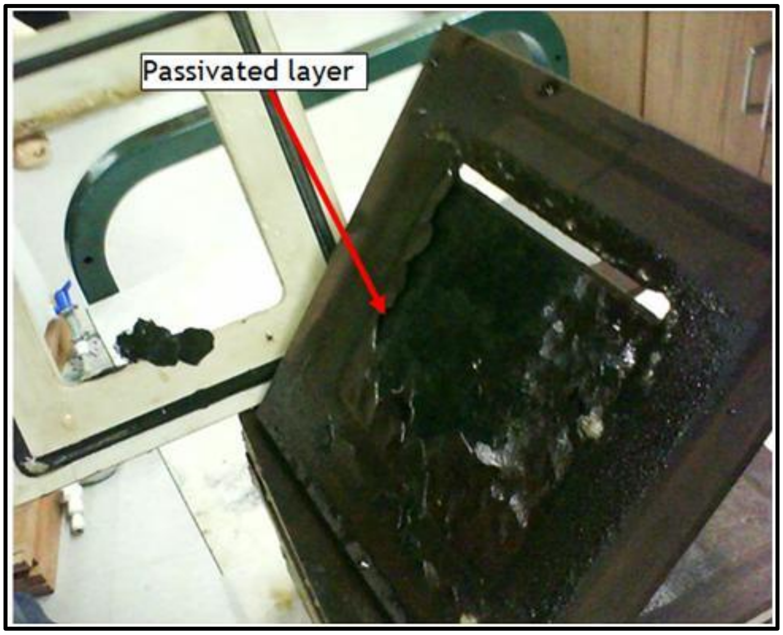


Figure 2.4. Iron electrode with a passivated layer after EC process

Aluminum electrodes have similar removal performance to iron electrodes even though the amount of hydroxide generated is less than the iron. The cost of aluminum electrodes is higher than iron electrodes, but the operation life is higher, too. In the present study, a combination of iron and aluminum electrodes was used.

2.2.2.7 Size of hydrogen bubbles

Hydrogen bubbles are formed at the cathode, trapping the generated coagulant or floc and driving them together with the flow direction. When the stream is released to an open clarifier, the bubbles will raise the floc particles to the surface, bringing all the removed contaminants to the surface, thus creating a sludge layer. Because the main objective is separating contaminants from the treated water, particle flotation by hydrogen bubbles is a main component of the EC process.

It is known that the smaller the bubble, the better the separation efficiency of any flotation process, due to smaller bubbles providing larger surface areas for particle attachment (Chen, Chen and Yue 2000). For restaurant wastewater treatment, EC process efficiency was studied by Chen et al. The authors found that the bubbles formed by EC were not sufficient for a high removal efficiency of suspended solids. The reasons were primarily related to the reactor configuration, which promoted the formation of large hydrogen, this, in turn, disturbed the flow and decreased the contact between particles and bubbles. Another reason that affects bubble size and generation is that the electrode surface, due to the passivation, has a rough surface, which provides larger adhering forces to bubbles than smooth surfaces, thus decreasing their generation (Chen, Chen and Yue 2000).

2.2.2.8 Other main parameters

The flow rate parameter is related to the operation time, which is the time that the wastewater stream is treated inside the EC reactor, and thus it is related to the amount of dissolved electrode metal and the EC performance efficiency.

The shape of the clarifier affects the degree of separation of the contaminants trapped by the hydrogen bubbles. In the clarifier, the reactor effluent is separated in three layers: The sludge layer at the top, treated water layer in the middle, and sediment layer at the bottom. In order to enhance the separation of the contaminants, the shape of the clarifier has to promote the rise of the hydrogen bubbles without breaking them up.

Effluent recycling should be beneficial because it affects the contact time. The objective of effluent recycling through the EC reactor is to remove the remaining contaminant in the wastewater and to remove EC by-product precipitates. Effluent recycling exposes the pollutants remaining in suspension to additional metal coagulants, and therefore, it is rough equivalent to decreasing flow rate. Therefore, to operate EC treatment at 0.5 L/min can be roughly compared with effluent recycling at 1 L/min of flow rate.

Figure 2.5 illustrates the EC parameters and their influence on performance efficiency; the parameters inside green rectangles were controlled in the experiments.

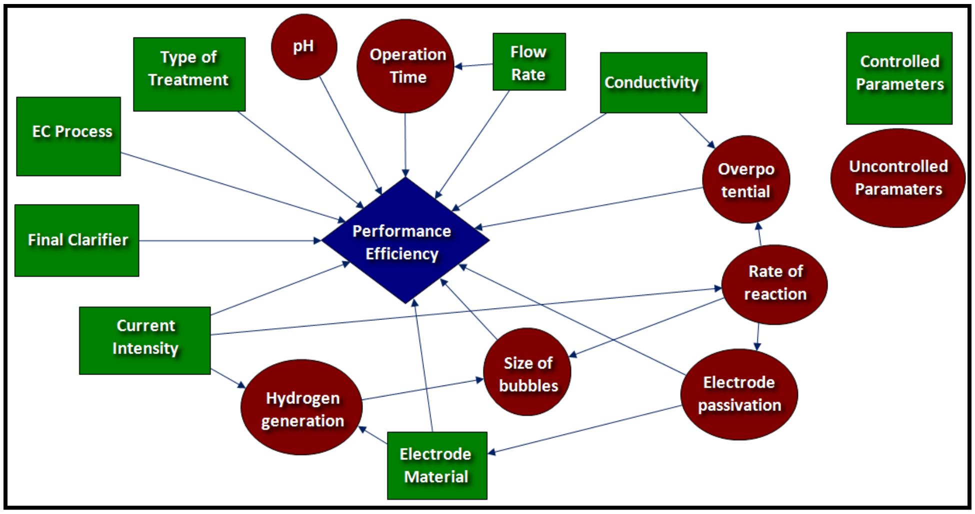


Figure 2.5. Influence of EC parameters

2.2.3 Heavy metal removal by EC

Removing arsenic (III) and chromium (VI) from aqueous solution was investigated by Khella using EC in an electrolytic cell. Optimal removal efficiencies greater than 90% were found with initial pH range from 2 to 4, at 30 min in electrolysis time, current density between 75 and 100 A/m^2, and iron electrodes (Khella, et al. 2008).

In wastewater treatment, removal of copper, nickel, zinc, cadmium, lead and iron using EC had significant efficiency. In a polymetallic solution (100 mh/L of each metal), more than 98% of removal efficiency was obtained in the first 5 minutes of operation time using aluminum electrodes, applying 11.5 mA/cm^2(Merzouk, et al. 2009). Aluminum electrodes were more effective than iron electrodes for the removal of the same heavy metals in a multi-stage treatment with EC as a stage of the process in the treatment of shipyard stormwater; the removal efficiency ranged between 60 to 100%. (Pulido and La Motta 2001)

3 Experimental Phase

3.1 Materials and Methods

The research had three stages: synthetic bilge water preparation, EC treatment, and sample analyzing. A description of all of the materials and methods used in the research will be presented before the description of each stage.

3.1.1 Materials

Materials used for the research are mainly used for the preparation of the synthetic bilge water, listed in the Table 3.1.

Table 3.1. Materials used in EC treatment

Type of Material	Brief description
Heavy Metals	
Copper, as CuCl2.2H2O	Cupric chloride. FW 170.48. Fisher Scientific
Nickel, as NiCl2.6H2O	Nickel chloride. FW 237.70. Matheson Coleman & Bell
Zinc, as ZnCl2	Zinc chloride anhydrous. EMD
Emulsion	
Oil	SAE 30 SJ/CF. Small engine oil. Briggs and Stratton
Tween 40, surfactant	D = 1.050. Acros organic
Paint	100% Acrylic latex. Valspar
NaCl	Sodium Chloride. FW 58.44. Fisher Scientific
EC	
Electrodes: Carbon steel, Aluminum	Area = 8.0162 cm^2; e = 0.7 cm. See Figure 3.1
Plastic plates	Hole area = 102.01 cm^2; e = 0.13 cm. See Figure 3.1

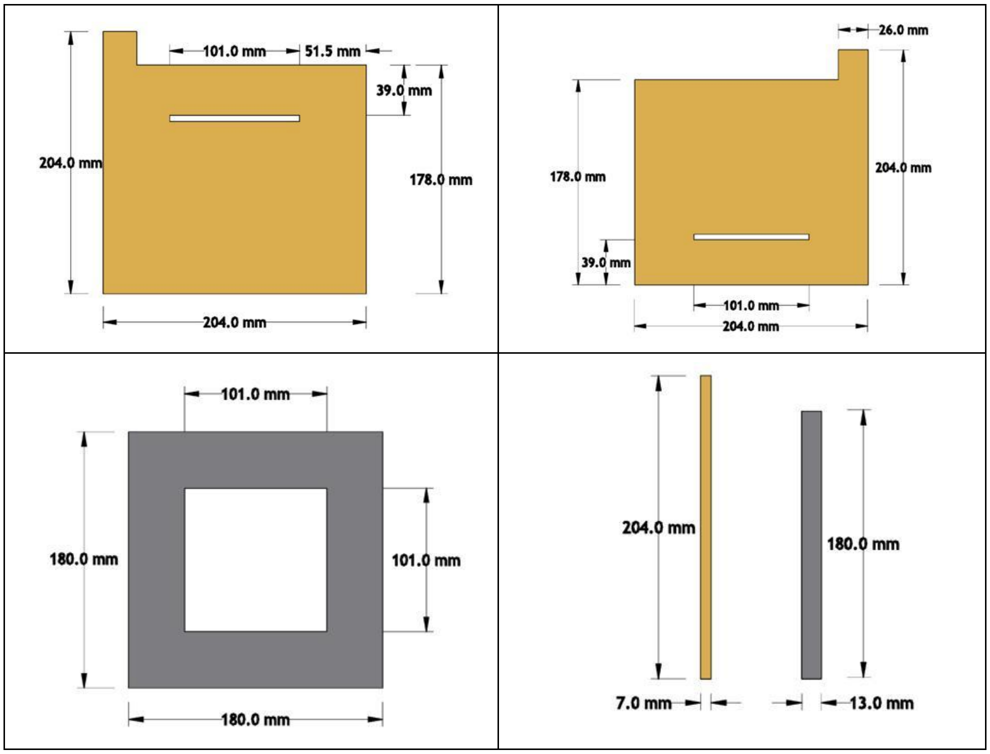


Figure 3.1. Shape configuration of electrode and plastic plate

Table 3.2 shows all the equipment used in the EC research; brief information is given on each piece.

Table 3.2. Equipment used in EC treatment

Table 3.2. (..cont)

Name	Brand	Model	Range	Image
Equipment for synthetic bilge water preparation				
Lab Mixer	Red Devil	5410		

Table 3.2. (..cont)

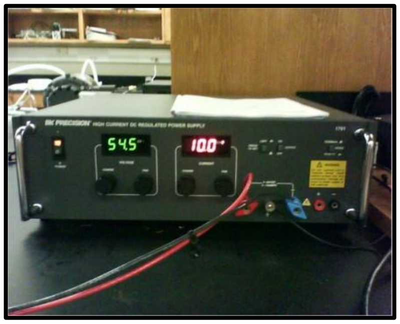
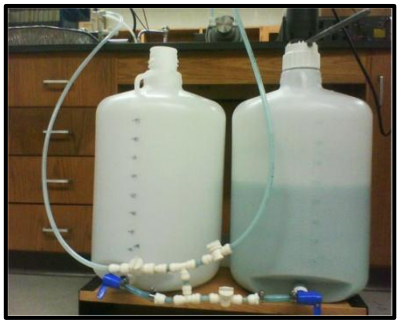
Name	Brand	Model	Range	Image
Equipment used in EC treatment				
Centrifugal pump flow rate controller	Baldor Reliance Vector Drive Motor Master Micropump	GC-M35 ID15J1F50-ER	Max 6000 RPM Max 150 Hz.0.37 kW	 
High current DC regulated power supply	BK Precision	1791	60V/10A max. 0.70 efficiency	
EC reactor	Ecolotron			
Carboy container with valve	Nalgene		45 L	

Table 3.2. (..cont)

Name	Brand	Model	Range	Image
Electric stirrer	Arrow Engineering	850	Max 1000 rpm	
Conic shape vessel	Nalgene		16 gal	
Equipment for sample analysis				
Portable Spectrophotometer	Hach Company	DR 2800	340 to 900nm	
Orion Benchtop meter	Thermo Scientific	Orion* 5-Star pH – ISE – Conductivity - DO Meter Benchtop	pH: -2.0 to +19.999 ISE: 0 to 19900 Cond: 0 to 3000 μS/cm TDS: 0 to 19999 mg/L DO: 0 to 90 mg/L	

Table 3.2. (..cont)

Name	Brand	Model	Range	Image
Analytical balance	Denver instruments	P/PI 2000	2000 g	
Oven	Fisher Scientific			
Portable turbidimeter	Hach	2100 P	0 to 1000 NTU	

3.1.2 *Methods*

Methods used in the sample analysis are shown in Table 3.3. There are three methods for determining concentration of heavy metal copper, nickel, and zincs; other methods shown are related to the work done in the laboratory like chlorine, total suspended solids, and turbidity.

Table 3.3. Methods used for sample analysis (compilation from Hach)

Table 3.3. (..cont)

Method	**Copper – Bicinchoninate Method**	
Brief Description	Copper in the sample reacts with a salt of bicinchoninic acid contained in CuVer 1 or CuVer 2. Copper Reagent to form a purple colored complex in proportion to the copper concentration. Test results are measured at 560 nm.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
8506 8026	3500	0.04 to 5 mg Cu/L

Method	**Nickel – Heptoxime Method**	
Brief Description	Nickel ion reacts with heptoxime to form a yellow-colored complex which is then extracted into chloroform to concentrate the color and enable a more sensitive determination. Chelating agents are added to the sample to overcome the interferences caused by cobalt, copper and iron. Readings are taken at 430 nm.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
8037	3500-Ni D	0.02 to 1.8 mg Ni/L

Method	**Zinc – Zincon Method**	
Brief Description	Zinc and other metals in the sample are complexed with cyanide. Adding cyclohexanone causes a selective release of zinc. The zinc reacts with 2-carboxy-2'-hydroxy-5'-sulfoformazyl benzene (zincon) indicator to form a blue-colored species. The blue color is masked by the brown color from the excess indicator. The intensity of the blue color is proportional to the amount of zinc present. Test results are measured at 620 nm.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
8009	3500 Zn – B	0.01 to 3.00 mg Zn/L

Method	**Chlorine free – DPD method**	
Brief Description	Chlorine in the sample as hypochlorous acid or hypochlorite ion (free chlorine or free available chlorine) immediately reacts with DPD (N,N-diethyl-p-phenylenediamine) indicator to form a pink color, the intensity of which is proportional to the chlorine concentration.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
8021	4500-Cl G	0.02 to 2.00 mg Cl/L

Table 3.3. (..cont)

Method	**Non filterable suspended solids – Gravimetric method**	
Brief Description	Chlorine in the sample as hypochlorous acid or hypochlorite ion (free chlorine or free available chlorine) immediately reacts with DPD (N,N-diethyl-p-phenylenediamine) indicator to form a pink color, the intensity of which is proportional to the chlorine concentration.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
8158 - 8164	2450	

Method	**Turbidity**
Brief Description	Ratio Nephelometric signal (90°) scatter light ratio to transmitted light. The optical system includes a tungsten-filament lamp, a 90° detector to monitor scattered light and a transmitted light detector. The instrument's microprocessor calculates the ratio of the signals from the 90° and transmitted light detectors. This ratio technique corrects for interferences from color and/or light absorbing materials (such as activated carbon) and compensates for fluctuations in lamp intensity, providing long-term calibration stability. The optical design also minimizes stray light, increasing measurement accuracy.
Range	0 – 1000 NTU

Method	**Oil and grease – Hexane extractable gravimetric method**	
Brief Description	Oil and Grease & Total Petroleum Hydrocarbons (TPH) include any material that may be recovered as a substance that is soluble in the n-hexane extractant. These include substances such as relatively non-volatile hydrocarbons, vegetable oils, animal fats, waxes, soaps, greases and related materials. When measuring oil and grease (HEM) gravimetrically, the substances are extracted from the sample with n-hexane, then the n-hexane is evaporated. The residue left is weighed to determine the concentration of oil and grease materials in mg/L.	
Hach Method US EPA approved	**ASTM equivalent**	**Range**
10056	5520 B	15 to 3000 mg HEM/L

3.1.3 Synthetic bilge water preparation

As mentioned before, bilge water is a complex oily emulsion with a significant amount of heavy metals. In order to prepare the oil in water emulsion, different concentrations of oil and surfactant were mixed with the lab mixer, and the emulsion was analyzed to find the optimal proportion which gives the maximum oil and grease concentration and consequently a stable emulsion. This optimal proportion was found mixing 5000 mg/L of oil with 2500 mg/L of Tween 40, as shown in Figure 3.2.

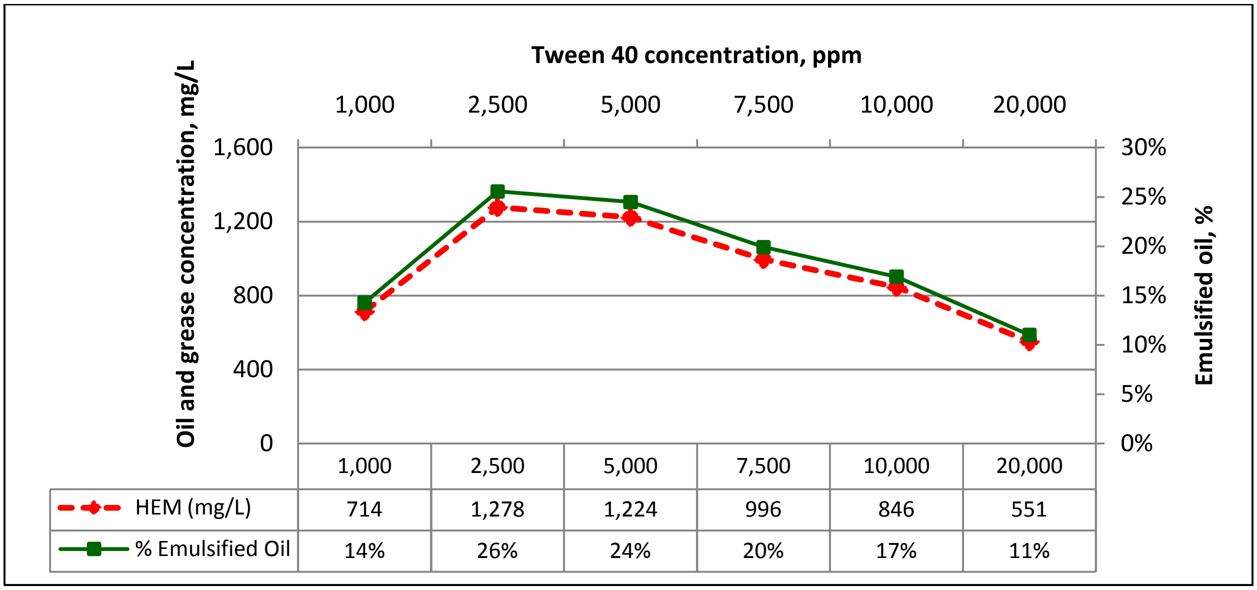


Figure 3.2. Emulsion curve with 5000 ppm of oil concentration

Having obtained the stable emulsion, 200 mg/l of paint were added in order to add colloidal particles to the emulsion and, in this way, to analyze turbidity removal efficiency. The emulsion was poured in the carboy filled with de-ionized water; the heavy metal load is mixed at this point. The heavy metal load had 5 mg/L of copper, 1.5 mg/L of nickel, and 2.5 mg/L of zinc. This procedure to prepare bilge water was followed each time the EC process was performed; the total volume of bilge water for treatment varied from 30 to 90 liters.

The electrodes were weighed before and after the treatment; due to the high rate of oxidation for the carbon steel electrodes, their surface was polished before each experiment, and the weight was measured no more than two days from the experiment date.

3.1.4 EC treatment

The EC system is shown in Figure 3.4. The bilge water is driven through the reactor by the gear pump at a controlled flow rate with the Baldor controller. The DC power supply applied a constant current to the electrodes connected in series and in up-down paths arrangement to create turbulence inside the reactor Figure 3.3.

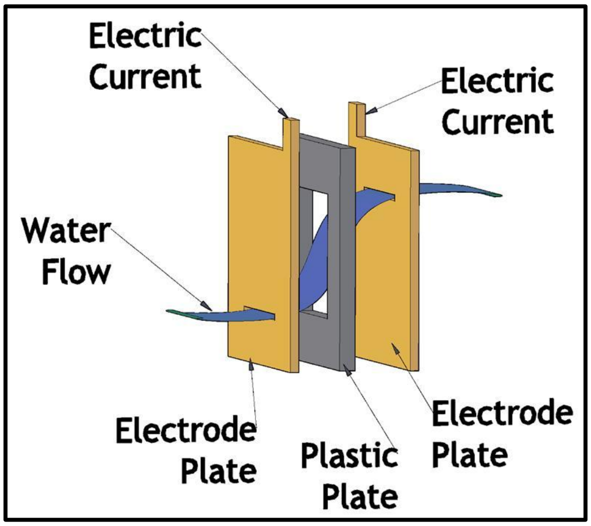


Figure 3.3. Electrode arrangement

The EC process is carried out during this time; all the reactions at the electrodes and in the wastewater stream should be complete. The effluent was conveyed to the conic clarifier where the pressure is released and the hydrogen bubbles raised towards the surface. After 10 minutes, the effluent in the conic clarifier was either extracted or put back to the reactor (effluent recycling) depending on the type of treatment; the 10 minutes period was considered sufficient for solid-liquid separation. Samples were taken from each effluent, after 10 minutes, for their respective analysis and an additional sample of the raw water was also collected.

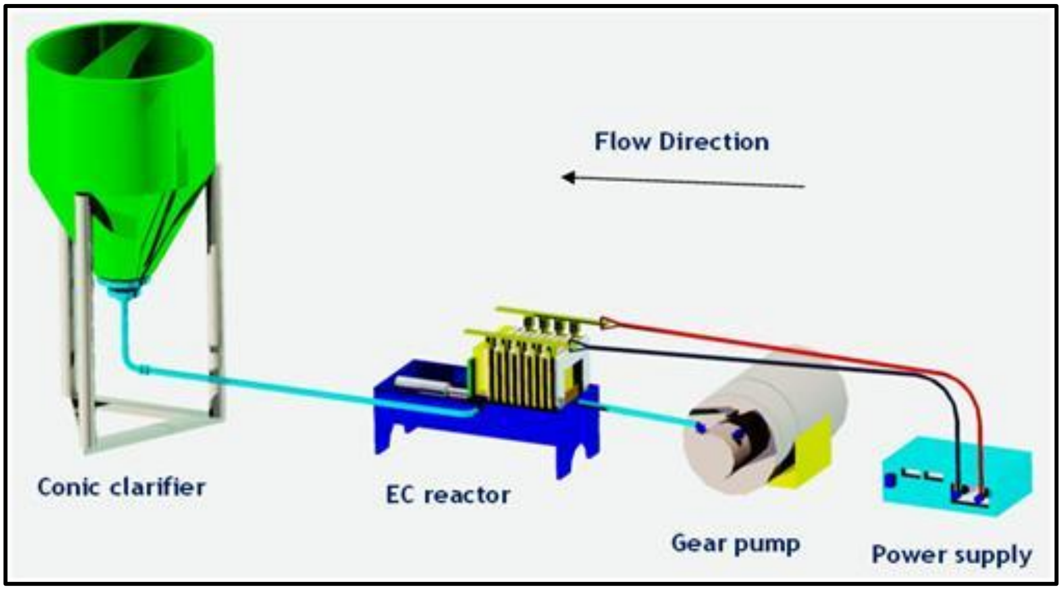


Figure 3.4. EC treatment system

3.1.4.1 Flow rate control

The flow rate was controlled with the Baldor controller that gives the pump frequencies up to 200 Hz. EC experiments were done either at 1 or 0.5 L/min; a calibration was made due to both the density of the influent and the shape configuration of the reactor. Figure 3.5 shows the calibration made with 1 liter of pumped water at different frequencies; therefore, 1 L/min of flow rate was obtained at 12.8 Hz; and 0.5 L/min, at 7.5 Hz.

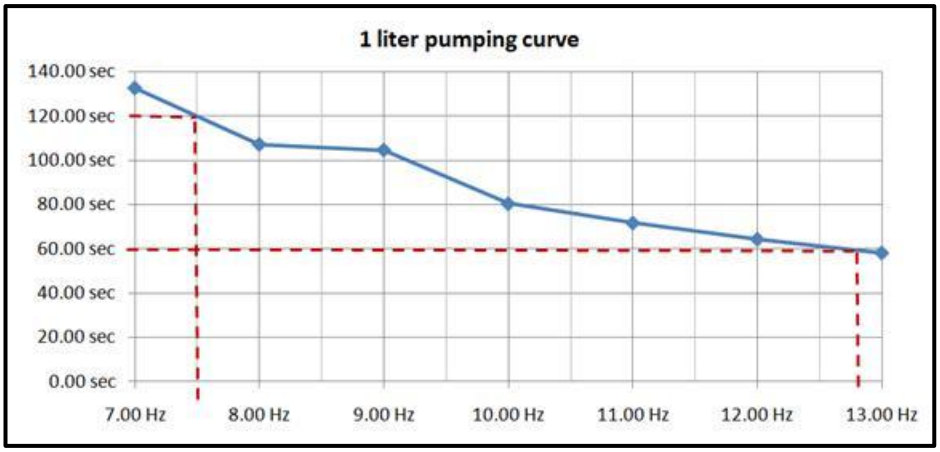
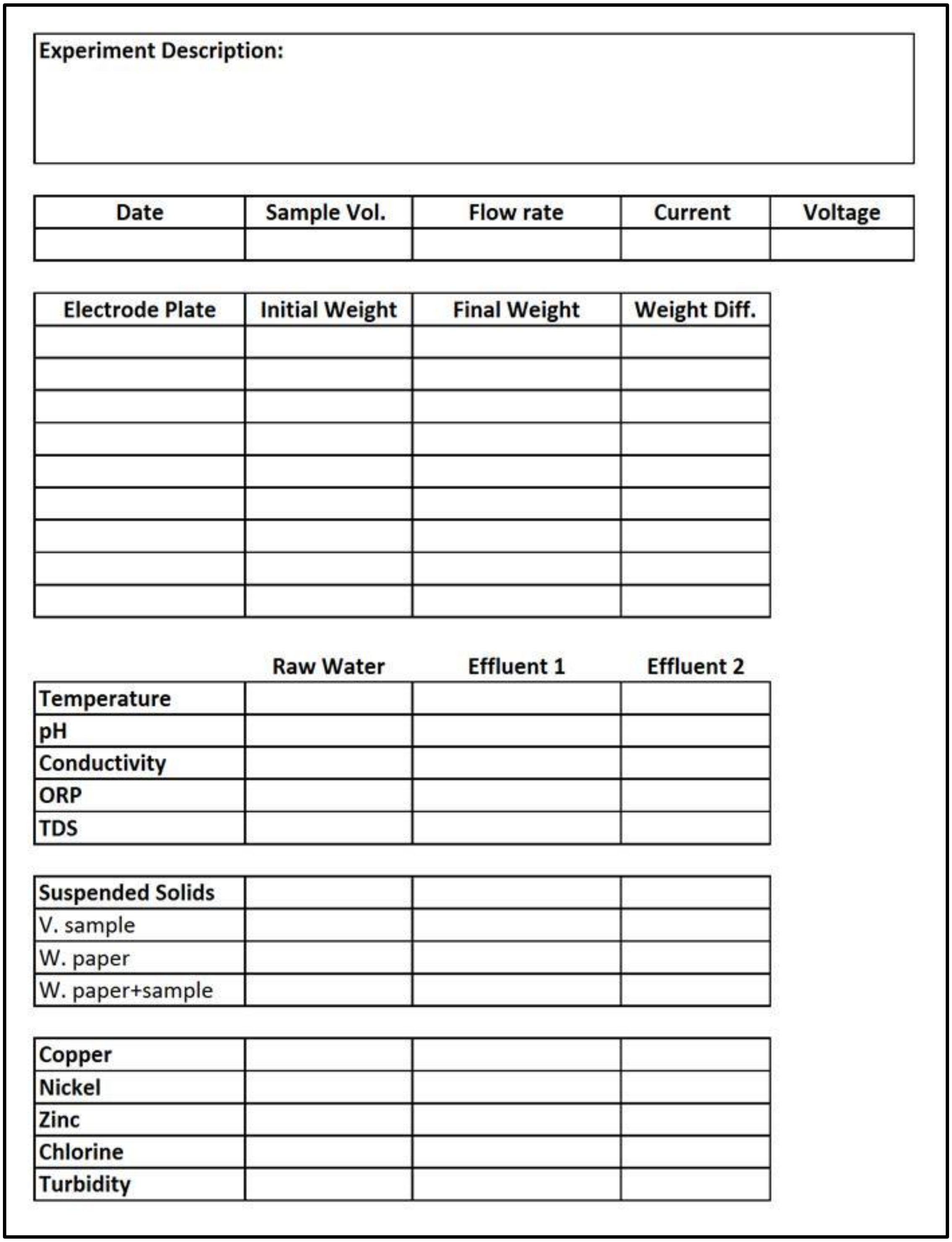


Figure 3.5. Pump calibration line for 1 liter of de-ionized water

3.1.5 Sample analysis

Samples were carried to the laboratory and were analyzed the same day. Samples analyzed on different days were digested following the procedure for each metal to be analyzed. Figure 3.6 shows the form used to record the different parameters measured in each experiment.



Experiment Description:

Date	Sample Vol.	Flow rate	Current	Voltage

Electrode Plate	Initial Weight	Final Weight	Weight Diff.

	Raw Water	Effluent 1	Effluent 2
Temperature			
pH			
Conductivity			
ORP			
TDS			

Suspended Solids			
V. sample			
W. paper			
W. paper+sample			

Copper			
Nickel			
Zinc			
Chlorine			
Turbidity			

Figure 3.6. Lab experiment format

Each parameter was determined following the respective procedure as presented in Table 3.3. Special attention was given to the glassware: First, it was washed with tap water, and then it was submerged for more than one hour in an acidic solution (1.3 M HCl). After that, the glassware was washed with de-ionized water in two passes to rinse the acid and let dry at room temperature.

Figure 3.7. Glassware drying at room temperature

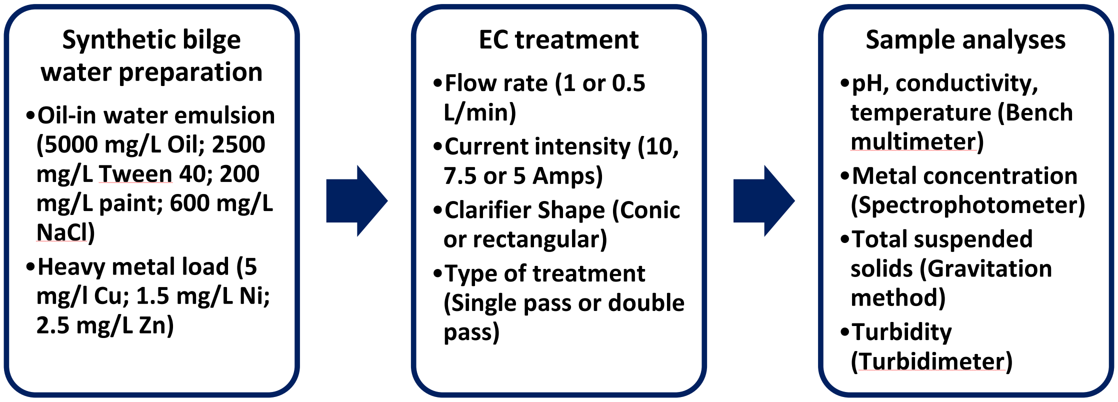
3.1.6 EC treatment experiments

Several experiments were performed in order to obtain the best contaminant removal efficiency at the lowest energy consumption and operation costs. Table 3.4 shows a summary of the experiments with the controlled parameters. The experiment S5 was repeated in S7 because the rust layer formation over the iron electrode surface and the need to confirm the results. The methodology used in the EC experiments is presented in the process diagram, Figure 3.8.

Table 3.4. EC experiments

ID	Date	Electrode	Current (A)	Flow rate (L/min)	Effluent Recycling	Clarifier
S1	3/20/2009	Al	10	1	✓	Conic
S2	3/24/2009	Al	10	0.5	✗	Conic
S3	3/26/2009	Cs	10	0.5	✗	Rectangular
S4	6/30/2009	Cs & Al	10	0.5	✗	Rectangular
S5*	7/9/2009	Cs & Al	10	1	✓	Conic
S6	9/27/2009	Cs & Al	5	1	✓	Conic
S7*	10/11/2009	Cs & Al	10	1	✓	Conic
S8	10/20/2009	Cs & Al	7.5	1	✓	Conic

Al = Aluminum; Cs = Carbon steel



Synthetic bilge water preparation

- Oil-in water emulsion (5000 mg/L Oil; 2500 mg/L Tween 40; 200 mg/L paint; 600 mg/L NaCl)
- Heavy metal load (5 mg/l Cu; 1.5 mg/L Ni; 2.5 mg/L Zn)

EC treatment

- Flow rate (1 or 0.5 L/min)
- Current intensity (10, 7.5 or 5 Amps)
- Clarifier Shape (Conic or rectangular)
- Type of treatment (Single pass or double pass)

Sample analyses

- pH, conductivity, temperature (Bench multimeter)
- Metal concentration (Spectrophotometer)
- Total suspended solids (Gravitation method)
- Turbidity (Turbidimeter)

Figure 3.8. Process diagram for EC experiments

4 Results and Discussion

4.1 Results

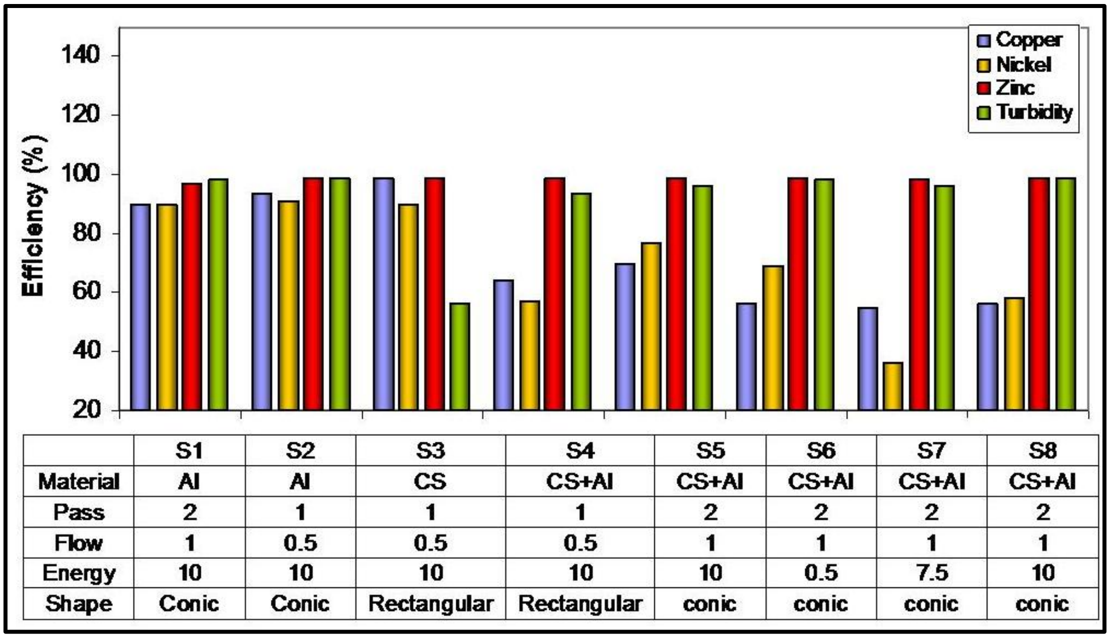
Data obtained from sample analysis include metal removal efficiency, specific energy consumption, dissolved metal concentration and operation costs. Sample identification is detailed in Table 3.4 and summarized in Table 4.1.

Table 4.1. Sample Ids with a brief description

ID	EC Process Description
S1	Aluminum, 2 passes, 1 L/min, 10 amps
S2	Aluminum, 0.5 L/min, 10 amps
S3	Carbon Steel, 0.5 L/min, 10 amps
S4	Carbon Steel & Aluminum, 0.5 L/min, 10 amps
S5	Carbon Steel & Aluminum, 2 passes overall, 1 L/min, 10 amps
S6	Carbon Steel & Aluminum, 2 passes Overall, 1 L/min, 0.5 Amps
S7	Carbon Steel & Aluminum, 2 passes Overall, 1 L/min, 7.5 Amps
S8	Carbon Steel & Aluminum, 2 passes Overall, 1 L/min, 10 Amps

4.1.1 Removal efficiency

Heavy metal removal efficiency was determined in each experiment, with different values of removal efficiency, as shown in Figure 4.1, and detailed in Table 4.2.



	S1	S2	S3	S4	S5	S6	S7	S8
Material	Al	Al	CS	CS+Al	CS+Al	CS+Al	CS+Al	CS+Al
Pass	2	1	1	1	2	2	2	2
Flow	1	0.5	0.5	0.5	1	1	1	1
Energy	10	10	10	10	10	0.5	7.5	10
Shape	Conic	Conic	Rectangular	Rectangular	conic	conic	conic	conic

Figure 4.1. Heavy metal removal efficiency with different EC operation

Table 4.2. Value of removal efficiency in each EC experiment

	S1	S2	S3	S4	S5	S6	S8	S7
Copper	91.6%	95.2%	99.2%	64.4%	69.6%	54.8%	54.4%	54.8%
Nickel	92.0%	92.7%	92.7%	56.0%	76.0%	67.3%	34.7%	58.7%
Zinc	98.0%	99.6%	99.6%	99.2%	99.6%	99.6%	99.6%	99.6%
Turbidity	99.7%	99.6%	56.0%	94.5%	98.5%	98.4%	96.4%	98.4%

Figure 4.2 shows the removal efficiency as a function of the current density (i), determined as the ratio between current intensity (I) and cross-sectional area (A_X) of the electrode. (A_X = 17.8 x 0.7 cm = 12.46 cm^2)

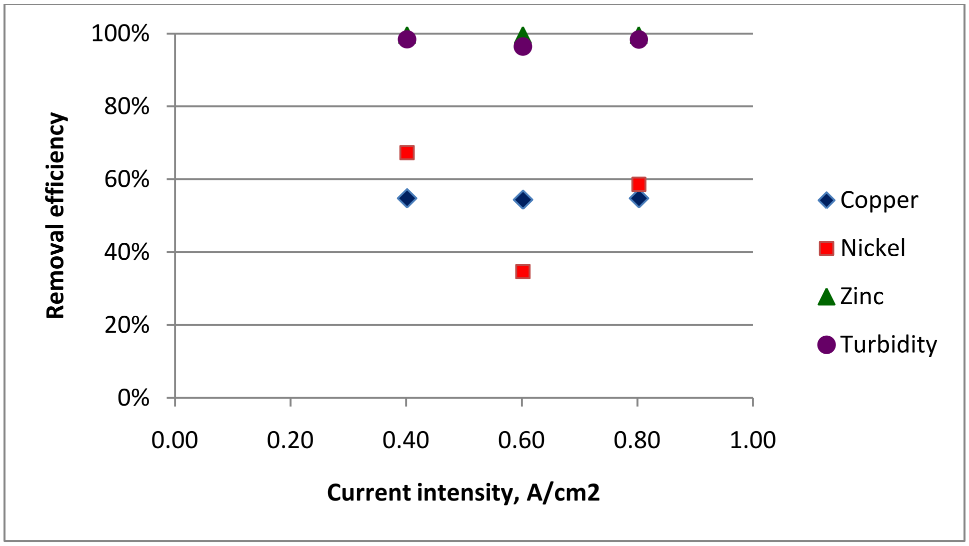


Figure 4.2. Heavy metal removal efficiency for different current intensities

4.1.2 Specific energy consumption (SEC)

Specific energy consumption (SEC) was determined as the relationship between voltage (U), current intensity (I), operation time (t) and mass of contaminant removed(m),

$$SEC\left[\frac{kwh}{g}\right]=\frac{U\times I\times t}{m_{removed}} \tag{22}$$

As SEC was linked to the operation cost, the numerator corresponds to the total energy consumption, which is the sum of energy used by the DC power supply and the pump. According to the respective manufacturers, the DC power supply has a 70% of efficiency when using the public network voltage, 115 V average, and the power used by the pump is 0.58 kw; hence, the SEC was calculated with the following equation,

$$SEC\left[\frac{kwh}{g}\right]=\frac{\left(U\times I\times t\right)_{pump}+\left(U\times I\times t\right)_{DCps}}{m_{removed}} \tag{23}$$

Figure 4.3 shows the SEC for each contaminant. As the power consumption is the same for all the contaminants, the observed variation in SEC was due for the changes in mass removed.

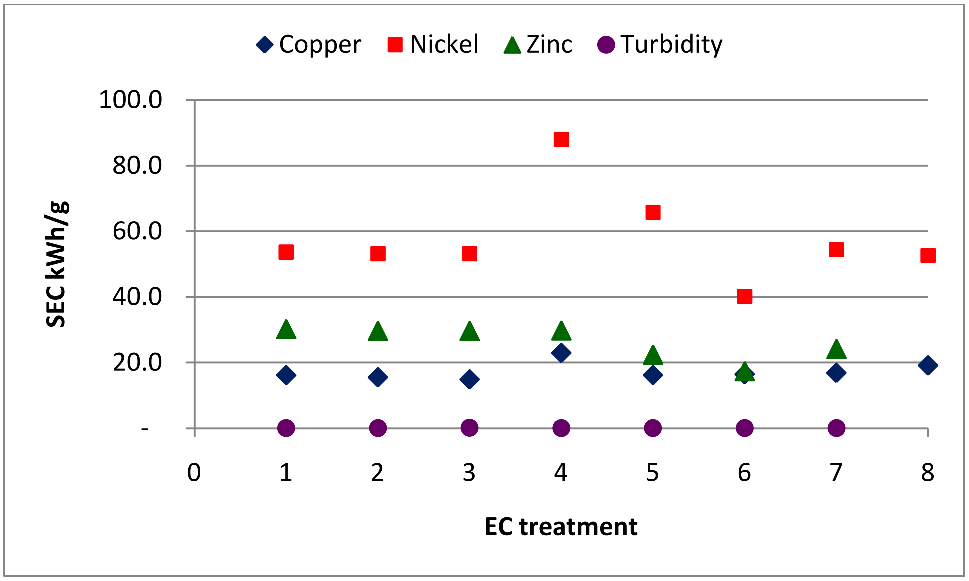


Figure 4.3. SEC for each contaminant

4.1.3 Dissolved metal concentration

The dissolved metal concentration (DMC) was calculated as the difference in mass of the electrodes divided by the total treated volume. EC treatment with recycling used two sets of electrodes, one for each cycle, therefore each cycle had its own DMC, and the total value is the sum of the value calculated for each cycle. Experiments S1 and S2 were developed using aluminum electrodes and S3 was developed using carbon steel electrodes. Experiments with combined electrodes were arranged with 7 electrodes of carbon steel and 2 final electrodes of aluminum. Figure 4.4 shows the DMC by type of treatment, the values obtained range from 125 to 443 mg/L for aluminum electrodes, and 137 to 291 mg/L for carbon steel electrodes. For presentation purposes, the DMC for each electrode is shown in the same chart.

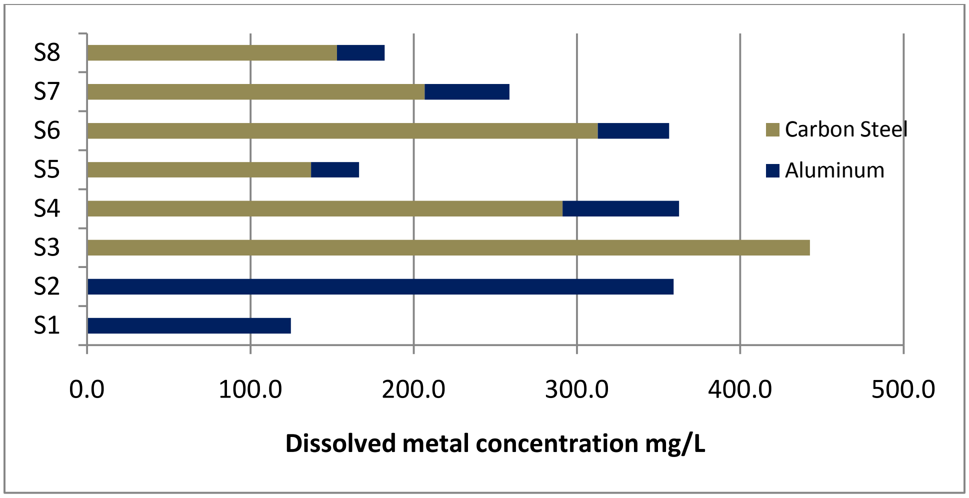


Figure 4.4. Dissolved metal concentration for each EC treatment

4.1.4 Operating costs

Operating costs were estimated as the cost by kWh for the electrical public network, given by the power provider, times the total power consumed and the cost of the electrode dissolved in each treatment. The power consumed by treatment iss the sum of the power used by the pump and the DC power supply.

$$Cost_{energy} = Cost\ energy\left[\frac{\$}{kwh}\right] \times E_{tot}\left[kwh\right] = Cost\ energy\left[\frac{\$}{kwh}\right] \times \left(E_{pump} + E_{DCpower}\right)\left[kwh\right] \quad (24)$$

The power consumed by the DC power supply was calculated using a manufacturer efficiency of 70%, and average electrical public network voltage of 115 V; current intensity (I) was 10 amps in most of the experiment but varied experiments S6 and S8; the DC power supply's manufacturer indicated that current intensity displayed in the machine can be used as the total current intensity value consumed for the treatment; the operation time (t) depended on the flow rate and the total volume treated.

$$E_{DCpower} = \frac{U \times I \times t}{efficiency}\text{, } kwh \quad (25)$$

$$E_{pump} = W_{pump} \times t\text{, } kwh \quad (26)$$

The electrode cost was calculated using the volume of dissolved electrode by treatment. The data given was the cost of each electrode per cubic meter, the electrode density and the mass of consumed electrode.

$$Cost_{electrode} = Cost\ electrode\left[\frac{\$}{m^3}\right] \times \frac{1}{Density}\left[\frac{m^3}{kg}\right] \times mass\ dissolved\left[kg\right] \tag{27}$$

Table 4.3 summarizes the information used to calculate the operating costs.

Table 4.3. Value of constant parameters used in operation costs

Parameter	Value	Reference
Cost of energy	0.02 $/kWh	(Entergy n.d.)
Cost of electrode Carbon steel Aluminum	 2.275 $/electrode 3.575 $/electrode	Ecolotron Proposal No. 08081001
Electrode volume (average)	5.61x104 m3	Value measured for each electrode
Electrode density (average) Carbon steel Aluminum	 27358.21 kg/m^3 1023.05 kg/m^3	Value calculated for each electrode
DC power supply efficiency	70%	BK Precission
Power used by the pump	0.58 kw	Baldor

Figure 4.5 shows the operation costs of EC treatment. Even when the EC treatments were dissimilar and impossible to compare, these values were presented as individual cost in order to understand the influence of each parameter in the total cost.

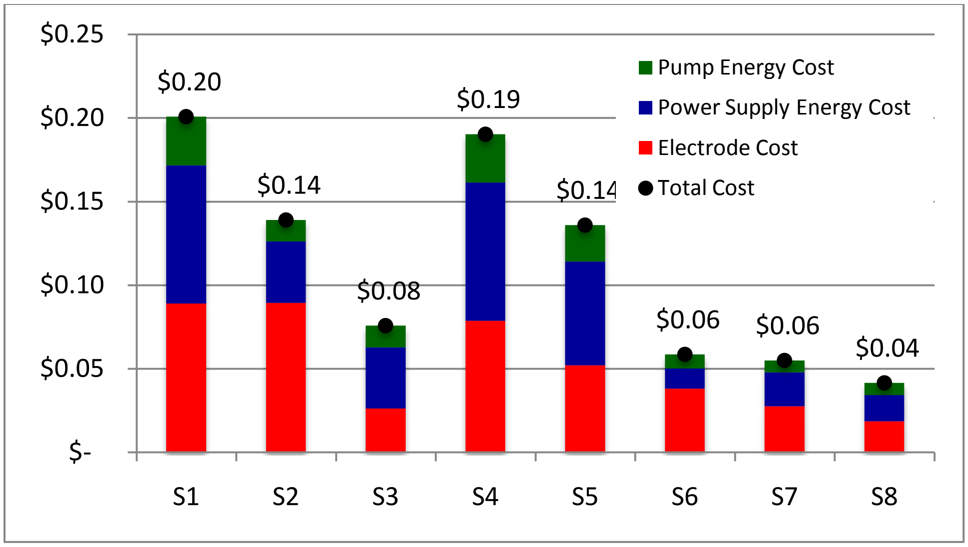
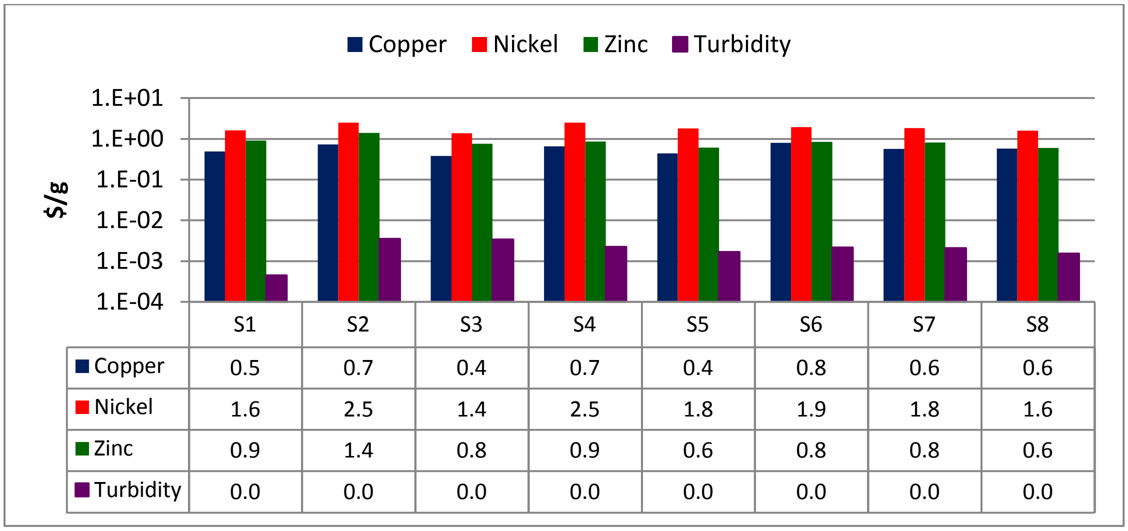


Figure 4.5. Operating costs for each EC treatment

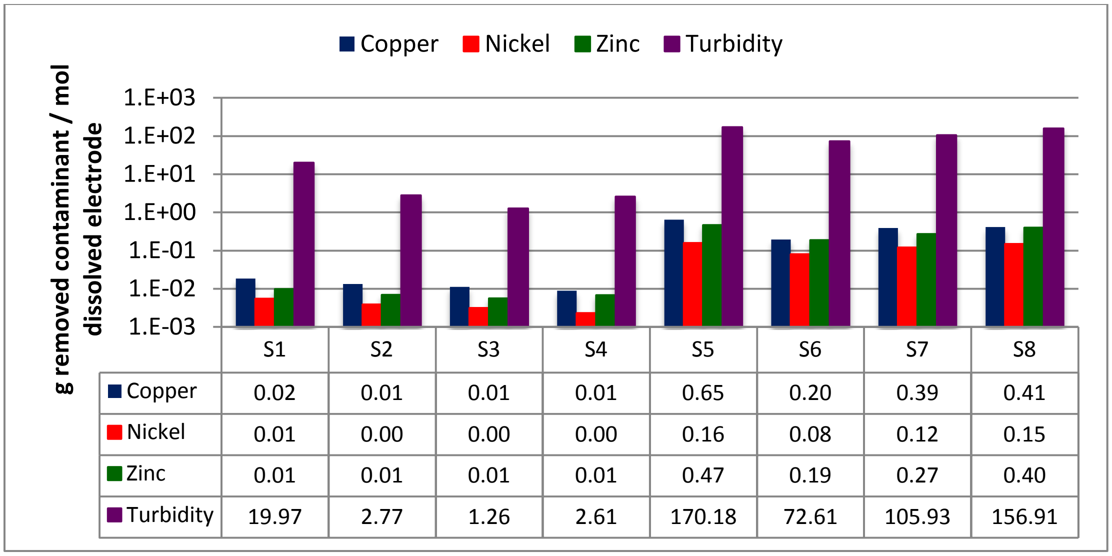
4.1.5 Mass of contaminant removed

The mass of contaminant removed was related to the total cost, and this relation is presented in Figure 4.6. Also, a relation with the mass of dissolved electrode, expressed in moles, is presented in Figure 4.7. Because combined electrodes were used in some experiments, the dissolved mass was converted to moles, so that the sum of total dissolved electrode can be calculated.



	S1	S2	S3	S4	S5	S6	S7	S8
🟦 Copper	0.5	0.7	0.4	0.7	0.4	0.8	0.6	0.6
🟥 Nickel	1.6	2.5	1.4	2.5	1.8	1.9	1.8	1.6
🟩 Zinc	0.9	1.4	0.8	0.9	0.6	0.8	0.8	0.6
🟪 Turbidity	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 4.6. Cost per gram of removed contaminant for each EC treatment.



	S1	S2	S3	S4	S5	S6	S7	S8
🟦 Copper	0.02	0.01	0.01	0.01	0.65	0.20	0.39	0.41
🟥 Nickel	0.01	0.00	0.00	0.00	0.16	0.08	0.12	0.15
🟩 Zinc	0.01	0.01	0.01	0.01	0.47	0.19	0.27	0.40
🟪 Turbidity	19.97	2.77	1.26	2.61	170.18	72.61	105.93	156.91

Figure 4.7. Mass of removed contaminant per mol of dissolved electrode

4.2 Discussion

Experiments S3 achieved the highest general removal efficiencies for each heavy metal. The results show that zinc and turbidity could be removed by EC independent of the type of treatment with an average removal efficiency of 99% and 93% respectively. Nickel and copper appeared harder to remove, achieving removal efficiency around 71 and 73% on average for each one.

The specific energy consumption presents the same trend: nickel has the higher value, requiring an average of 57 kwh to remove 1 gram. Copper and zinc have similar SEC, 17 and 25 kwh/g.

Even though experiments S3 and S5 show better and similar performances, those can be compared with their DMC values. S3 (only carbon steel electrode at 0.5 l/min of flow rate) shows the largest DMC, 443 mg/L, compared to 137 mg/L of DMC for S5 (combined electrodes, flow rate 1 L/min, effluent recycling). Comparing them in terms of operation costs, S3 has lower value than S5 - $0.08 and $0.14.

The analysis of cost per gram of removed contaminant confirms that nickel needs an enhanced EC treatment; it has the largest value with respect to the rest of heavy metals with an average of 1.95 $/g removed. On the other hand, zinc and copper have similar values, 0.60 and 0.88 $/g, and the turbidity has an average cost of 0.002 $/g.

An additional analysis was done relating the mass of removed contaminant to the moles of dissolved electrode. This analysis indicates the contaminant removal efficiency of each mol of the electrode. Comparing S3 and S5, the combination of Al and CS electrodes have higher removal efficiencies than the use of CS electrodes.

Experiment S5 achieved the optimal configuration EC process, therefore experiments S6, S7 and S8 were done using this configuration. To find the optimal application of current intensity S6, S7, and S8 were done using 0.5, 10 and 7.5 amps, respectively. For this type of EC treatment configuration, the current density does not have significant incidence in removal efficiency.

The experiments performed with the EC reactor demonstrated that flotation by hydrogen bubbles is an important component of this technology. Therefore, flotation optimization is needed to achieve better metal removal efficiency. Table 4.2 demonstrates that the best turbidity removal efficiency was consistently achieved using the conic clarifier. However, the best turbidity removal was not always associated with best metal removal.

For instance, experiment S3 (rectangular clarifier, no effluent recycling, carbon steel electrodes) had the lowest turbidity removal and the highest metal removal.

On the other hand, Figure 4.5 shows that the runs using a conical clarifier (S6, S7 and S8) were consistently more economical than those with rectangular clarifier.

5 Conclusions and recommendations

5.1 Conclusions

- For heavy metal removal, the configuration of the EC treatment using combined electrodes, aluminum and carbon steel; flow rate of 1 L/min; effluent recycling; and 7.5 amps, has good performance for zinc with 99% removal efficiency. Copper and nickel are hard to remove: they achieved an efficiency of 70%; thus, they require enhanced methods, like the addition of a base to raise the pH after the EC reactor.

- Current intensity does not have significant incidence on the removal efficiency using this type of reactor. The combination of electrode materials resulted in higher efficiency and lower costs.

- The optimal configuration for EC treatment has low operation costs compared with the rest of EC treatments. Power supply and electrode cost represent 60% of the total cost for the optimal configuration; therefore, a special control of these parameters is needed in order to decrease the costs. Nickel has the highest cost in this EC treatment; it requires $1.95 per gram to be removed.

5.2 Recommendations

- It is necessary to develop additional experiments with the EC reactor in order to optimize metal removal efficiency. These experiments could include the use of electroflotation as a final process, the addition of chemicals to the EC reactor effluent to enhance metal precipitation, and the modification in the arrangement of the electrodes to change the flow path.

- Operational problems were found with the carbon steel electrodes due to the passivated layer and the corresponding decrease in oxidation during EC. Giving special attention to the electrodes is recommended.

- Metals tend to adhere to the glassware surface and can increase the metal concentration during the sample analyzing. Complete cleaning with acid and de-ionized water is recommended.

6 Bibliography

Alaska Department of Environmental Conservation. "Alaska Cruise Ship Initiative Part 1 Final Report." Alaska Department of Environmental Conservation (ADEC), Juneau, AK, 2000.

Asselin, Mélanie, Patrick Drogui, Satinder Kaur Brar, Hamel Benmoussa, and Jean-Francois Blais. "Organics removal in oily bilge water by electrocoagulation process." *Journal of Hazardous Materials* (Elsevier B.V.) 151, no. 2-3 (March 2008): 446-455.

Bensadok, K., S. Benammar, F. Lapicque, and G. Nezzal. "Electrocoagulation of cutting oil emulsions using aluminium plate electrodes." *Journal of Hazardous Materials* 152, no. 1 (2008): 423-430.

Chen, Guohua. "Electrochemical technologies in wastewater treatment." *Separation and Purification Techonology* (Elsevier B.V.) 38, no. 1 (2004): 11-41.

Chen, X. M., G. Chen, and P.L. Yue. "Separation of pollutants from restaurant wastewater by electrocoagulation." *Separation and Purification Technology* (Elsevier Science) 19, no. 1-2 (2000): 65-76.

Chen, Xueming, Guohua Chen, and Po Lock Yue. "Electrocoagulation and electroflotation of restaurant wastewater." *Journal of Environmental Engineering* (ASCE) 126, no. 9 (September 2000): 858-863.

Chen, Xueming, Guohua Chen, and Po Lock Yue. "Investigation on the electrolysis voltage of electrocoagulation." *Chemical Engineering Sciences* (Elsevier) 57, no. 13 (July 2002): 2449-2455.

Entergy. "Business High Voltage Service." *Entergy.* http://www.entergy-neworleans.com/your_business/tariffs.aspx (accessed June 3, 2009).

EPA. *National Recommended Water Quality Criteria.* June 24, 2009. http://www.epa.gov/waterscience/criteria/wqctable/index.html (accessed August 17, 2009).

EPA. "Uniform National Discharge Standards for Vessels of the Armed Forces." Thecnical Development Document, Environmental Protection Agency, 1999.

Gomes, Jewel A.G., et al. "Arsenic removal by electrocoagulation using combined Al-Fe electrode systems and characterization of products." *Journal of Hazardous Materials* (Elsevier Scientific Pub. Co.) 2, no. 139 (1 2007): 220-231.

Heidmann, Ilona, and Wolfgang Camano. "Removal of Zn(II), Cu(II), Ni(II), Ag(I) and Cr(VI) present in aqeuos solutions by aluminium electrocoagulation." Edited by Elsevier B.V. *Journal of Hazardous Materials*, no. 152 (2008): 931-941.

Huhnsom, M., K. Pruksathorn, S. Damronglerd, H. Vergnes, and P. Duverneuil. "Electrochemical treatment of heavy metals (Cu2+, Cr6+, Ni2+) from industrial effluent and modeling of copper reduction." *Water Res.* 39, no. 4 (2005): 610-606.

Join Systems, Inc. *Environmental Facilities: Bilge Treatment System*. 2005. http://www.join.co.kr/Environmental%20Facilities/index_4.html (accessed August 14, 2009).

Kabdaşli, Işik, Tülin Arslan, Tuğba Ölmez-Hanci, Idil Arslan-Alaton, and Olcay Tünay. "Complexing agent and heavy metal removals from metal platting effluents by electrocoagulation with stainless steel electrodes." *Journal of Hazardous Materials*, no. 165 (2009): 838-845.

Khella, Kalpana, Bhawna Verma, Vimal C. Srivastava, and Kaushal K. Srivastava. "Electrocoagulation study for the removal of arsenic and chromium from aqueous solution." *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering* (Taylor and Francis Group) 43, no. 5 (April 2008): 554-562.

Kobya, Mehmet, Orhan Taner Can, and Mahmut Bayramoglu. "Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes." *Journal of Hazardous Materials* (Elsevier Science B.V.) 100, no. 1-3 (June 2003): 163-178.

MARPOL. "International convention for the prevention of the pollution from the ships." International Maritime Organization, London, 1973.

Merzouk, B., B. Gourich, A. Sekki, K. Madani, and M. Chibane. "Removal turbidity and separation of heavy metals using electrocoagulation - electroflotation technique." *Journal of Hazardous Materials* (Elsevier B.V.) 164 (2009): 215-222.

Mollah, Mohammad Y.A., et al. "Treatment of orange II azo-dye by electrocoagulation (EC) technique in a continous flow cell using sacrificial iron electrodes." *Journal of Hazardou Materials* (Elsevier Scientific Pub. Co.) 109, no. 1-3 (June 2004): 165-171.

Mollah, Mohammad Y.A., Paul Morkovsky, Jewel A.G. Gomes, Mehmet Kesmez, José Parga, and David L. Cocke. "Fundamentals, present and future perspectives of electrocoagulation." *Journal of Hazardous Materials* (Elesevier Scientific Pub. Co.) 114, no. 1-3 (2004): 199-210.

Moreno, Hector A., et al. "Electrochemical Reactions for Electrocoagulation Using Iron Electrodes." *Industrial & Engineering Chemistry Research* 48, no. 4 (2009): 2275-2282.

Ogutveren, Ulker Bakir, and Savas Koparal. "Electrocoagulation for oil-water emulsion treatment." *Journal of Environmental Science and Health* 32, no. 9 & 10 (1997): 2507-2520.

Oldham, Heith B., and Jan C. Myland. *Fundamentals of Electrochemical Science*. Peterborough, Ontario: Academic Press, Inc, 1994.

Parga, Jose R., et al. "Arsenic removal via electrocoagulation from heavy metal contaminated groundwater in La Comarca Lagunera Mexico." *Journal of Hazardous Materials* B124 (2005): 247-254.

Pulido, Maria Elena, and Enrique J. La Motta. "Heavy metal removal from shipyard storm water runoff by electrochemical treatment." PhD Tesis, Deparment of Civil and Environmental Engineering, University of New Orleans, New Orleans, 2001.

Thella, Kalpana, Bhawna Verma, Vimal C. Srivastava, and Kaushal K. Srivastava. "Electrocoagulation study for the removal of arsenic and chromium from aqueous solution." *Journal of Environmental Science and Health Part A: Toxic/Hazardous Substances & Environmental Engineering* 43, no. 5 (April 2008): 554-562.

U.S. Environmental Protection Agency. "Cruise ship discharge assessment report." Oceans and Coastal Protection Division. Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency (EPA), USA, 2008.

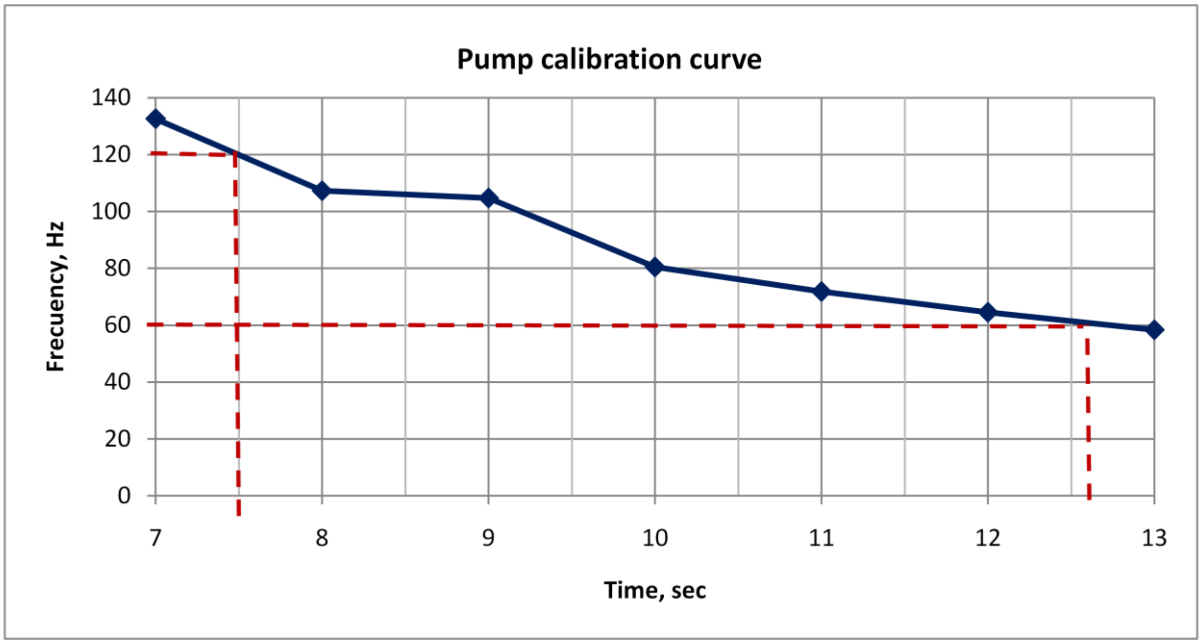
Vasudevan, Subramanyan, Jeganathan Jayaraj, Jothinathan Lakshmi, and Ganapathy Sozhan. "Removal of iron from drinking water by electrocoagulation: adsorption and kinetic studies." *Korean Journal of Chemical Engineering* (Springer New York) 26, no. 4 (July 2009): 1058-1064.

Yang, Chen-Lu. "Electrochemical coagulation for oily water demulsification." *Separation and Purification Technology* 54 (2007): 388-395.

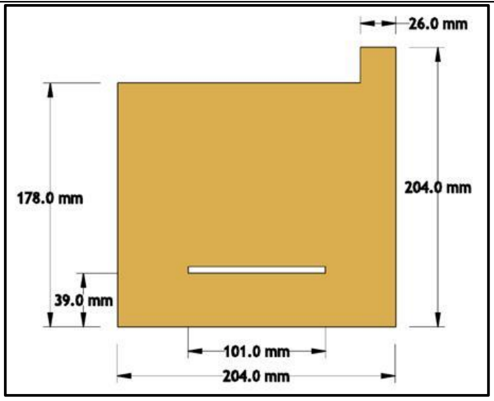
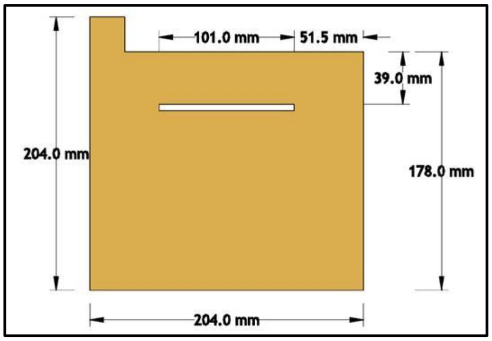
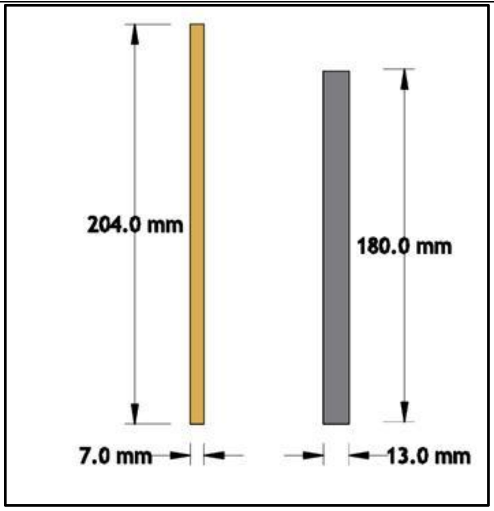
Appendices

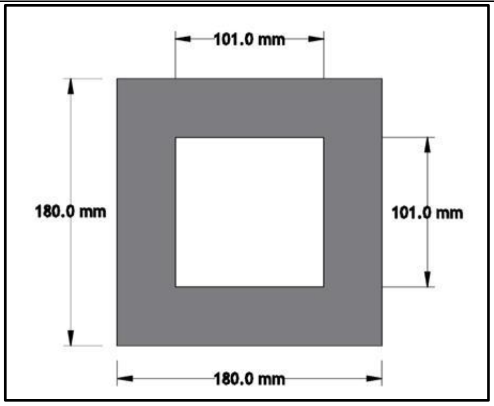
Appendix A: Pump calibration curve

HZ	RPM	t sec	min	sec	
7.00 Hz	208	132.60 sec	2	12	36
8.00 Hz	237	107.25	1	47	15
9.00 Hz	237	104.72	1	44	43
10.00 Hz	297	80.47	1	20	28
11.00 Hz	327	71.82	1	11	49
12.00 Hz	356	64.53	1	4	32
13.00 Hz	386	58.37	0	58	22



Appendix B: Electrode geometric shape

Electrode plate area	36483 **mm2** 364.83 **cm2** 3.65 x10^{-2} **m2**	 
Electrode cross section area	1428 **mm2** 14.28 **cm2** 1.43 x 10^{-3} **m2**	

Plastic plate gray area	22199 **mm2** 221.99 **cm2** 2.22×10^{-2} **m2**	
Chamber volume *Volume of blank area*	132613 **mm3** 132.61 **cm3** 1.33×10^{-4} **m3** 0.13 **liters**	

Appendix C: Electrode density

Volume 561134 mm^3
0.000561 m^3

Electrode	**Aluminum**				
	W1 (g)	**D1 (kg/m3)**	**W2 (g)**	**D2 (kg/m3)**	**Avg Density (kg/m3)**
A1	575.62	1025.82	575.52	1025.64	1025.73
A2	579.98	1033.59	578.95	1031.75	1032.67
A3	564.52	1006.03	563.75	1004.66	1005.35
A4	576.23	1026.90	575.45	1025.51	1026.21
A5	564	1005.11	563.26	1003.79	1004.45
A6	563.78	1004.72	562.89	1003.13	1003.92
A7	566.86	1010.20	565.94	1008.56	1009.38
A8	565.43	1007.66	564.01	1005.13	1006.39
A9	568.75	1013.57	567.97	1012.18	1012.88
Aluminum Average Density			1023.05	**Kg/m3**	

Electrode	**Carbon Steel**				
	W1 (g)	**D1 (kg/m3)**	**W2 (g)**	**D2 (kg/m3)**	**Avg Density (kg/m3)**
CS1	1530.76	2727.98	1530.7	2727.87	2727.92
CS2	1543.12	2750.00	1540.61	2745.53	2747.77
CS3	1530.05	2726.71	1528.35	2723.68	2725.20
CS4	1541.46	2747.04	1538.81	2742.32	2744.68
CS5	1538.66	2742.05	1536.79	2738.72	2740.39
CS6	1538.65	2742.04	1536.15	2737.58	2739.81
CS7	1534.7	2735.00	1532.61	2731.27	2733.14
CS8	1542.02	2748.04	1539.48	2743.52	2745.78
CS9	1537.98	2740.84	1536.19	2737.65	2739.25
Carbon Steel Average Density			2738.21	**Kg/m3**	

Appendix D: Electrode and energy costs

Electrode	$/40 electrodes	$/electrode	Volume (m3)	$/m3
Carbon Steel	91	2.275	5.61E-04	4054.29
Aluminum	143	3.575	5.61E-04	6371.03
Note: Values taken from Ecolotron Proposal No. 08081001				

Cost of energy	
kWh	$ 0.01676
Note: From Entergy, Business High Voltage Service, http://www.entergy-neworleans.com/your_business/tariffs.aspx	

Appendix E: Emulsion tests

Oil concentration: 2,500 ppm

Sample ID	1	**Date**	Thursday, January 15, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	5	**g**	10,000.00	**ppm**
Emulsion Sample	226	**ml**	430	**ml**
	204	**ml**		
Weight				
Dish	6.3481	**g**		
Dish + HEM	6.5982	**g**		
HEM	0.2501	**g**	23%	**emulsified Oil**
HEM Concentration	0.000582	**g/ml**	581.63	**mg/L**

Sample ID	2	**Date**	Thursday, January 15, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	1.25	**g**	2,500.00	**ppm**
Emulsion Sample	188	**ml**	372	**ml**
	184	**ml**		
Weight				
Dish	6.3312	**g**		
Dish + HEM	6.6046	**g**		
HEM	0.2734	**g**	29%	**emulsified Oil**
HEM Concentration	0.000735	**g/ml**	734.95	**mg/L**

Sample ID	3	**Date**	Friday, January 16, 2009	
Water	500	**ml**		
Oil	1.27	**g**	2,540.00	**ppm**
Tween 40	1.26	**g**	2,520.00	**ppm**

Emulsion Sample	188	**ml**	432	**ml**
	244	**ml**		
Weight				
Dish	6.3292	**g**		
Dish + HEM	6.6465	**g**		
HEM	0.3173	**g**	29%	**emulsified Oil**
HEM Concentration	0.000734	**g/ml**	734.49	**mg/L**

Sample ID	4	**Date**	Friday, January 16, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	0.5	**g**	1,000.00	**ppm**
Emulsion Sample	212	**ml**	410	**ml**
	198	**ml**		
Weight				
Dish	6.2619	**g**		
Dish + HEM	6.4248	**g**		
HEM	0.1629	**g**	16%	**emulsified Oil**
HEM Concentration	0.000397	**g/ml**	397.32	**mg/L**

Sample ID	5	**Date**	Sunday, January 18, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	1.25	**g**	2,500.00	**ppm**
Emulsion Sample	208	**ml**	369	**ml**
	161	**ml**		
Weight				
Dish	6.3333	**g**		
Dish + HEM	6.4193	**g**		
HEM	0.086	**g**	9%	**emulsified Oil**
HEM Concentration	0.000233	**g/ml**	233.06	**mg/L**

Sample ID	6	**Date**	Monday, January 19, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	2.5	**g**	5,000.00	**ppm**
Emulsion Sample	198	**ml**	370	**ml**
	172	**ml**		
Weight				
Dish	6.3321	**g**		
Dish + HEM	6.6153	**g**		
HEM	0.2832	**g**	31%	**emulsified Oil**
HEM Concentration	0.000765	**g/ml**	765.41	**mg/L**

Sample ID	7	**Date**	Monday, January 19, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	3.75	**g**	7,500.00	**ppm**
Emulsion Sample	172	**ml**	432	**ml**
	260	**ml**		
Weight				
Dish	6.3453	**g**		
Dish + HEM	6.6055	**g**		
HEM	0.2602	**g**	24%	**emulsified Oil**
HEM Concentration	0.000602	**g/ml**	602.31	**mg/L**

Sample ID	8	**Date**	Monday, January 19, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	10	**g**	20,000.00	**ppm**
Emulsion Sample	172	**ml**	432	**ml**
	260	**ml**		
Weight				
Dish	6.3453	**g**		

Dish + HEM	6.6055	**g**		
HEM	0.2602	**g**	24%	**emulsified Oil**
HEM Concentration	0.000602	**g/ml**	602.31	**mg/L**

Sample ID	9	**Date**	Monday, January 19, 2009	
Water	500	**ml**		
Oil	1.25	**g**	2,500.00	**ppm**
Tween 40	3.75	**g**	7,500.00	**ppm**
Emulsion Sample	172	**ml**	432	**ml**
	260	**ml**		
Weight				
Dish	6.3453	**g**		
Dish + HEM	6.6055	**g**		
HEM	0.2602	**g**	24%	**emulsified Oil**
HEM Concentration	0.000602	**g/ml**	602.31	**mg/L**

Oil concentration: 5,000 ppm

Sample ID	1	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	0.5	**g**	1,000.00	**ppm**
Emulsion Sample	395	**ml**	395	**ml**
	0	**ml**		
Weight				
Dish	6.2486	**g**		
Dish + HEM	6.5306	**g**		
HEM	0.282	**g**	14%	**Emulsified Oil**
HEM Concentration	0.000714	**g/ml**	713.92	**mg/L**

Sample ID	2	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		

Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	1.25	**g**	2,500.00	**ppm**
Emulsion Sample	168	**ml**	411	**ml**
	243	**ml**		
Weight				
Dish	6.2101	**g**		
Dish + HEM	6.4888	**g**		
HEM	0.2787	**g**	14%	**Emulsified Oil**
HEM Concentration	0.000678	**g/ml**	678.10	**mg/L**

Sample ID	3	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	2.5	**g**	5,000.00	**ppm**
Emulsion Sample	216	**ml**	436	**ml**
	220	**ml**		
Weight				
Dish	6.347	**g**		
Dish + HEM	6.7582	**g**		
HEM	0.4112	**g**	19%	**Emulsified Oil**
HEM Concentration	0.000943	**g/ml**	943.12	**mg/L**

Sample ID	4	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	3.75	**g**	7,500.00	**ppm**
Emulsion Sample	244	**ml**	392	**ml**
	148	**ml**		
Weight				
Dish	6.3181	**g**		
Dish + HEM	6.7085	**g**		
HEM	0.3904	**g**	20%	**Emulsified Oil**

HEM Concentration	0.000996	**g/ml**	995.92	**mg/L**

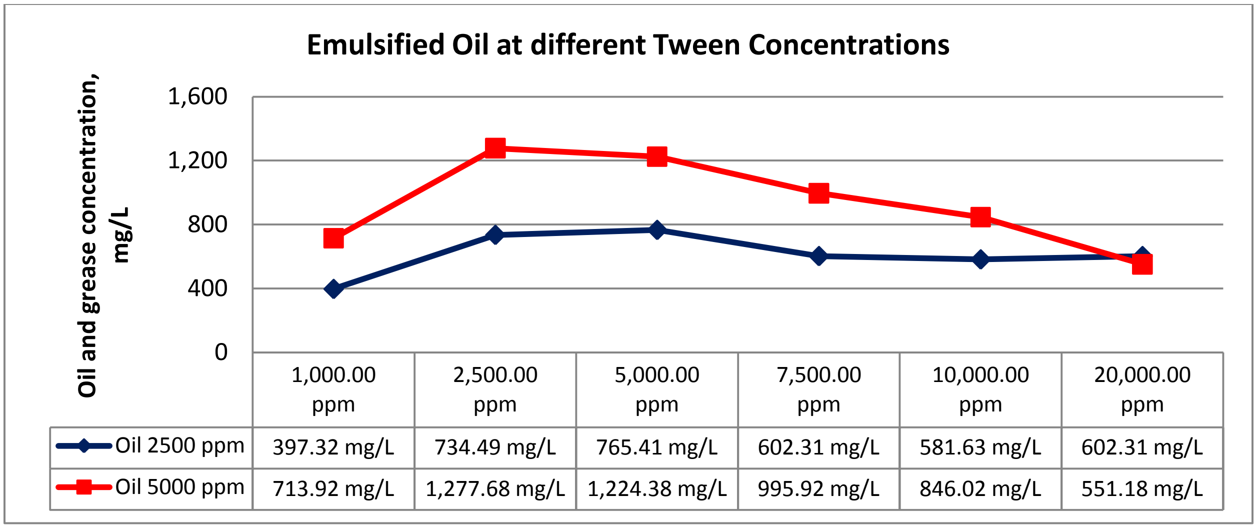
Sample ID	5	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	5	**g**	10,000.00	**ppm**
Emulsion Sample	226	**ml**	352	**ml**
	126	**ml**		
Weight				
Dish	6.311	**g**		
Dish + HEM	6.6088	**g**		
HEM	0.2978	**g**	17%	**Emulsified Oil**
HEM Concentration	0.000846	**g/ml**	846.02	**mg/L**

Sample ID	6	**Date**	Tuesday, January 20, 2009	
Water	500	**ml**		
Oil	1.25	**g**	5,000.00	**ppm**
Tween 40	2.5	**g**	2,500.00	**ppm**
Emulsion Sample	153	**ml**	345	**ml**
	192	**ml**		
Weight				
Dish	6.3238	**g**		
Dish + HEM	6.7646	**g**		
HEM	0.4408	**g**	26%	**Emulsified Oil**
HEM Concentration	0.001278	**g/ml**	1277.68	**mg/L**

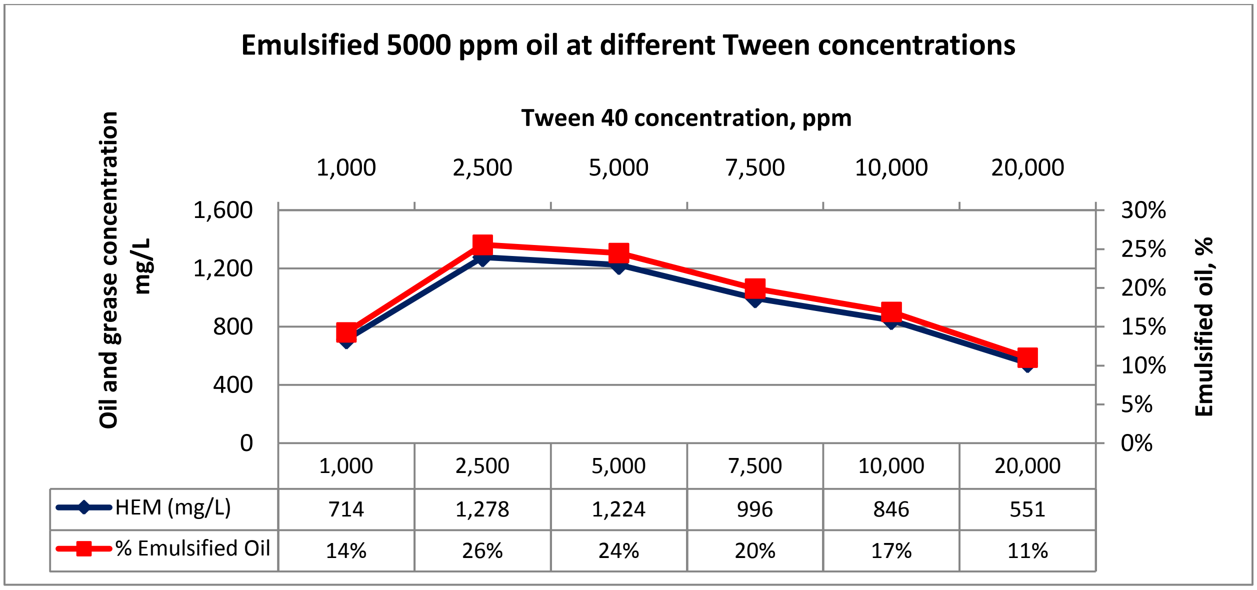
Sample ID	7	**Date**	Wednesday, January 21, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	10	**g**	20,000.00	**ppm**
Emulsion Sample	180	**ml**	422	**ml**

	242	**ml**		
Weight				
Dish	6.316	**g**		
Dish + HEM	6.5486	**g**		
HEM	0.2326	**g**	11%	**Emulsified Oil**
HEM Concentration	0.000551	**g/ml**	551.18	**mg/L**

Sample ID	8	**Date**	Wednesday, January 21, 2009	
Water	500	**ml**		
Oil	2.5	**g**	5,000.00	**ppm**
Tween 40	2.5	**g**	5,000.00	**ppm**
Emulsion Sample	200	**ml**	406	**ml**
	206	**ml**		
Weight				
Dish	6.3251	**g**		
Dish + HEM	6.8222	**g**		
HEM	0.4971	**g**	24%	**Emulsified Oil**
HEM Concentration	0.001224	**g/ml**	1,224.38	**mg/L**


Emulsified Oil at different Tween Concentrations

	1,000.00 ppm	2,500.00 ppm	5,000.00 ppm	7,500.00 ppm	10,000.00 ppm	20,000.00 ppm
◆ Oil 2500 ppm	397.32 mg/L	734.49 mg/L	765.41 mg/L	602.31 mg/L	581.63 mg/L	602.31 mg/L
■ Oil 5000 ppm	713.92 mg/L	1,277.68 mg/L	1,224.38 mg/L	995.92 mg/L	846.02 mg/L	551.18 mg/L


Emulsified 5000 ppm oil at different Tween concentrations

	1,000	2,500	5,000	7,500	10,000	20,000
◆ HEM (mg/L)	714	1,278	1,224	996	846	551
■ % Emulsified Oil	14%	26%	24%	20%	17%	11%

Appendix F: Electrocoagulation experiments

Material **Aluminum electrodes**
Date **3/20/2009**

Dosage for Volume		45	**L**
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	225	
Tween 40	2500	112.5	
Paint	200	9	
Mica	200	9	
NaCl	200	9	
	mg/L	**mg**	
Copper	5	604.7	***as $CuCl_2.2H_2O$***
Nickel	1.5	273.3	***as $NiCl_2.6H_2O$***
Zinc	2.5	234.5	***as $ZnCl_2$***

	Weight (g) - 1 Stage			**Weight (g) - 2 Stage**		
No.	**B/Test**	**A/Test**	**Dif.**	**B/Test**	**A/Test**	**Dif.**
1	575.52	575.42	0.1	580.1	580.05	0.05
2	578.95	577.04	1.91	580.6	580.11	0.49
3	563.75	561.97	1.78	580.42	578.92	1.5
4	575.45	573.78	1.67	580.78	579.22	1.56
5	563.26	561.62	1.64	581.36	580.15	1.21
6	562.89	561.4	1.49	580.38	579.24	1.14
7	565.94	564.39	1.55	580.96	579.63	1.33
8	564.01	562.52	1.49	581.68	580.48	1.2
9	567.97	566.11	1.86	582.15	581.65	0.5
		Sum	**13.49**		**Sum**	**8.98**
				Total		22.47 g

	1Stage	**2 Stage**	**After Filtration**
Cupper	0.5	0.42	**mg/L**
Zinc	0.34	0.05	**mg/L**
Nickel	0.17	0.12	**mg/L**
Turbidity		**46.7**	**NTU**
HEM	34	14.2	**mg/L**
Vol	90	72	**L**
Al Dose	149.89	124.72	**mg/L**

	Influent	Effluent	1Stage	Effluent	2Stage	
		B/Filt	A/Filt	B/Filt	A/Filt	
pH	5.18	5.51	6.82	6.54	7.2	
Conductivity	423	430	472	430	437	**μS/cm**
ORP	56.1	86.7	10.2	26.6	-11.5	**mV**
TDS	207	211	231	211	214	**mg/L**
Temp	20.4	22	20.5	32	20.5	**C**
Total Solids	7448		5564		3398	**mg/L**

Current	10.7	**Amp**
Voltage	54	**V**
Q	1	**L/min**

Remarks: Two stage. Effluent recirculated into the reactor

Material	Aluminum electrodes
Date	3/24/2009

Weight (g) - 1 Stage

No.	B/Test	A/Test	Dif.
1	575.42	575.37	0.05
2	577.04	575.46	1.58
3	561.97	560.57	1.4
4	573.78	572.09	1.69
5	561.62	560.08	1.54
6	561.4	559.73	1.67
7	564.39	562.03	2.36
8	562.52	560.82	1.7
9	566.11	563.73	2.38
		Sum	**14.37**

Vol	40	**L**
Al Dose	359.25	**mg/L**

	B/Filt	A/Filt	
Cupper	0.37	0.24	**mg/L**
Zinc	0.27	< 0.01 (-0.04)	**mg/L**
Nickel	0.11	0.11	**mg/L**
Turbidity	437	66.5	**NTU**
HEM	126.8	12.5	**mg/L**

	Raw	B/Filt	A/Filt	
pH	5.72	5.94	7.05	
Conductivity	494	483	513	**µS/cm**
ORP	74.8	61.6	-3.1	**mV**
TDS	242	237	252	**mg/L**
Temp	21.3	30.6	26	**C**
Total Solids	8960	3686	3056	**mg/L**

Current	10	**Amp**
Voltage	48	**V**
Q	0.5	**L/min**
Time	90	**min**

Note: Flow rate set up to 0.5 L/min. Reactor Time = 90 min

Dosage for Volume		45	**L**
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	225	
Tween 40	2500	112.5	
Paint	200	9	
Mica	200	9	
NaCl	200	9	
	mg/L	**mg**	
Copper	5	604.7	***as CuCl2.2H2O***
Nickel	1.5	273.3	***as NiCl2.6H2O***
Zinc	2.5	234.5	***as ZnCl2***

Material	Carbon Steel Electrodes
Date	3/26/2009

Weight (g) - 1 Stage

No.	**B/Test**	**A/Test**	**Dif.**
1	1530.76	1530.7	0.06
2	1543.12	1540.61	2.51
3	1530.05	1528.35	1.7
4	1541.46	1538.81	2.65
5	1538.66	1536.79	1.87
6	1538.65	1536.15	2.5
7	1534.7	1532.61	2.09
8	1542.02	1539.48	2.54
9	1537.98	1536.19	1.79
		Sum	**17.71**

Vol	40	**L**
Fe dose	442.75	**mg/L**

	B/Filt	**A/Filt**	
Cupper	< 0.04 (-0.51)	< 0.04 (-1.19)	**mg/L**
Zinc	< 0.01 (-0.05)	< 0.01 (-0.08)	**mg/L**
Nickel		0.11	**mg/L**
Turbidity	440	225	**NTU**
HEM	175.6	8.2	**mg/L**

	Raw	**B/Filt**	**A/Filt**	
pH	5.75	6.87	6.37	
Conductivity	590	658	613	**µS/cm**
ORP	71.8	7.5	36.7	**mV**
TDS	289	323	300	**mg/L**
Temp	21.2	28.8	23.3	**C**
Total Solids	8960	3686	3056	**mg/L**
Susp. Solids				

Current	10	**Amp**
Voltage	29	**V**
Q	0.5	**L/min**
Time	90	**min**

Note: Flow rate set up to 0.5 L/min. Reactor Time = 90 min

Dosage for Volume		45	**L**
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	225	
Tween 40	2500	112.5	
Paint	200	9	
Mica	200	9	
NaCl	200	9	
	mg/L	**mg**	
Copper	5	604.7	***as CuCl2.2H2O***
Nickel	1.5	273.3	***as NiCl2.6H2O***
Zinc	2.5	234.5	***as ZnCl2***

Material	Carbon Steel Electrodes
Date	6/25/2009

Weight (g) - 1 Stage

No.	B/Test	A/Test	Dif.
1	1530.05	1529.79	0.26
2	1540.65	1536.9	3.75
3	1528.12	1524.91	3.21
4	1539.1	1535.42	3.68
5	1536.62	1533.74	2.88
6	1536.53	1532.64	3.89
7	1532.63	1529.77	2.86
8	1539.91	1536.21	3.7
9	1536.19	1533.54	2.65
		Sum	**26.88**

Vol	88	**L**
Dosage	305.5	**mg/L**

	Effluent	Eff w/ polymer	
Copper	1.39	2.95	**mg/L**
Zinc	0.02	0.5	**mg/L**
Nickel	0.89	0.27	**mg/L**
Turbidity	109	39.3	**NTU**
HEM	13.4	16	**mg/L**

	Effluent	Eff w/ polymer	Raw Water	
pH	6.6	6.9	5.8	
Conductivity	682	675	610	**µS/cm**
ORP (orp probe)	-343	-589		**mV**
(pH probe)	29.6	14.1		**mV**
Temperature	20.2	19.7	20.3	**oC**

Current	10	**Amp**
Voltage	26	**V**
Q	0.5	**L/min**
Time		**min**

Note: With Rectangular Tank, Sludge chamber, upper output.

Using Polymer in effluent after flotation tank

Dosage: **3 drops/L** **68.6 mg/L**

Dosage for Volume		**90 L**	
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	450	
Tween 40	2500	225	
Paint	200	18	
Mica	100	9	
NaCl	200	18	
	mg/L	**mg**	
Copper	5	1214.1	***as CuCl2.2H2O (13.49 mg/L)***
Nickel	1.5	546.3	***as NiCl2.6H2O (6.07 mg/L)***
Zinc	2.5	468.9	***as ZnCl2 (5.21 mg/L)***

Material	Carbon Steel Electrodes + Aluminum Electrodes
Date	6/30/2009

Carbon Steel **Weight (g) - 1 Stage**

No.	B/Test	A/Test	Dif.
1	1529.79	1529.63	0.16
2	1536.9	1536.63	0.27
3	1524.91	1524.24	0.67
4	1535.42	1529.44	5.98
5	1533.74	1527.32	6.42
6	1532.64	1526.63	6.01
7	1529.77	1523.08	6.69
		Sum	**26.2**

Aluminum

5	559.1	555.6	3.5
9	563.01	560.09	2.92
		Sum	**6.42**

Total Metal	32.62	**g**
Vol	88	**L**
Dosage	370.68	**mg/L**

	Effluent	Eff w/ polymer	
Copper	2.48	1.78	**mg/L**
Zinc	0.12	0.02	**mg/L**
Nickel	0.79	0.66	**mg/L**
Turbidity	55.4	11.7	**NTU**
HEM	31.4	4.2	**mg/L**

	Effluent	Eff w/ polymer	Raw Water	
pH	7.8	7.9	6	
Conductivity	770	767	690	**µS/cm**
ORP (orp probe)				**mV**
(pH probe)				**mV**
Temperature	19.7	19.9	20.1	**oC**

Current	10	**Amp**	**Constant**
Voltage	26	**V**	

Q 0.5 **L/min**

Time 176 **min**

Note: With Rectangular Tank, Sludge chamber, upper output.

Using Polymer in effluent after flotation tank

Dosage: **1 drops/L** **22.9 mg/L**

Use the 9th cell with aluminum electrodes

Voltage control

Dosage for Volume		90	**L**
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	450	
Tween 40	2500	225	
Paint	200	18	
Mica	100	9	
NaCl	200	18	
	mg/L	**mg**	
Copper	5	1214.1	***as $CuCl_2.2H_2O$ (13.49 mg/L)***
Nickel	1.5	546.3	***as $NiCl_2.6H_2O$ (6.07 mg/L)***
Zinc	2.5	468.9	***as $ZnCl_2$ (5.21 mg/L)***

Material Carbon Steel Electrodes + Aluminum Electrodes

Date 7/9/2009

Carbon Steel Weight (g) - 1st Pass

No.	B/Test	A/Test	Dif.
11	1517.07	1517.07	0
12	1542.96	1540.18	2.78
13	1528.91	1527.05	1.86
14	1522.27	1519.68	2.59
15	1530.91	1528.58	2.33
16	1458.84	1456.28	2.56
17	1532.77	1531.14	1.63

Sum **13.75 g**

2nd Pass

No.	B/Test	A/Test	Dif.
1	1529.07	1529.07	0
2	1535.35	1535.15	0.2
3	1520.97	1520.56	0.41
4	1528.55	1527.39	1.16
5	1525.27	1524.82	0.45
6	1526.85	1525.16	1.69
7	1522.58	1521.74	0.84

Sum **4.75 g**

Aluminum

3	558.02	556.9	1.12
7	559.79	558.15	1.64

Sum **2.76 g**

5	554.59	553.94	0.65
9	559.17	558.61	0.56

Sum **1.21 g**

First Pass		
Vol	90	**L**
Carbon diss	152.78	**mg/L**
Alum diss	30.67	**mg/L**

Second Pass		
Vol	45	**L**
Carbon diss	105.56	**mg/L**
Alum diss	26.89	**mg/L**

		1st pass		**2nd Pass**		
	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
Copper		1.62	1.54	1.52	1.51	**mg/L**
Zinc		0.04	0.01 (<0.01)	0.03	0.01	**mg/L**
Nickel		0.95	0.45	0.39	0.36	**mg/L**
HEM		8.4	5.4	1.2 (< 5)	1.02 (< 5)	**mg/L**
Turbidity		176	7.76	14.8	6	**NTU**
TSS		28	1.3	11		**mg/L**
	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
pH	7.7	7.6	7.7	8.45	8.4	
Conductivity	807	765	767	717	715	**µS/cm**
ORP (orp probe)						**mV**
(pH probe)						**mV**
Temperature						**oC**
TDS	396	375	376	351	350	**mg/L**

First Pass			**Second Pass**	
Current	10 **Amp**	**Constant**	**Current**	10 **Amp**
Voltage	27 **V**		**Voltage**	32 **V**
Q	1 **L/min**		**Q**	1 **L/min**
Time	90 **min**		**Time**	45 **min**

Note: With Conic Clarifier and 2 passes
Use the 9th cell with aluminum electrodes
Voltage control at 5min

Dosage for Volume		90 **L**	
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	450	
Tween 40	2500	225	
Paint	200	18	
Mica	0	0	No added
NaCl	200	18	
	mg/L	**mg**	
Copper	5	1214.1	***as CuCl2.2H2O (13.49 mg/L)***
Nickel	1.5	546.3	***as NiCl2.6H2O (6.07 mg/L)***
Zinc	2.5	468.9	***as ZnCl2 (5.21 mg/L)***

Material Carbon Steel Electrodes + Aluminum Electrodes
Date 9/27/2009

Carbon Steel **Weight (g) - 1st Pass**

No.	B/Test	A/Test	Dif.
1	1524.17	1523.88	0.29
2	1524.56	1520.19	4.37
3	1515.04	1514.15	0.89
4	1516.67	1515.75	0.92
5	1509.98	1508.96	1.02
6	1518.36	1517.35	1.01
7	1512.72	1512.08	0.64
		Sum	**9.14** g

2nd Pass

No.	B/Test	A/Test	Dif.
11	1520.17	1519.96	0.21
12	1527.85	1527.04	0.81
13	1519.03	1517.67	1.36
14	1444.2	1443.15	1.05
15	1506.58	1505.1	1.48
16	1508.9	1507.89	1.01
17	1522.7	1521.5	1.2
		Sum	**7.12**

Aluminum

5	549.59	549.05	0.54
9	554.18	553.51	0.67
		Sum	**1.21** g

3	553.39	552.67	0.72
7	554.44	554.1	0.34
		Sum	**1.06**

First Pass		
Vol	28	**L**
Carbon diss	326.43	**mg/L**
Alum diss	43.21	**mg/L**

Second Pass		
Vol	24	**L**
Carbon diss	296.67	**mg/L**
Alum diss	44.17	**mg/L**

		1st pass		**2nd Pass**		
	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
Copper		3.01	2.67	2.26	2.06	**mg/L**
Zinc		-0.03 (< 0.01)	-0.04 (< 0.01)	-0.02 (< 0.01)	-0.02 (< 0.01)	**mg/L**
Nickel		1.73	0.99	0.49	0.58	**mg/L**
HEM		10.7	2.7	1.0	1.0	**mg/L**
Chlorine		-0.10 (< 0.02)	-0.08 (< 0.02)	-0.03 (< 0.02)	-0.01 (< 0.02)	**mg/L**
Turbidity		93.7	51.2	15.7	5.2	**NTU**
Susp solids		48.9		22.2		**mg/L**
Total solids	10378.0	3352.0	2962.0	3086.0	2992.0	

	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
Temperature	18.1	18.9	18.3	19.2	18.7	**oC**
pH	7.85	7.71	7.51	8.83	8.64	
Conductivity	1107	1200	1195	1162	1159	**µS/cm**
ORP (orp probe)						**mV**

(pH probe)						**mV**
TDS	543	588	586	569	568	**mg/L**

First Pass				**Second Pass**		
Current	5	**Amp**	**Constant**	**Current**	5	**Amp**
Voltage	12	**V**		**Voltage**	12	**V**
Q	1	**L/min**		**Q**	1	**L/min**
Time	28	**min**		**Time**	24	**min**

Note: With Conic Clarifier and 2pass
Use the 9th cell with aluminum electrodes
Voltage control at 10min
ClNa increase up to 600 mg/L

Dosage for Volume		30 **L**	
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	150	
Tween 40	2500	75	
Paint	200	6	
Mica	0	0	No added
NaCl	600	18	
	mg/L	**mg**	
Copper	5	404.7	***as CuCl2.2H2O (13.49 mg/L)***
Nickel	1.5	182.1	***as NiCl2.6H2O (6.07 mg/L)***
Zinc	2.5	156.3	***as ZnCl2 (5.21 mg/L)***

Material Carbon Steel Electrodes + Aluminum Electrodes

Date 10/11/2009

Carbon Steel **Weight (g) - 1st Pass**

No.	B/Test	A/Test	Dif.
1	1520.22	1519.89	0.33
2	1516.49	1515.55	0.94
3	1508.51	1507.37	1.14
4	1511.78	1511.18	0.6
5	1502.94	1501.84	1.1
6	1513.27	1512.63	0.64
7	1506.4	1505.12	1.28

Sum **6.03** **g**

2nd Pass

No.	B/Test	A/Test	Dif.
11	1518.39	1518.34	0.05
12	1525.58	1525.29	0.29
13	1516.01	1515.27	0.74
14	1442.06	1441.77	0.29
15	1503.75	1502.95	0.8
16	1506.36	1506.1	0.26
17	1519.99	1519.36	0.63

Sum **3.06**

Aluminum

5	548.44	547.55	0.89
9	552.85	552.53	0.32

Sum **1.21** **g**

3	552.66	552.09	0.57
7	554.12	553.61	0.51

Sum **1.08**

First Pass		
Vol	27	**L**
Carbon diss	223.33	**mg/L**
Alum diss	44.81	**mg/L**

Second Pass		
Vol	17	**L**
Carbon diss	180.00	**mg/L**
Alum diss	63.53	**mg/L**

		1st pass		**2nd Pass**		
	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
Copper		2.23	2.03	2.28	1.83	**mg/L**
Zinc		-0.01 (< 0.01)	-0.04 (< 0.01)	-0.03 (< 0.01)	-0.03 (< 0.01)	**mg/L**
Nickel		0.68	0.75	0.62	0.77	**mg/L**
HEM		2.7	1.2	0.8	0.4	**mg/L**
Chlorine		-0.09 (< 0.02)	-0.04 (< 0.02)	-0.02 (< 0.02)	0.0 (< 0.02)	**mg/L**
Turbidity		49.6	18.9	16	5.26	**NTU**
Susp solids		31.3		28.2		**mg/L**
Total solids		2458.3	3356	4966	2132	**mg/L**

	Raw Water	**Non-Filtered**	**Filtered**	**Non-Filtered**	**Filtered**	
Temperature	19.6	21.3	19.4	18.6	20.3	**oC**
pH	7.77	9.42	9.2	9.3	9.57	
Conductivity		1234	1234	1232	11	**µS/cm**

ORP (orp probe)					**mV**
(pH probe)					**mV**
TDS	605	605	604	568	**mg/L**

First Pass				**Second Pass**		
Current	10	**Amp**	**Constant**	**Current**	10	**Amp**
Voltage	22.3	**V**		**Voltage**	21.2	**V**
Q	1	**L/min**		**Q**	1	**L/min**
Time	27	**min**		**Time**	17	**min**

Note: With Conic Clarifier and 2pass
Use the 9th cell with aluminum electrodes
Voltage control at 10min
ClNa increase up to 600 mg/L
Electrodes polished

Dosage for Volume		30 **L**	
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	150	
Tween 40	2500	75	
Paint	200	6	
Mica	0	0	No added
NaCl	600	18	
	mg/L	**mg**	
Copper	5	404.7	***as CuCl2.2H2O (13.49 mg/L)***
Nickel	1.5	182.1	***as NiCl2.6H2O (6.07 mg/L)***
Zinc	2.5	156.3	***as ZnCl2 (5.21 mg/L)***

Material Carbon Steel Electrodes + Aluminum Electrodes

Date 10/20/2009

Carbon Steel **Weight (g) - 1st Pass**

No.	B/Test	A/Test	Dif.
1	1519.26	1519.12	0.14
2	1514.95	1514.3	0.65
3	1506.54	1505.72	0.82
4	1510.42	1509.63	0.79
5	1500.7	1499.83	0.87
6	1511.76	1510.98	0.78
7	1503.89	1503.16	0.73

Sum **4.78 g**

2nd Pass

No.	B/Test	A/Test	Dif.
11	1517.54	1517.48	0.06
12	1524.92	1524.92	0
13	1514.51	1514.06	0.45
14	1441.23	1441	0.23
15	1502.26	1501.41	0.85
16	1505.47	1505.23	0.24
17	1518.67	1518.32	0.35

Sum **2.18**

Aluminum

5	547.47	547.02	0.45
9	552.48	552.11	0.37

Sum **0.82 g**

3	552.01	551.72	0.29
7	553.52	553.3	0.22

Sum **0.51**

First Pass		
Vol	28.5	**L**
Carbon diss	167.72	**mg/L**
Alum diss	28.77	**mg/L**

Second Pass		
Vol	17	**L**
Carbon diss	128.24	**mg/L**
Alum diss	30.00	**mg/L**

		1st pass		**2nd Pass**		
	Raw Water	Non-Filtered	Filtered	Non-Filtered	Filtered	
Copper		2.78	2.19	2.28	2.12	**mg/L**
Zinc		0.16	-0.10 (< 0.01)	-0.05 (< 0.01)	-0.06 (< 0.01)	**mg/L**
Nickel		1.77	1	0.98	1.58	**mg/L**
HEM		5.1	1.7	1.1	0.6	**mg/L**
Chlorine		-0.07 (< 0.02)	-0.02 (< 0.02)	-0.05 (< 0.02)	0.0 (< 0.02)	**mg/L**
Turbidity		52.3	16.3	35.8	5.48	**NTU**
Susp solids		32.0		26.7		**mg/L**
Total solids		3244.0	4096.0	3936.0	2462.0	**mg/L**

	Raw Water	Non-Filtered	Filtered	Non-Filtered	Filtered	
Temperature		18.3	18.1	18.6	20.3	**oC**
pH		9.45	9.06	9.3	9.57	
Conductivity		1180	1181	1232	11	**µS/cm**

ORP (orp probe)					**mV**
(pH probe)					**mV**
TDS	579	579	604	568	**mg/L**

First Pass				**Second Pass**		
Current	7.5	**Amp**	**Constant**	**Current**	7.5	**Amp**
Voltage	17.7	**V**		**Voltage**	15.5	**V**
Q	1	**L/min**		**Q**	1	**L/min**
Time	28.5	**min**		**Time**	17	**min**

Note: With Conic Clarifier and 2pass

Use the 9th cell with aluminum electrodes

Voltage control at 10min

ClNa increase up to 600 mg/L

Polished Electrodes

Samples preserved and analyzed different days

Dosage for Volume		30	**L**
Component	**Concentration**	**Weight**	**Note**
	mg/L	**g**	
Oil	5000	150	
Tween 40	2500	75	
Paint	200	6	
Mica	0	0	No added
NaCl	600	18	
	mg/L	**mg**	
Copper	5	404.7	***as CuCl2.2H2O (13.49 mg/L)***
Nickel	1.5	182.1	***as NiCl2.6H2O (6.07 mg/L)***
Zinc	2.5	156.3	***as ZnCl2 (5.21 mg/L)***

Appendix G: Efficiency analysis calculations

Type of treatment:	Conic Clarifier, two passes		**Date:**	3/20/2009	
Electrodes	Carbon Steel			Aluminum	
Current, I	10	amps			
Avg. Voltage, U	115	V			
Flow rate, Q	1	L/min			
Electrode Density	1023.05	Kg/m3			Kg/m3
	1023047.4	g/m3			g/m3
Volume					
1st pass, V1	90	L			
2nd pass, V2	90	L			
Overall, Vt	180	L			
Running Time, t					
1st pass, t1	1.5	h			
2nd pass, t2	1.5	h			
Overall, t	3.0	h			
Electrode Consumption					
1st pass	13.5	g			g
	1.32E-05	m3		#DIV/0!	m3
2nd pass	9.0	g			g
	8.78E-06	m3		#DIV/0!	m3
Overall	22.5	g		0.0	g
	2.20E-05	m3		#DIV/0!	m3

Dissolved Metal Concentration

	Carbon Steel		Combined		Aluminum	
1st pass	149.9	**mg/L**	149.9	**mg/L**	0.0	**mg/L**
2nd pass	99.8	**mg/L**	99.8	**mg/L**	0.0	**mg/L**
Overall	124.8	**mg/L**	124.8	**mg/L**	0.0	**mg/L**

Electrode Cost

Electrode Unit Cost	4054.3	**$/m3**	6371.0	**$/m3**
1st Pass Cost	0.053	**$**	#DIV/0!	**$**
2nd Pass Cost	0.036	**$**	#DIV/0!	**$**
Overall Cost	0.089	**$**	#DIV/0!	**$**

Electrode surface Area	371.15	**cm2**		**cm2**
# Electrodes	9	**u**		**u**
Total Surface Area one side	2969.2	**cm2**	0.0	**cm2**
Total Surface Area	5938.4	**cm2**	0	**cm2**
Curent Density	0.002	**A/cm2**	#DIV/0!	**A/cm2**
	0.011	**A/in2**	#DIV/0!	**A/in2**
	1.68	**mA/cm2**	#DIV/0!	**mA/cm2**
Cost per kWh	0.02	**$/kWh**		

Power supply Energy Consumption & Cost

Equipment Efficiency	70%		given by the manufacturer	
1st pass	2.46	**kWh**	0.04	**$**
2nd pass	2.46	**kWh**	0.04	**$**
Overall	4.93	**kWh**	0.08	**$**

Pump Energy Consumption & Cost

Pump Power	0.58	kW	given by the manufacturer

1st pass	0.87	**kWh**	0.01	**$**
2nd pass	0.87	**kWh**	0.01	**$**
Overall	1.74	**kWh**	0.03	**$**

Total Energy Consumption and Electrode Consumption

	Power Supply & Pump		**Electrode**	
1st pass	3.33	**kWh**	13.5	**g**
2nd pass	3.33	**kWh**	9.0	**g**
Overall	6.67	**kWh**	22.5	**g**

Total Treatment Costs

	Energy	**Aluminum**	**Total**
1st pass	$0.06	$0.05	$0.11
2nd pass	$0.06	$0.04	$0.09
Overall	$0.11	$0.09	$0.20

First Pass **Vol** 90 **L**

Specific energy comsumption	**Co (mg/L)**	**Ci (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Ci**	**Cost $/g**	**mg pollutant/g electrode**
Copper	5	0.5	450	45	0.405	8.23	90.0%	0.27	3.0E-02
Nickel	1.5	0.17	135	15.3	0.1197	27.86	88.7%	0.91	8.9E-03
Zinc	2.5	0.34	225	30.6	0.1944	17.15	86.4%	0.56	1.4E-02
Oil	5000	34	450000	3060	446.94	0.01	99.3%	0.00	3.3E+01

Second Pass **Vol** 90 **L**

Specific energy comsumption	**Ci (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Ci-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	0.5	0.42	45	37.8	0.0072	463.10	16.0%	12.70	8.0E-04
Nickel	0.17	0.12	15.3	10.8	0.0045	740.95	29.4%	20.33	5.0E-04
Zinc	0.34	0.05	30.6	4.5	0.0261	127.75	85.3%	3.50	2.9E-03
Oil	34	14.2	3060	1278	1.782	1.87	58.2%	0.05	2.0E-01

Overall			90 L	45 L					
Specific energy comsumption	**Co (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	0.42			0.4122	16.18	91.6%	0.49	1.8E-02
Nickel	1.5	0.12			0.1242	53.69	92.0%	1.62	5.5E-03
Zinc	2.5	0.05			0.2205	30.24	98.0%	0.91	9.8E-03
Oil	5000	14.2			448.722	0.01	99.7%	0.00	2.0E+01

Electrodes	Aluminum		**Date**	3/24/2009
Current, I	10	**amps**		
Avg. Voltage, U	115	**V**		
Volumen, V	40	**L**		
Flow Rate, Q	0.5	**L/min**		
Running Time, t	1.3	**h**		
Electrode Density	1023.05	**Kg/m3**		
	1023047.4	**g/m3**		
Electrode consumption	14.4	**g**		
	1.40463E-05	**m3**		
Dissolved Metal Concentration	359.3	**mg/L**		
Electrode Unit Cost	6371.0	**$/m3**		
Total Electrode Cost	0.089	**$**		
Electrode surface Area	371.15	**cm2**		
# Electrodes	9	**u**		
Total Surface Area one side	2969.2	**cm2**		
Total Surface Area	5938.4	**cm2**		
Current Density one side	0.003367911	**A/cm2**		
	0.021728412	**A/in2**		
Current Density	0.001683955	**A/cm2**	0.013472	**A/cm2**
	0.010864206	**A/in2**		

Specific energy consumption	**Co**	**Cf**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency**	**Cost $/g**	**g pollutant/g electrode**
Cupper	5	0.24	200	9.6	0.1904	15.53	95%	0.730309	0.01325
Nickel	1.5	0.11	60	4.4	0.0556	53.19	93%	2.500915	0.003869
Zinc	2.5	0.01	100	0.4	0.0996	29.69	100%	1.396093	0.006931
Turbidity	1000	4.37	40000	174.8	39.8252	0.07	100%	0.003492	2.771413
Oil	5000	126.8	200000	5072	194.928	0.02	97%	0.000713	13.56493

Cost per kWh		0.02	**$/kWh**	
Equipment Efficiency		70%		given by the manufacturer
Power supply consumption		2.19	**kWh**	
Power supply energy cost	$	0.04	$	
Pump power		0.58	**kW**	given by the Manufacturer
Pump energy consumption		0.77	**kWh**	
Pump energy cost	$	0.01	**$**	
Pump + Rectifier energy		2.96	**kWh**	
Pump + Rectifier energy cost	$	0.05	**$**	
Energy + Electrode Cost		0.139	**$**	

Electrodes	Carbon Steel	**Date**	3/26/2009	
Current, I	10	**amps**		
Avg. Voltage, U	115	**V**	29	
Volumen, V	40	**L**		
Flow rate, Q	0.5	**L/min**		
Running Time, t	1.3	**h**		
Electrode Density	2738.21	**Kg/m3**		
	2738214.0	**g/m3**		
Electrode consumption	17.7	**g**		
	6.4677E-06	**m3**		
Dissolved Metal Concentration	442.8	**mg/L**		
Electrode Unit Cost	4054.3	**$/m3**		
Total Electrode Cost	0.026	**$**		
Electrode surface Area	371.15	**cm2**		
# Electrodes	9	**u**		
Total Surface Area one side	2969.2	**cm2**		
Total Surface Area	5938.4	**cm2**		
Current Density one side	0.003	**A/cm2**		
	0.022	**A/in2**		
Current Density	0.002	**A/cm2**	0.013472	**A/cm2**
	0.011	**A/in2**		

Specific energy consumption	**Co**	**Cf**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency**	**Cost $/g**	**g pollutant/g electrode**
Cupper	5	0.04	200	1.6	0.1984	14.90	99%	0.381974	0.011203
Nickel	1.5	0.11	60	4.4	0.0556	53.19	93%	1.363017	0.003139
Zinc	2.5	0.01	100	0.4	0.0996	29.69	100%	0.760881	0.005624
Turbidity	1000	440	40000	17600	22.4	0.13	56%	0.003383	1.264822
Oil	5000	175.6	200000	7024	192.976	0.02	96%	0.000393	10.89644

Cost per kWh	0.02	**$/kWh**	
Equipment Efficiency	70%		given by the manufacturer
Power supply consumption	2.19	**kWh**	
Power supply energy cost	$0.04	$	
Pump power	0.58	**kW**	given by the Manufacturer
Pump energy consumption	0.77	**kWh**	
Pump energy cost	$0.01	**$**	
			0.575
Pump + Rectifier energy	2.96	**kWh**	
Pump + Rectifier energy cost	$0.05	**$**	
Energy + Electrode Cost	0.076	**$**	

Electrodes	Carbon Steel		with tank flotation		Date	6/25/2009
Current, I	10	amps				
Avg. Voltage, U	115	V	26			
Volumen, V	90	L				
Flow rate, Q	0.5	L/min				
Running Time, t	3.0	h				
Electrode Density	2738.21	Kg/m3				
	2738214.0	g/m3				
Electrode consumption	17.7	g				
	6.4677E-06	m3				
Dissolved Metal Concentration	196.8	mg/L				
Electrode Unit Cost	4054.3	$/m3				
Total Electrode Cost	0.026	$				
Electrode surface Area	371.15	cm2				
# Electrodes	9	u				
Total Surface Area one side	2969.2	cm2				
Total Surface Area	5938.4	cm2				
Curent Density one side	0.003	A/cm2				
	0.022	A/in2				
Curent Density	0.002	A/cm2	0.013472	A/cm2		
	0.011	A/in2				

Specific energy comsumption	Co	Cf	Mo (mg)	Mf (mg)	Mremoved (g)	SEC KWh/g	Efficiency	Cost $/g	g pollutant/g electrode
Cupper	5	1.39	450	125.1	0.3249	20.48	72%	0.424	0.0091
Nickel	1.5	0.89	135	80.1	0.0549	121.19	41%	2.509	0.0015
Zinc	2.5	0.02	225	1.8	0.2232	29.81	99%	0.617	0.0062

Cost per kWh	0.02	**$/kWh**	
Equipment Efficiency	70%		given by the manufacturer
Power supply consumption	4.93	**kWh**	
Power supply energy cost	$0.08	$	
Pump power	0.58	**kW**	given by the Manufacturer
Pump energy consumption	1.73	**kWh**	
Pump energy cost	$0.03	**$**	
			0.575
Pump + Rectifier energy	6.65	**kWh**	
Pump + Rectifier energy cost	$0.11	**$**	
Energy + Electrode Cost	0.138	**$**	

Type of treatment	with tank flotation and 9th cell of aluminum electrode					**Date**	6/30/2009	
Electrodes	Carbon Steel		Combined		Aluminum			
Current, I	10	**amps**						
Avg. Voltage, U	115	**V**						
Volumen, V	90	**L**						
Flow rate, Q	0.5	**L/min**						
Running Time, t	3.0	**h**						
Electrode Density	2738.21	**Kg/m3**			1023.05	**Kg/m3**		
	2738214.0	**g/m3**			1023047.4	**g/m3**		
Electrode consumption	26.2	**g**	32.6	**g**	6.4	**g**		
	9.5683E-06	**m3**			6.27537E-06	**m3**		
Dissolved Metal Concentration	291.1	**mg/L**	362.4444	**mg/L**	71.3	**mg/L**		
Electrode Unit Cost	4054.3	**$/m3**			6371.0	**$/m3**		
Total Electrode Cost	0.039	**$**	$0.08	**$**	0.040	**$**		
Electrode surface Area	12.46	**cm2**			12.46	**cm2**		
# Electrodes	7	**u**			2	**u**		
Total Surface Area one side	74.76	**cm2**			12.46	**cm2**		
Total Surface Area	149.52	**cm2**			24.92	**cm2**		
Current Density one side	0.134	**A/cm2**			0.803	**A/cm2**		
	0.863	**A/in2**			5.178	**A/in2**		
Current Density	0.067	**A/cm2**	66.88	**mA/cm2**	0.401	**A/cm2**	401.28	**mA/cm2**
	0.431	**A/in2**			2.589	**A/in2**		

Specific energy consumption	**Co**	**Cf**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	1.78	450	160.2	0.29	22.96	64%	0.66	8.88E-03
Nickel	1.5	0.66	135	59.4	0.08	88.01	56%	2.52	2.32E-03
Zinc	2.5	0.02	225	1.8	0.22	29.81	99%	0.85	6.84E-03
Turbidity	1000	55.4	90000	4986	85.01	0.08	94%	0.00	2.61E+00

Oil	5000	31.4	450000	2826	447.17	0.01	99%	0.00	1.37E+01

Cost per kWh	0.02	**$/kWh**	
Equipment Efficiency	70%		given by the manufacturer
Power supply consumption	4.93	**kWh**	
Power supply energy cost	$0.08	$	
Pump power	0.58	**kW**	given by the Manufacturer
Pump energy consumption	1.73	**kWh**	
Pump energy cost	$0.03	**$**	
			0.575
Pump + Rectifier energy	6.65	**kWh**	
Pump + Rectifier energy cost	$0.11	**$**	
Energy + Electrode Cost	0.190	**$**	

Conic Clarifier, two passes		**Date**	7/9/2009		
Electrodes	Carbon Steel			Aluminum	
Current, I	10	**amps**			
Avg. Voltage, U	115	**V**			
Flow rate, Q	1	**L/min**			
Electrode Density	2738.21	**Kg/m3**		1023.05	**Kg/m3**
	2738214.0	**g/m3**		1023047.4	**g/m3**
Volume					
1st pass, V1	90	**L**			
2nd pass, V2	45	**L**			
Overall, Vt	135	**L**			
Running Time, t					
1st pass, t1	1.5	**h**			
2nd pass, t2	0.8	**h**			
Overall, t	2.3	**h**			
Electrode Consumption					
Molecular Weight	55.847	**g/mol Fe**		26.98154	**g/mol Al**
1st pass	13.8	**g**		2.8	**g**
	5.02E-06	**m3**		2.70E-06	**m3**
	2.46E-01	**mol Fe**		1.02E-01	**mol Al**
2nd pass	4.7	**g**		1.2	**g**
	1.73E-06	**m3**		1.18E-06	**m3**
	8.51E-02	**mol Fe**		4.48E-02	**mol Al**
Overall	18.5	**g**		4.0	**g**
	6.76E-06	**m3**		3.88E-06	**m3**
	3.31E-01	**mol Fe**		1.47E-01	**mol Al**
Dissolved Metal Concentration					
	Carbon Steel		**Combined**	**Aluminum**	

1st pass	152.8	**mg/L**			30.7	**mg/L**
	2.74E-03	**mol/L**	3.87E-03	**mol/L**	1.14E-03	**mol/L**
2nd pass	105.6	**mg/L**			26.9	**mg/L**
	1.89E-03	**mol/L**	2.89E-03	**mol/L**	9.97E-04	**mol/L**
Overall	137.0	**mg/L**			29.4	**mg/L**
	2.45E-03	**mol/L**	3.54E-03	**mol/L**	1.09E-03	**mol/L**

Electrode Cost

Electrode Unit Cost	4054.3	**$/m3**	**Combined**		6371.0	**$/m3**
1st Pass Cost	0.020	**$**	$0.03	**$**	0.011	**$**
2nd Pass Cost	0.007	**$**	$0.01	**$**	0.005	**$**
Overall Cost	0.027	**$**	$0.05	**$**	0.025	**$**

Cross sectional Area	12.46	**cm2**	12.46	**cm2**
# Electrodes	7	**u**	2	**u**
Curent Density	0.803	**A/cm2**	0.161	**A/cm2**
	802.57	**mA/cm2**	160.51	**mA/cm2**
Cost per kWh	0.02	**$/kWh**		

Power supply Energy Consumption & Cost

Equipment Efficiency	70%		given by the manufacturer	
1st pass	2.46	**kWh**	$0.04	**$**
2nd pass	1.23	**kWh**	$0.02	**$**
Overall	3.70	**kWh**	$0.06	**$**

Pump Energy Consumption & Cost

Pump Power	0.58	kW	given by the manufacturer	
1st pass	0.87	**kWh**	$0.01	**$**
2nd pass	0.44	**kWh**	$0.01	**$**
Overall	1.31	**kWh**	$0.02	**$**

Total Energy Consumption and Electrode Consumption

	Power Supply & Pump		Electrode	
1st pass	3.33	**kWh**	0.3	**mol**
2nd pass	1.67	**kWh**	0.1	**mol**
Overall	5.00	**kWh**	0.5	**mol**

Total Treatment Costs

	Energy	Carbon	Aluminum	Total
1st pass	$0.06	$0.02	$0.01	$0.09
2nd pass	$0.03	$0.01	$0.00	$0.04
Overall	$0.08	$0.03	$0.02	$0.14

First Pass **Vol** 90 **L**

Specific energy consumption	Co (mg/L)	Ci (mg/L)	Mo (mg)	Mf (mg)	Mremoved (g)	SEC KWh/g	Efficiency Co-Ci	Cost $/g	g pollutant/g electrode
Copper	5	1.62	450	145.8	0.30	10.96	67.6%	$0.29	8.7E-01
Nickel	1.5	0.95	135	85.5	0.05	67.36	36.7%	$1.76	1.4E-01
Zinc	2.5	0.04	225	3.6	0.22	15.06	98.4%	$0.39	6.4E-01
Turbidity	1000	176	90000	15840	74.16	0.04	82.4%	$0.00	2.1E+02
Oil	5000	8.4	450000	756	449.24	0.01	99.8%	$0.00	1.3E+03

Second Pass **Vol** 45 **L**

Specific energy comsumption	Ci (mg/L)	Cf (mg/L)	Mo (mg)	Mf (mg)	Mremoved (g)	SEC KWh/g	Efficiency Ci-Cf	Cost $/g	g pollutant/g electrode
Copper	1.62	1.52	72.9	68.4	0.00	370.48	6.2%	$8.84	3.5E-02
Nickel	0.95	0.36	42.75	16.2	0.03	62.79	62.1%	$1.50	2.0E-01
Zinc	0.04	0.01	1.8	0.45	0.00	1234.92	75.0%	$29.46	1.0E-02
Turbidity	176	14.8	7920	666	7.25	0.23	91.6%	$0.01	5.6E+01
Oil	8.4	5	378	225	0.15	10.90	40.5%	$0.26	1.2E+00

Overall			90 L	45 L					
Specific energy comsumption	**Co (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	1.52			0.31	16.20	69.6%	$0.44	6.5E-01
Nickel	1.5	0.36			0.08	65.77	76.0%	$1.79	1.6E-01
Zinc	2.5	0.01			0.22	22.45	99.6%	$0.61	4.7E-01
Turbidity	1000	14.8			81.41	0.06	98.5%	$0.00	1.7E+02
Oil	5000	5			449.40	0.01	99.9%	$0.00	9.4E+02

Conic Clarifier, two passes		**Date**	9/27/2009		
Electrodes	Carbon Steel			Aluminum	
Current, I	5	**amps**			
Avg. Voltage, U wall	115	**V**			
Flow rate, Q	1	**L/min**			
Electrode Density	2738.21	**Kg/m3**		1023.05	**Kg/m3**
	2738214.0	**g/m3**		1023047.4	**g/m3**
Volume					
1st pass, V1	28	**L**			
2nd pass, V2	24	**L**			
Overall, Vt	52	**L**			
Running Time, t					
1st pass, t1	0.5	**h**			
2nd pass, t2	0.4	**h**			
Overall, t	0.9	**h**			
Electrode Consumption					
Molecular Weight	55.847	**g/mol Fe**		26.98154	**g/mol Al**
1st pass	9.1	**g**		1.2	**g**
	3.34E-06	**m3**		1.18E-06	**m3**
	1.64E-01	**mol Fe**		4.48E-02	**mol Al**
2nd pass	7.1	**g**		1.1	**g**
	2.60E-06	**m3**		1.04E-06	**m3**
	1.27E-01	**mol Fe**		3.93E-02	**mol Al**
Overall	16.3	**g**		2.3	**g**
	5.94E-06	**m3**		2.22E-06	**m3**
	2.91E-01	**mol Fe**		8.41E-02	**mol Al**

Dissolved Metal Concentration

	Carbon Steel		Combined		Aluminum	
1st pass	326.4	mg/L			43.2	mg/L
	5.85E-03	mol/L	7.45E-03	mol/L	1.60E-03	mol/L
2nd pass	296.7	mg/L			44.2	mg/L
	5.31E-03	mol/L	6.95E-03	mol/L	1.64E-03	mol/L
Overall	312.7	mg/L			43.7	mg/L
	5.60E-03	mol/L	7.22E-03	mol/L	1.62E-03	mol/L

Electrode Cost

			Combined			
Electrode Unit Cost	4054.3	$/m3			6371.0	$/m3
1st Pass Cost	0.014	$	$0.02	$	0.005	$
2nd Pass Cost	0.011	$	$0.01	$	0.004	$
Overall Cost	0.024	$	$0.04	$	0.014	$

Cross sectional Area	12.46	cm2	12.46	cm2
# Electrodes	7	u	2	u
Curent Density	0.401	A/cm2	0.401	A/cm2
	401.28	mA/cm2	401.28	mA/cm2
Cost per kWh	0.02	$/kWh		

Power supply Energy Consumption & Cost

Equipment Efficiency	70%		given by the manufacturer	
1st pass	0.38	kWh	$0.01	$
2nd pass	0.33	kWh	$0.01	$
Overall	0.71	kWh	$0.01	$

Pump Energy Consumption & Cost

Pump Power	0.58	kW	given by the manufacturer

1st pass	0.27	**kWh**	$0.00	**$**
2nd pass	0.23	**kWh**	$0.00	**$**
Overall	0.50	**kWh**	$0.01	**$**

Total Energy Consumption and Electrode Consumption

	Power Supply & Pump		**Electrode**	
1st pass	0.65	**kWh**	0.2	**mol**
2nd pass	0.56	**kWh**	0.2	**mol**
Overall	1.21	**kWh**	0.4	**mol**

Total Treatment Costs

	Energy	**Carbon**	**Aluminum**	**Total**
1st pass	$0.01	$0.01	$0.00	$0.03
2nd pass	$0.01	$0.01	$0.00	$0.02
Overall	$0.02	$0.02	$0.01	$0.06

First Pass **Vol** 28 **L**

Specific energy consumption	**Co (mg/L)**	**Ci (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Ci**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	3.01	140	84.28	0.06	11.74	39.8%	$0.53	2.7E-01
Nickel	1.5	1.76	42	49.28	-0.01	-89.84	-17.3%	($4.02)	-3.5E-02
Zinc	2.5	0.01	70	0.28	0.07	9.38	99.6%	$0.42	3.3E-01
Turbidity	1000	93.7	28000	2623.6	25.38	0.03	90.6%	$0.00	1.2E+02
Oil	5000	10.7	140000	299.6	139.70	0.00	99.8%	$0.00	6.7E+02

Second Pass **Vol** 24 **L**

Specific energy consumption	**Ci (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Ci-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	3.01	2.26	72.24	54.24	0.02	31.14	24.9%	$1.34	1.1E-01

Nickel	1.76	0.49	42.24	11.76	0.03	18.39	72.2%	$0.79	1.8E-01
Zinc	0.01	1.00E-02	0.24	0.24	0.00	#DIV/0!	0.0%	#DIV/0!	0.0E+00
Turbidity	93.7	15.7	2248.8	376.8	1.87	0.30	83.2%	$0.01	1.1E+01
Oil	10.7	5	256.8	120	0.14	4.10	53.3%	$0.18	8.2E-01

Overall			**90 L**	**45 L**					
Specific energy consumption	**Co (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	2.26			0.07	16.48	54.8%	$0.79	2.0E-01
Nickel	1.5	0.49	42	11.76	0.03	40.16	67.3%	$1.94	8.1E-02
Zinc	2.5	0.01	70	0.24	0.07	17.41	99.6%	$0.84	1.9E-01
Turbidity	1000	15.7			27.25	0.04	98.4%	$0.00	7.3E+01
Oil	5000	5			139.84	0.01	99.9%	$0.00	3.7E+02

Conic Clarifier, two passes **Date** 10/11/2009

Electrodes	Carbon Steel		Aluminum	
Current, I	10	**amps**		
Avg. Voltage, U wall	115	**V**		
Flow rate, Q	1	**L/min**		
Electrode Density	2738.21	**Kg/m3**	1023.05	**Kg/m3**
	2738214.0	**g/m3**	1023047.4	**g/m3**
Volume				
1st pass, V1	27	**L**		
2nd pass, V2	17	**L**		
Overall, Vt	44	**L**		
Running Time, t				
1st pass, t1	0.5	**h**		
2nd pass, t2	0.3	**h**		
Overall, t	0.7	**h**		
Electrode Consumption				
Molecular Weight	55.847	**g/mol Fe**	26.98154	**g/mol Al**
1st pass	6.0	**g**	1.2	**g**
	2.20E-06	**m3**	1.18E-06	**m3**
	1.08E-01	**mol Fe**	4.48E-02	**mol Al**
2nd pass	3.1	**g**	1.1	**g**
	1.12E-06	**m3**	1.06E-06	**m3**
	5.48E-02	**mol Fe**	4.00E-02	**mol Al**
Overall	9.1	**g**	2.3	**g**
	3.32E-06	**m3**	2.24E-06	**m3**
	1.63E-01	**mol Fe**	8.49E-02	**mol Al**

Dissolved Metal Concentration

	Carbon Steel		Combined		Aluminum	
1st pass	223.3	**mg/L**			44.8	**mg/L**
	4.00E-03	**mol/L**	5.66E-03	**mol/L**	1.66E-03	**mol/L**
2nd pass	180.0	**mg/L**			63.5	**mg/L**
	3.22E-03	**mol/L**	5.58E-03	**mol/L**	2.35E-03	**mol/L**
Overall	206.6	**mg/L**			52.0	**mg/L**
	3.70E-03	**mol/L**	5.63E-03	**mol/L**	1.93E-03	**mol/L**

Electrode Cost

			Combined			
Electrode Unit Cost	4054.3	**$/m3**			6371.0	**$/m3**
1st Pass Cost	0.009	**$**	$0.01	**$**	0.005	**$**
2nd Pass Cost	0.005	**$**	$0.01	**$**	0.004	**$**
Overall Cost	0.013	**$**	$0.03	**$**	0.014	**$**

Cross sectional Area	12.46	**cm2**			12.46	**cm2**
# Electrodes	7	**u**			2	**u**
Current Density at 5 electrodes	0.803	**A/cm2**			0.803	**A/cm2**
	802.57	**mA/cm2**			802.57	**mA/cm2**

Cost per kWh	0.02	**$/kWh**

Power supply Energy Consumption & Cost

Equipment Efficiency	70%		given by the manufacturer	
1st pass	0.74	**kWh**	$0.01	**$**
2nd pass	0.47	**kWh**	$0.01	**$**
Overall	1.20	**kWh**	$0.02	**$**

Pump Energy Consumption & Cost

Pump Power	0.58	kW	given by the manufacturer	
1st pass	0.26	**kWh**	$0.00	**$**
2nd pass	0.16	**kWh**	$0.00	**$**
Overall	0.43	**kWh**	$0.01	**$**

Total Energy Consumption and Electrode Consumption

	Power Supply & Pump		**Electrode**	
1st pass	1.00	**kWh**	0.2	**mol**
2nd pass	0.63	**kWh**	0.1	**mol**
Overall	1.63	**kWh**	0.2	**mol**

Total Treatment Costs

	Energy	**Carbon**	**Aluminum**	**Total**
1st pass	$0.02	$0.01	$0.00	$0.03
2nd pass	$0.01	$0.00	$0.00	$0.02
Overall	$0.03	$0.01	$0.01	$0.06

First Pass **Vol** 27 **L**

Specific energy consumption	**Co (mg/L)**	**Ci (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Ci**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	2.23	135	60.21	0.07	13.37	55.4%	$0.41	4.9E-01
Nickel	1.5	1.73	40.5	46.71	-0.01	-161.08	-15.3%	-$4.91	-4.1E-02
Zinc	2.5	0.01	67.5	0.27	0.07	14.88	99.6%	$0.45	4.4E-01
Turbidity	1000	49.6	27000	1339.2	25.66	0.04	95.0%	$0.00	1.7E+02
Oil	5000	10.7	135000	288.9	134.71	0.01	99.8%	$0.00	8.8E+02

Second Pass **Vol** 17 **L**

Specific energy consumption	**Ci (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Ci-Cf**	**Cost $/g**	**g pollutant/g electrode**

Copper	2.23	2.26	37.91	38.42	0.00	-1234.92	-1.3%	-$37.97	-5.4E-03
Nickel	1.73	0.62	29.41	10.54	0.02	33.38	64.2%	$1.03	2.0E-01
Zinc	0.01	0.01	0.17	0.17	0.00	#DIV/0!	0.0%	#DIV/0!	0.0E+00
Turbidity	49.6	16	843.2	272	0.57	1.10	67.7%	$0.03	6.0E+00
Oil	10.7	5	181.9	85	0.10	6.50	53.3%	$0.20	1.0E+00

Overall			**90 L**	**45 L**					
Specific energy consumption	**Co (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Cf**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	2.26	135	38.42	0.10	16.88	54.8%	$0.57	3.9E-01
Nickel	1.5	0.62	40.5	10.54	0.03	54.41	58.7%	$1.84	1.2E-01
Zinc	2.5	0.01	67.5	0.17	0.07	24.21	99.6%	$0.82	2.7E-01
Turbidity	1000	16			26.23	0.06	98.4%	$0.00	1.1E+02
Oil	5000	5			134.81	0.01	99.9%	$0.00	5.4E+02

Conic Clarifier, two passes			**Date**	**10/20/2009**	
Electrodes	**Carbon Steel**			**Aluminum**	
Current, I	7.5	**amps**			
Avg. Voltage, U wall	115	**V**			
Flow rate, Q	1	**L/min**			
Electrode Density	2738.21	**Kg/m3**		1023.05	**Kg/m3**
	2738214.0	**g/m3**		1023047.4	**g/m3**
Volume					
1st pass, V1	28.5	**L**			
2nd pass, V2	17	**L**			
Overall, Vt	45.5	**L**			
Running Time, t					
1st pass, t1	0.5	**h**			
2nd pass, t2	0.3	**h**			
Overall, t	0.8	**h**			
Electrode Consumption					
Molecular Weight	55.847	**g/mol Fe**		26.98154	**g/mol Al**
1st pass	4.8	**g**		0.8	**g**
	1.75E-06	**m3**		8.02E-07	**m3**
	8.56E-02	**mol Fe**		3.04E-02	**mol Al**
2nd pass	2.2	**g**		0.5	**g**
	7.96E-07	**m3**		4.99E-07	**m3**
	3.90E-02	**mol Fe**		1.89E-02	**mol Al**
Overall	7.0	**g**		1.3	**g**
	2.54E-06	**m3**		1.30E-06	**m3**
	1.25E-01	**mol Fe**		4.93E-02	**mol Al**

Dissolved Metal Concentration

	Carbon Steel		Combined		Aluminum	
1st pass	167.7	**mg/L**			28.8	**mg/L**
	3.00E-03	**mol/L**	4.07E-03	**mol/L**	1.07E-03	**mol/L**
2nd pass	128.2	**mg/L**			30.0	**mg/L**
	2.30E-03	**mol/L**	3.41E-03	**mol/L**	1.11E-03	**mol/L**
Overall	153.0	**mg/L**			29.2	**mg/L**
	2.74E-03	**mol/L**	3.82E-03	**mol/L**	1.08E-03	**mol/L**

Electrode Cost

Electrode Unit Cost	4054.3	**$/m3**	**Combined**		6371.0	**$/m3**
1st Pass Cost	0.007	**$**	$0.01	**$**	0.003	**$**
2nd Pass Cost	0.003	**$**	$0.01	**$**	0.002	**$**
Overall Cost	0.010	**$**	$0.02	**$**	0.008	**$**

Cross sectional Area	12.46	**cm2**	12.46	**cm2**
# Electrodes	7	**u**	2	**u**
Current Density at 5 electrodes	0.602	**A/cm2**	0.602	**A/cm2**
	601.93	**mA/cm2**	601.93	**mA/cm2**

Cost per kWh	0.02	**$/kWh**

Power supply Energy Consumption & Cost

Equipment Efficiency	70%		given by the manufacturer	
1st pass	0.59	**kWh**	$0.01	**$**
2nd pass	0.35	**kWh**	$0.01	**$**
Overall	0.93	**kWh**	$0.02	**$**

Pump Energy Consumption & Cost

Pump Power	0.58	kW	given by the manufacturer	
1st pass	0.28	**kWh**	$0.00	**$**
2nd pass	0.16	**kWh**	$0.00	**$**
Overall	0.44	**kWh**	$0.01	**$**

Total Energy Consumption and Electrode Consumption

	Power Supply & Pump		**Electrode**	
1st pass	0.86	**kWh**	0.1	**mol**
2nd pass	0.51	**kWh**	0.1	**mol**
Overall	1.37	**kWh**	0.2	**mol**

Total Treatment Costs

	Energy	**Carbon**	**Aluminum**	**Total**
1st pass	$0.01	$0.01	$0.00	$0.02
2nd pass	$0.01	$0.00	$0.00	$0.01
Overall	$0.02	$0.01	$0.01	$0.04

First Pass **Vol** 28.5 **L**

Specific energy consumption	**Co (mg/L)**	**Ci (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Ci**	**Cost $/g**	**g pollutant/g electrode**
Copper	5	2.78	142.5	79.23	0.063	13.60	44.4%	$0.39	5.5E-01
Nickel	1.5	1.77	42.75	50.445	-0.008	-111.86	-18.0%	($3.22)	-6.6E-02
Zinc	2.5	0.16	71.25	4.56	0.067	12.91	93.6%	$0.37	5.8E-01
Turbidity	1000	52.3	28500	1490.55	27.009	0.03	94.8%	$0.00	2.3E+02
Oil	5000	5.1	142500	145.35	142.355	0.01	99.9%	$0.00	1.2E+03

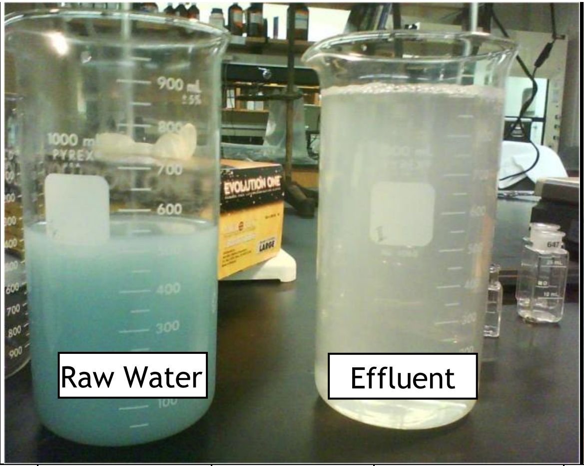
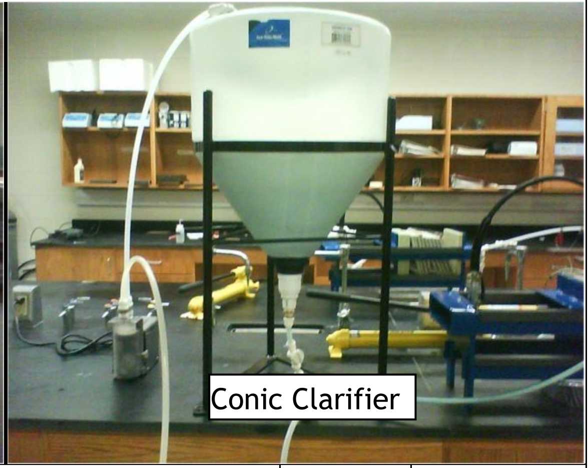
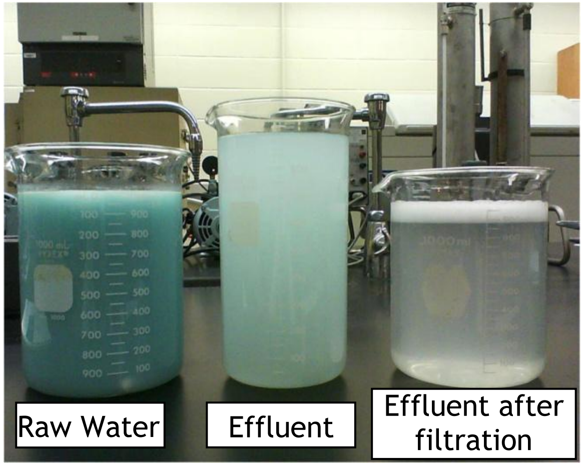
Second Pass **Vol** 17 **L**

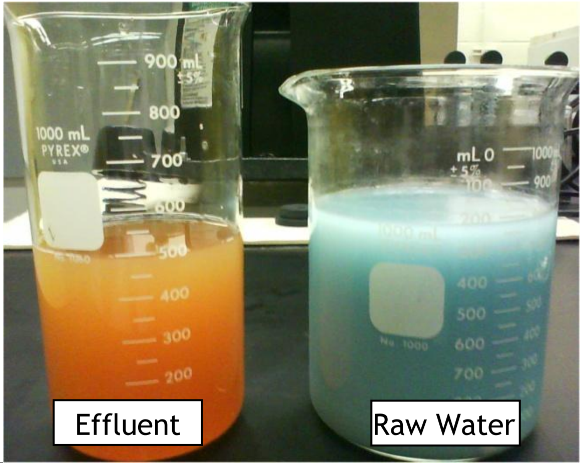
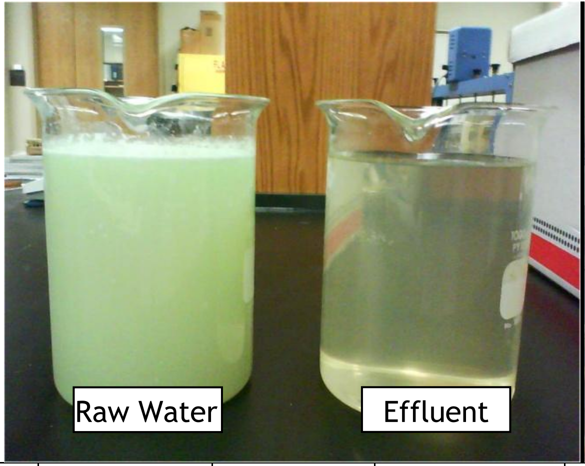
Specific energy consumption	**Ci (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Ci-Cf**	**Cost $/g**	**g pollutant/g electrode**

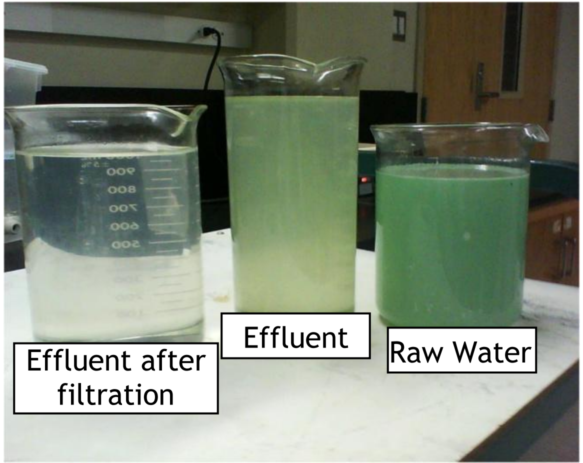
Copper	2.78	2.28	47.26	38.76	0.009	60.40	18.0%	$1.63	1.5E-01
Nickel	1.77	0.98	30.09	16.66	0.013	38.23	44.6%	$1.03	2.3E-01
Zinc	0.16	0.01	2.72	0.17	0.003	201.35	93.8%	$5.43	4.4E-02
Turbidity	52.3	35.8	889.1	608.6	0.281	1.83	31.5%	$0.05	4.8E+00
Oil	5.1	5	86.7	85	0.002	302.02	2.0%	$8.15	2.9E-02

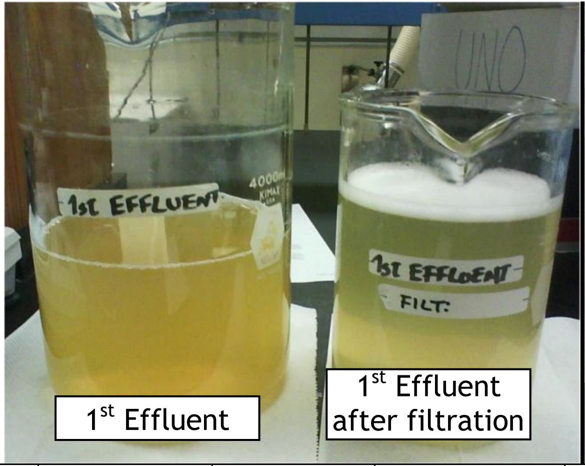
Overall			**90 L**	**45 L**					
Specific energy consumption	**Co (mg/L)**	**Cf (mg/L)**	**Mo (mg)**	**Mf (mg)**	**Mremoved (g)**	**SEC KWh/g**	**Efficiency Co-Cf**	**Cost $/g**	**g pollutant/mol electrode**
Copper	5	2.28			0.072	19.15	54.4%	$0.58	4.1E-01
Nickel	1.5	0.98	42.75	16.66	0.026	52.67	34.7%	$1.60	1.5E-01
Zinc	2.5	0.01			0.069	19.85	99.6%	$0.60	4.0E-01
Turbidity	1000	35.8			27.290	0.05	96.4%	$0.00	1.6E+02
Oil	5000	5			142.356	0.01	99.9%	$0.00	8.2E+02

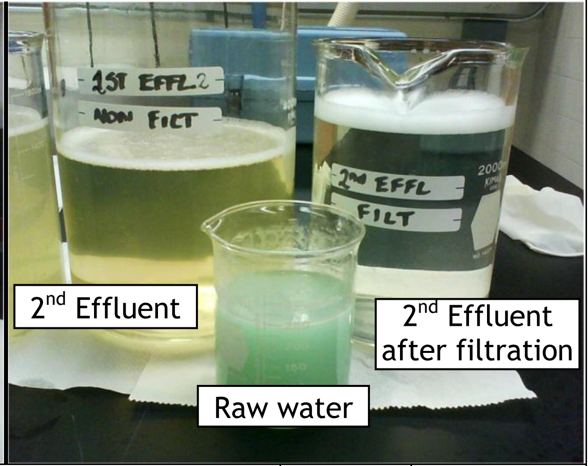
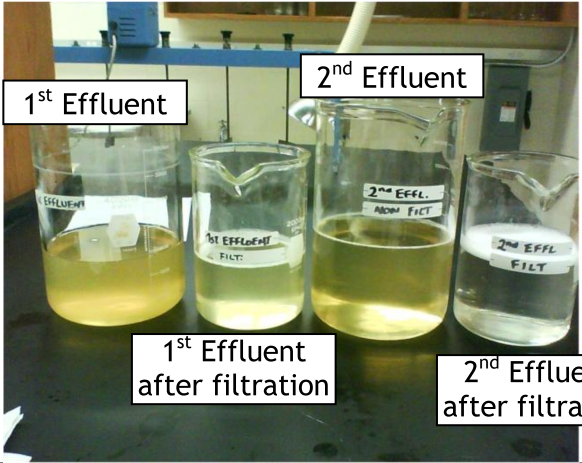
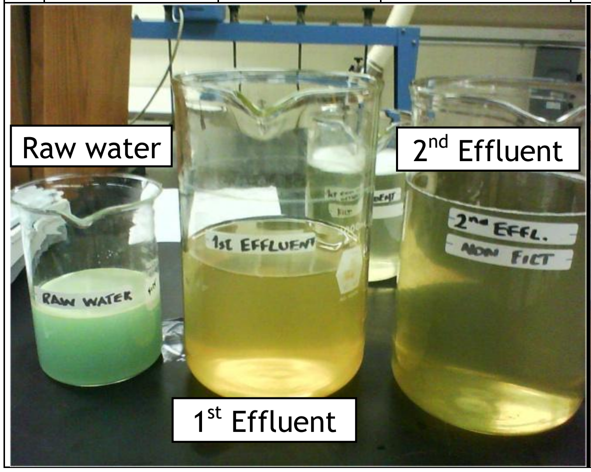
Appendix H: Pictures

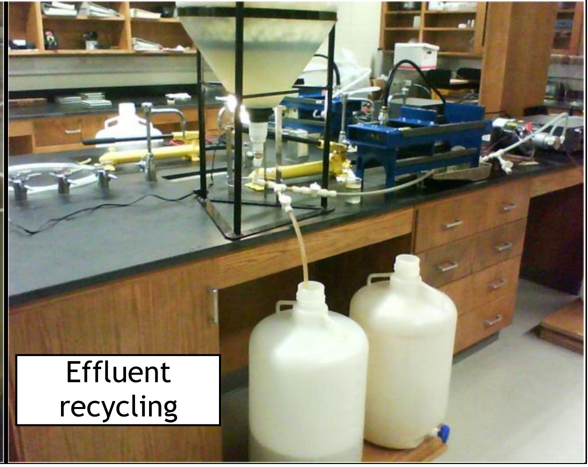
<table>
<tr><th>ID</th><th>Date</th><th>Electrode</th><th>Current (A)</th><th>Flow rate (L/min)</th><th>Recycle</th><th>Clarifier</th></tr>
<tr><td>S1</td><td>3/20/2009</td><td>Al</td><td>10</td><td>1</td><td>✓</td><td>Conic</td></tr>
<tr><td colspan="7">  </td></tr>
<tr><td>S2</td><td>3/24/2009</td><td>Al</td><td>10</td><td>0.5</td><td>✗</td><td>Conic</td></tr>
<tr><td colspan="7"> </td></tr>
<tr><td>S3</td><td>3/26/2009</td><td>Cs</td><td>10</td><td>0.5</td><td>✗</td><td>Rectangular</td></tr>
</table>

<table>
<tr><th>ID</th><th>Date</th><th>Electrode</th><th>Current (A)</th><th>Flow rate (L/min)</th><th>Recycle</th><th>Clarifier</th></tr>
<tr><td colspan="7">
</td></tr>
<tr><td>S4</td><td>6/30/2009</td><td>Cs & Al</td><td>10</td><td>0.5</td><td>✗</td><td>Rectangular</td></tr>
<tr><td colspan="7">


</td></tr>
<tr><td>S5</td><td>7/9/2009</td><td>Cs & Al</td><td>10</td><td>1</td><td>✓</td><td>Conic</td></tr>
<tr><td colspan="7">
</td></tr>
<tr><td>S6</td><td>9/27/2009</td><td>Cs & Al</td><td>5</td><td>1</td><td>✓</td><td>Conic</td></tr>
</table>

<table>
<tr><th>ID</th><th>Date</th><th>Electrode</th><th>Current (A)</th><th>Flow rate (L/min)</th><th>Recycle</th><th>Clarifier</th></tr>
<tr><td colspan="7">


</td></tr>
<tr><td>S7</td><td>10/11/2009</td><td>Cs & Al</td><td>10</td><td>1</td><td>✓</td><td>Conic</td></tr>
<tr><td colspan="7">
</td></tr>
<tr><td>S8</td><td>10/20/2009</td><td>Cs & Al</td><td>7.5</td><td>1</td><td>✓</td><td>Conic</td></tr>
<tr><td colspan="7">


</td></tr>
</table>

Vita

Milton G. Andrade born in Guayaquil, Ecuador in January, 1980; is the 4th son of Nicolas and Juanita. From his dad he got the love for the engineering and from his mom he got the love for goodness. In 2004, he got his Bachelor of Science in Civil Engineering at the Escuela Superior Politecnica del Litoral in Guayaquil. Between 2005 and 2006, he lived in a Salesian Mission, in the Ecuadorian amazonic jungle, working in social development projects with shuar natives. After a couple of years working as an environmental consulter, in 2008 he went to New Orleans, United States, honored with a Graduate Research Assistantship, to get his Master of Science in Civil and Environmental Engineering at the University of New Orleans. His research focused on electrochemical techniques for wastewater treatment.

Milton's home address is La Saiba Bloque C-3 Apt. # 102, Guayaquil, Ecuador; his e-mail address is mal_007@hotmail.com.

This thesis was typed by the author. All the illustrations, tables, pictures were made by the author.

Nemo dat quon non habet.