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Evaluation of an Electro-Disinfection Technology as an Alternative to Chlorination of Municipal Wastewater Effluents

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EVALUATION OF AN ELECTRO-DISINFECTION TECHNOLOGY AS AN ALTERNATIVE TO CHLORINATION OF MUNICIPAL WASTEWATER EFFLUENTS

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ABSTRACT

This research evaluated and demonstrated the disinfection efficiency of an electrochemical system for total coliform removal from wastewater effluents after secondary treatment. Four bench scale batch electrochemical cells were assembled and operated in the laboratory: the first electro-disinfection reactor was set with aluminum electrodes, the second with standard 316 stainless steel electrodes, the third one with titanium electrodes, and the fourth one with a standard 316 stainless steel cathode and a titanium anode. During the electro-disinfection process the water sample was placed on the reactor/disinfector to which direct current (DC) was charged.

The results showed that total coliform counts in the treated water decreased significantly and that the characteristics of the effluent were highly improved, especially when stainless steel or titanium electrodes were employed. A bactericidal efficiency of 98.7 % or higher was achieved within a contact time of less than 15 min and a current density lower than 7.5 mA/cm^2 when stainless steel electrodes were used, and a contact time of less than 5 min and a current density lower than 3.5 mA/cm^2 when the stainless steel/titanium cell was utilized.

Electrochlorination does not seem to be the predominant disinfective means of the process. Production of other short lived and more powerful killing substances such as H_2O_2, [O], ·OH, and ·HO$_2$ provide the strong disinfecting action of the system within a short contact time. The bactericidal efficiency of the process generally increased with the current density and contact time, and the impact of these factors was much larger than that of salinity.

The results obtained suggest that this electrochemical treatment is applicable to wastewater effluents. However, further investigation on the optimum operating conditions and a detailed comparative study of energy consumption by the electrochemical treatment system and the conventional methods are needed before constructing an industrial application system in the future. It is also indispensable to find out if halogenated hydrocarbons and other toxic compounds are produced during the process.

CHAPTER 1

INTRODUCTION

Disinfection is the final step involved in the treatment of municipal wastewater. Up to now, chlorination is the most prevalent wastewater disinfection method. However, despite its effectiveness, presently there are serious safety concerns and ecological problems associated with its use.

Storage, shipping, and handling of all forms of chlorine pose a risk to public health, and, as a result, increased safety regulations have been issued. Chlorine is a greenish-yellow gas which is an irritant poison when inhaled even in small quantities. According to the National Transportation Safety Board and the Coast Guard, a large leak of chlorine gas can travel two miles in only 10 minutes and remain acutely toxic to a distance of about 20 miles. As a consequence, many wastewater treatment plants using massive yearly amounts of chlorine gas have made the decision to switch from chlorine gas to an alternative disinfectant.

Additional disadvantages associated with the use of this chemical are: formation of undesirable hazardous compounds (such as THMs, known carcinogens); chlorine residual can harm aquatic systems; the level of total dissolved solids in the treated effluent is increased; some parasitic species have shown resistance to low doses of chlorine; long-term effects of discharging dechlorinated compounds into the environment are unknown.

Alternatives to disinfection with chlorine gas and hypochlorite have been developed to avoid some of these problems. Methods such as ultraviolet radiation, ozonation, and ClO_2 treatment have demonstrated effective reduction of pathogenic organisms in water and wastewater but are usually expensive or less convenient than chlorination. Consequently, new-fangled methods of wastewater disinfection that are effective, reliable, economic, and environmentally friendly are urgently needed.

As the country moves into a new era of treatment requirements, wastewater disinfection strategies must respond to a variety of site specific issues. Compliance with specific water quality discharge or receiving water limitations is commonly required by the National Pollutant Discharge Elimination System. Such limitations can vary depending on the different state regulations and on the characteristics of the particular receiving water body.

The Louisiana Pollutant Discharge Elimination System Permit that regulates wastewater treatment discharges in the New Orleans metropolitan area establishes 0.5 mg/l of total residual chlorine as limitation to ensure protection of aquatic life and maintenance of the Mississippi River as aquatic habitat. Due to the fact that concentrations of total residual chlorine are acutely and chronically toxic to aquatic organisms in freshwater at levels above 0.019 mg/l and 0.011 mg/l respectively, a future limitation might be established based upon the critical low flow of the Mississippi River and dilution factors. If such a limitation were imposed, the wastewater treatment plants would be required to provide for dechlorination of the effluent prior to discharge.

Under these circumstances, several wastewater treatment facilities are considering the elimination of chlorine gas and are looking for alternative wastewater disinfection processes. To satisfy this need, this research evaluates and demonstrates the efficiency of an electrochemical system to be used for disinfection of municipal wastewater effluents after secondary treatment.

This practice is different from the conventional electrochlorination which relies on the production of a concentrated hypochlorite solution by electrolyzing a side brine. During the electro-disinfection process, all the water is forced through a contactor/disinfector that is equipped with electrodes on which direct current (DC) or alternative current (AC) is charged. Experiments have demonstrated that the electro-disinfection process can kill a large spectrum of microorganisms, from viruses to bacteria within a short contact time for potable water, raw water supply, milk and liquid foodstuffs, and treated wastewater effluent (Li, Lo and Sin, 2002). The main advantage of the electro-disinfection process is the production of disinfective conditions *in situ* in the treatment device, thus avoiding the drawbacks of common chlorination such as transport and storage of dangerous chlorine.

At this time the mechanism of the disinfective action of the process, the production of lethal species, and their nature and influence on bacteria seem to be unknown in their greatest part. They depend on the nature of the electrodes, the quality of water, the type of current used, energy input, and other operational conditions (Patermarakis, 1990). Therefore, further investigations are needed to elucidate the killing mechanisms of the electro-disinfection process.

1.1 OBJECTIVES OF THIS INVESTIGATION

The main objective of the research project reported herein is to evaluate the innovative electro-disinfection technology in the laboratory for the disinfection of wastewater effluents, examining the effects of critical operational parameters on the process performance such as electrode material, residence time, energy consumption, and salinity of the wastewater.

Additional specific research objectives of the dissertation are as follows:

1. Evaluate three different electrode materials.

2. Determine optimum system operating parameters.

3. Document that chlorine species and other strong oxidants are generated in the process.

4. Evaluate the effect of the process on selected wastewater characteristics (pH, ORP, conductivity, temperature).

CHAPTER 2

LITERATURE REVIEW

2.1 WASTEWATER DISINFECTION

Disinfection refers to the inactivation and/or destruction of pathogenic (disease-causing) organisms in order to prevent the spread of waterborne diseases (Metcalf & Eddy, 2003). Wastewater disinfection is practiced using many different means to improve water quality for subsequent downstream use, such as growing shellfish, irrigating crops, public water supply or for swimming. A water body receiving inadequately disinfected wastewater effluent is definitely an avenue for the propagation and transmission of disease.

The organisms of concern in municipal wastewater include enteric bacteria, viruses, and protozoa. Some common microorganisms found in domestic wastewater and the diseases associated with them are presented in Table 1.

There are millions of coliform bacteria and large numbers of fecal streptococci in a liter of raw domestic wastewater. The numbers of these indicator organisms may vary widely in different wastewaters and, from time to time, in any particular wastewater, as presented in Table 2 (WEF, 1996).

Table 1. Infectious agents potentially present in raw domestic wastewater

Organism	Disease
Bacteria	
Escherichia coli	Gastroenteritis
Legionella pneumophila	Legionellosis
Leptospira	Leptospirosis
Salmonella typhi	Typhoid fever
Salmonella	Salmonellosis
Shigella	Shigellosis
Vibrio cholerae	Cholera
Yersinia enterolitica	Yerinosis
Viruses	
Adenovirus	Respiratory disease
Enteroviruses	Gastroenteritis, heart anomalies, meningitis
Hepatitis A	Infectious hepatitis
Norwalk agent	Gastroenteritis
Reovirus	Gastroenteritis
Rotavirus	Gastroenteritis
Protozoa	
Balantidium coli	Balantidiasis
Cryptosporidium	Cryptosporidiosis
Entamoeba histolytica	Amebiasis
Giardia lamblia	Giardiasis
Helminths	
Ascaris lumbricoides	Ascariasis
Enterobius vericularis	Enterobiasis
Fasciola hepatica	Fascioliasis
Hymenolepis nana	Hymenolepiasis
Taenia saginata	Taeniasis
T. solium	Taeniasis
Trichuris trichuira	Trichuriasis

Source: Metcalf & Eddy, Wastewater Engineering, 4th Edition (2003).

Table 2. Typical wastewater influent concentration ranges for pathogenic and indicator organisms (WEF, 1996).

Organisms	Minimum no./100ml	Maximum no./100ml
Total coliforms	1,000,000	-
Fecal coliforms	340,000	49,000,000
Fecal streptococci	64,000	4,500,000
Virus	0.5	10,000
Cryptosporidium oocysts	85	1,370
Giardia cysts	80	320

A comparison of Tables 2 and 3, which shows typical microorganisms ranges for secondary effluent, demonstrates that conventional treatment of domestic wastewater disinfection cannot be considered sufficient for removal and control of pathogens.

Table 3. Secondary effluent ranges for pathogenic and indicator organisms before disinfection (WEF, 1996).

Organisms	Minimum no./100ml	Maximum no./100ml
Total coliforms	45,000	2,020,000
Fecal coliforms	11,000	1,580,000
Fecal streptococci	2,000	146,000
Virus	0.1	1,000
Salmonella sp.	12	570

Currently, regulators are using many methods to monitor and control the disinfection processes at municipal wastewater treatment plants (WWTPs). In general, standards are directed toward control of chlorine-based disinfection systems and may include limits on detention time, mixing requirements, dosage or residual requirements, and even turbidity and upstream process specifications requiring a high degree of disinfection (WEF, 1996).

In addition, compliance with specific water quality discharge or receiving water limitations is commonly required in the WWTP's National Pollutant Discharge Elimination System permit. Such limitations can vary depending on the different state regulations and on the characteristics of the particular receiving water body (for example, designated uses or dilution capacity), and they usually include a geometric mean or median value, and a maximum value.

The Louisiana Pollutant Discharge Elimination System Permit (NPDES Permit No. LA0038091) that regulates wastewater treatment discharges in the New Orleans metropolitan area establishes the following limitations to ensure protection of aquatic life and maintenance of the receiving water (Mississippi River) as aquatic habitat:

- BOD_5: 30 mg/l (monthly average) and 45 mg/l (weekly average)

- TSS: 30 mg/l (monthly average) and 45 mg/l (weekly average)

- Fecal coliform: 200 MPN/100ml (monthly average) and 400 MPN /100ml (weekly average)

- pH: shall not be less than 6.0 nor greater than 9.0

- Total Residual Chlorine: 0.5 mg/l

- There shall be no discharge of floating solids or visible foam in other than trace amounts

The Mississippi River is as a water body for secondary contact recreation and drinking water supply.

2.1.1 Disinfection Methods

The methods for water disinfection broadly fall into two major categories: physical and chemical (Metcalf & Eddy, 2003).

- Chemical Action:

A variety of chemical agents can be used to inactivate microorganisms. These include halogens and derivatives (Cl_2, Br_2, I_2, HOCl, OCl, ClO_2, HOBr, HOI, etc.), oxygenated and

highly oxidizing compounds (ozone, hydrogen peroxide, phenols, alcohols, persulfate and percarbonate, peracetic acid, potassium permanganate, etc.), dyes, quaternary ammonium compounds, strong acids and bases, and enzymes.

- Physical Action:

Physical disinfectants that can be used are electromagnetic radiation (ultrasonic waves, heat, visible light, UV light, gamma radiation, X-rays), particle radiation (electro beam), and electrical current. Usually these methods are not feasible for disinfecting large quantities of wastewater because of the high cost.

The three most common methods of disinfection in the U.S. are chlorination, ozonation, and ultraviolet (UV) disinfection. All three disinfection methods can effectively meet the discharge permit requirements for treated wastewater. However, the vast majority of wastewater treatment systems use *chlorination* for disinfection. It can be applied as chlorine gas, hypochlorite solutions, and other chlorine compounds in solid or liquid form. Along with meeting the desired characteristics, chlorine has the added advantage of a long history of use and therefore it is fairly well understood.

2.1.2 Mechanisms of Disinfectants

The mechanisms for microbial inactivation include the following:

- Laceration of the cell wall: damage or destruction of the cell wall will result in cell lysis and death.

- Modification of cell permeability: agents such as phenolic compounds and detergents alter the permeability of the cytoplasmic membrane. These substances destroy the selective permeability of the membrane and allow vital nutrients, such as nitrogen and phosphorous, to escape.

- Modification of the nature of the protoplasm: heat, radiation, and highly acidic or alkaline agents alter the colloidal nature of the protoplasm. Heat will coagulate the cell protein, and acids or bases will denature proteins, producing a lethal effect.

- Alteration of nucleic acids.

- Disruption of protein synthesis.

- Induction of abnormal redox processes.

- Inhibition of enzyme activity: oxidizing agents, such as chlorine, can alter the chemical arrangement of enzymes and deactivate them.

Depending on the disinfectant and microorganism type, combinations of these mechanisms can also be responsible for pathogen inactivation. In water treatment, it is believed that the primary factors controlling disinfection efficiency are: (1) the ability of the disinfectant to oxidize or rupture the cell wall; and (2) the ability of the disinfectant to diffuse into the cell and interfere with cellular activity.

A variety of factors influence the disinfection efficiency, including contact time, chemical nature, and concentration of the disinfecting agent as well as the initial mixing mode and point of injection, nature and intensity of the physical agents, temperature, type, concentration and age of the microorganisms, and the nature of the liquid carrier.

2.1.3 Chlorine Disinfection

The addition of chlorine compounds to water for disinfection is called chlorination. Chlorine has many attractive features that contribute to its wide use in industry. Four of the key attributes of chlorine are (EPA 832-F-99-062, 1999):

- It effectively inactivates a wide range of pathogens commonly found in wastewater

- It leaves a residual in the water that is easily measured and controlled

- It is economical

- It has an extensive track record of successful use in improving water treatment operations.

Chlorine is available in a number of different forms:

- *Gas (Cl$_2$):* Also known as elemental chlorine, it is the most commonly used form of chlorine. This toxic, yellow-green gas is stored as a liquid under pressure.

- *Sodium hypochlorite solution (NaOCl):* This solution is clear, light yellow, highly alkaline, and corrosive with a strong chlorine odor. It is often referred to as liquid bleach and contains 5 to 15% chlorine. Currently, sodium hypochlorite can be generated *on site* using an electrochemical process.

- *Calcium hypochlorite (Ca(OCl)$_2$):* This highly corrosive compound is a white, dry solid containing 70% chlorine. It is commercially available in granular, powdered, or tablet form.

- *Chlorine Dioxide (ClO$_2$):* Chlorine dioxide is a strongly oxidizing gas. It is a better virus inactivator than Cl$_2$.

Some of the theories that have been suggested over time to explain the germicidal effects of various chlorine compounds include (Metcalf & Eddy, 1991):

- *Oxidation:* Chlorine diffuses into the cell and oxidizes the cell protoplasm.

- *Protein precipitation:* Chlorine precipitates proteins and may change the chemical arrangement of enzymes or inactivate them directly. So the cell is unable to use its food to produce energy, and it is incapable of reproduction.

- *Modification of cell wall permeability:* Chlorine may destroy the cell wall membrane, allowing vital solutes and nutrients, such as nitrogen and phosphorus, to diffuse out of the cell.

- *Hydrolysis:* Chlorine hydrolyzes the cell wall polysaccharides, which weakens the cell wall and can dehydrate the cell.

Even though the theories mentioned above may all play a part in the destruction of pathogens, the primary mechanism depends on the particular type of microorganisms, the chlorine compound (or species) used, and the characteristics of the wastewater. Also, other factors, such as temperature, alkalinity, and nitrogen-containing compounds, determine the effectiveness of the chlorination process.

Although chlorine gas is extensively used today to disinfect water, high security measures are required specifically with respect to controlled dosing and storage. Several large cities have switched to hypochlorite to avoid the transportation of chlorine through populated areas. Some concerns associated with the use of this chemical for disinfection are listed below (EPA 832-F-99-062, 1999):

- The chlorine residual, even at low concentrations, is toxic to aquatic life and may require dechlorination.

- Chlorine oxidizes certain types of organic matter in wastewater, creating more hazardous compounds or undesirable disinfection byproducts (DBPs), such as THMs, known carcinogens.

- The chloride content of the wastewater is increased as well as the level of total dissolved solids in the treated effluent.

- Chlorine residual is unstable in the presence of high concentrations of chlorine-demanding materials, thus requiring higher doses to effect adequate disinfection.

- Some parasitic species have shown resistance to low doses of chlorine, including oocysts of *Cryptosporidium parvum*, cysts of *Endamoeba histolytica* and *Giardia lamblia*, and eggs of parasitic worms. These parasites cause gastroenteritis and other illnesses.

- Long-term effects of discharging dechlorinated compounds into the environment are unknown.

- All forms of chlorine are highly corrosive and toxic, and therefore, storage, shipping, and handling pose a risk, requiring increased safety regulations.

2.1.3.1 Chlorine Chemistry

When chlorine gas or hypochlorite salts are added to water, hydrolysis and ionization take place to form hypochlorous acid (HOCl) and hypochlorite ions (OCl⁻) (Metcalf & Eddy, 2003):

Hydrolysis:

$$Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$$ ....(Chlorine Gas)

$$Ca\,(OCl)_2 + 2H_2O \leftrightarrow 2HOCl + Ca(OH)_2$$ ....(Calcium Hypochlorite)

$$NaOCl + H_2O \leftrightarrow HOCl + NaOH$$..(Sodium Hypochlorite)

Ionization:

$$HOCl \leftrightarrow H^+ + OCl^-$$
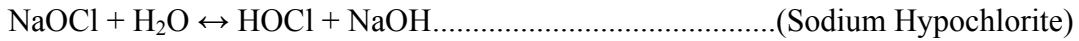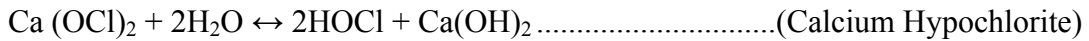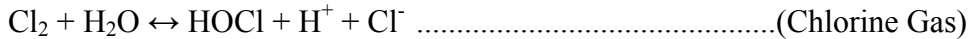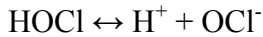
The concentration of chlorine existing in the form of hypochlorous acid and hypochlorite ions is called *free available chlorine*. Hypochlorous acid is the most powerful disinfectant among all the chlorine species.

When chlorine is first added to water containing some impurities, the chlorine immediately reacts with the dissolved inorganic or organic substances and is then unavailable for disinfection. The amount of chlorine used in this initial reaction is the chlorine demand of the water. If dissolved ammonia (NH_3) is present in the water, the chlorine will react with it to form compounds called chloramines. Only after the chlorine demand is satisfied and the reaction with all the dissolved ammonia is complete is the chlorine actually available in the form of HOCl and OCl^-. The equations for the successive reactions of HOCl and NH_3 are as follows:

$$NH_3 + HOCl \leftrightarrow NH_2Cl + H_2O$$ ....(Monochloramine)

$$NH_2Cl + HOCl \leftrightarrow NHCl_2 + H_2O$$ ....(Dichloramine)

$$NHCl_2 + HOCl \leftrightarrow NCl_3 + H_2O$$ ....(Nitrogen Trichloride)
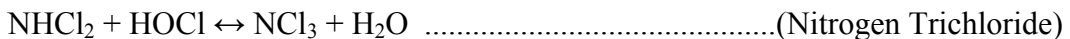
These reactions are very dependent on the pH, temperature, contact time, and the ratio of chlorine to ammonia. The chlorine in these compounds is called *combined available chlorine* and it is also a disinfectant, but slow-reacting. Chloramines are more stable than free chlorine and consequently are very effective for controlling bacterial regrowth in water distribution systems. Concern during the past two decades over formation of chlorinated organics in water treatment and distribution systems increased interest in chloramine disinfection because they form very few DBPs (Metcalf & Eddy, 2003).

2.1.3.2 Gas Chlorination

Chlorine gas is provided in 45.4 kg (100 lb) or 1 ton (907.2 kg) containers and transported in railroad cars or tanker trucks. Chlorine is placed in the container as a liquid. The liquid boils at room temperature, reducing to a gas and building pressure in the cylinder. At room temperature of 21°C, a chlorine cylinder will have a pressure of 5.8 atm (EPA 832-F-99-062, 1999).

Chlorine is relatively simple to apply and control. It is introduced into the wastewater by solution feeders or gas injectors. A gas chlorinator meters the gas flows and mixes it with water, which is then injected as a water solution of pure chlorine. As the compressed liquid chlorine is withdrawn from the cylinder, it expands as a gas, withdrawing heat from the cylinder.

Because chlorine is hazardous, safety precautions must be exercised during all phases of shipment, storage, handling, and use. Emergency response plans are needed for onsite storage of gaseous chlorine. Also a routine operation and maintenance schedule should be developed and followed for any chlorine disinfection system.

For optimum performance, a chlorine disinfection system should display plug flow behavior and be highly turbulent for complete initial mixing in less than 1 second. The contact chamber should have rounded corners to prevent dead flow areas and be baffled to minimize short-circuiting and allow adequate contact time. The two important process control parameters for any chlorination system are the dose and the chlorine residual. Chlorine dosage will vary based on chlorine demand, wastewater characteristics, and discharge requirements. The dose usually ranges from 5 to 20 mg/L. The operational process control parameters are the contact time and the indicator bacteria results (EPA 832-F-99-062, 1999).

Chlorination/dechlorination systems are more complex to operate and maintain than chlorination alone. *Dechlorination* is the process of removing the free and combined chlorine residuals that exists after chlorination to reduce the toxic effects of chlorinated effluents discharged to receiving waters or to be used for reuse applications (Metcalf & Eddy, 2003). Sulfur dioxide, sodium bisulfite, and sodium metabisulfite are the commonly used dechlorinating chemicals. Activated carbon has also been used. The total chlorine residuals can usually be reduced to a level that is not toxic to aquatic life (Connell, 2002).

The cost of chlorine disinfection systems is dependent on the manufacturer, the site, the capacity of the plant, and the characteristics of the wastewater to be disinfected. Hypochlorite compounds are more expensive than chlorine gas. The total cost of chlorination will be increased by approximately 30 to 50% with the addition of dechlorination (EPA 832-F-99-062, 1999).

The annual O&M costs for chlorine disinfection include power consumption, chemicals and supplies, miscellaneous equipment repairs, and personnel costs. Listed in Table 4 are the results of a 1995 study conducted by the Water Environment Research Federation for secondary effluents from disinfection facilities (EPA 832-F-99-062, 1999).

Table 4. Estimated Total Annualized Cost for Chlorination/Dechlorination

| Flow (mgd) | | Cl$_2$ Dose | Capital Costs ($) | | | | O&M |
ADWF	PWWF	(mg/L)	Chlorination	Dechlorination	UFC*	Total	Costs ($)
1	2.25	5	410,000	290,000	239,000	1,127,000	49,300
10	20	5	1,804,000	546,000	264,000	3,137,000	158,200
100	175	5	10,131,000	1,031,000	788,000	14,340,000	660,000
1	2.25	10	441,000	370,000	239,000	1,260,000	59,200
10	20	10	2,051,000	664,000	264,000	3,575,000	226,700
100	175	10	10,258,000	1,258,000	788,000	14,765,000	721,800
1	2.25	20	445,000	374,000	239,000	1,270,000	76,600
10	20	20	2,113,500	913,500	264,000	3,949,000	379,100
100	175	20	10,273,000	1,273,000	788,000	14,801,000	1,311,000

*UFC: Uniform Fire Code
ADWF: average dry weather flow; PWWF: peak wet weather flow
Source: Wastewater Technology Fact Sheet. EPA 832-F-99-062 (September 1999)

2.1.3.3 Hypochlorination

The majority of utilities in the United States transitioned from using gaseous chlorine to the bulk manufactured sodium or calcium hypochlorite due to safety concerns associated with the use, storage and transportation of chlorine gas (Casson and Bess, 2003). The implementation of the Clean Air Act (CAA) Risk Management Plan (RMP) by the USEPA for the storage of hazardous chemicals (June 1999) and the re-registration of chlorine gas by the USEPA Office of Pesticide Programs as a pesticide (Fall 2001) also has accelerated especially the use of liquid sodium hypochlorite in the water and wastewater treatment industry.

Combining chlorine with calcium or sodium produces hypochlorites. Calcium hypochlorites are sold in powder or tablet forms and can contain chlorine concentrations up to 67%. Sodium hypochlorite is a liquid (bleach) and is found in concentrations up to 16%. The compounds are mixed with water and fed into the treated water with solution feed pumps.

Concerns associated with the use of commercially produced hypochlorites include high transportation costs and a lack of long-term stability. In addition, safety concerns exist and are associated with the handling, dosing, dilution, and accidental spilling or release.

The stability of hypochlorite solutions is dependent upon the following: concentration, alkalinity and pH, storage temperature, concentration of impurities (e.g., Ni^{2+} and Cu^{2+}) that may catalyze hypochlorite decomposition, and exposure to sunlight. The rate of reduction in the strength of a sodium hypochlorite solutions increases with increasing hypochlorite strength, increasing solution temperature, and increasing holding time (Casson and Bess, 2003).

Reductions in the concentration of hypochlorite solutions in the storage tank may make it difficult for some operators to apply the correct chlorine dose. An incorrect chlorine dose may result in an insufficient residual being maintained in a drinking water distribution system or an excess of chlorine being discharged from a wastewater treatment plant into a receiving water. In addition, the loss of strength in hypochlorite solutions may also result in the formation of undesirable by-products (e.g., chlorate) as shown in the following equation: $3\ ClO^- \rightarrow 2\ Cl^- + ClO_3^-$ (Casson and Bess, 2003).

2.1.3.3.1 <u>On-Site Sodium Hypochlorite Generation</u>

Sodium hypochlorite can be generated using an electrochemical process which requires three basic components: a source of direct electrical current (usually a rectifier connected to an AC power source), an electrolytic cell, and electrical conductors. On-site generation of sodium hypochlorite has been a key process in water treatment for municipal and industrial applications for more than 30 years.

The goal of the process is to control the conditions in the electrolytic cell so that the desired products are generated. The general operation to produce sodium hypochlorite on-site is straightforward (Casson and Bess, 2003):

1. Salt (NaCl) is dissolved in a tank to form a concentrated (30%) brine solution.

2. The brine solution is reduced in concentration with demineralized water to 3%.

3. The diluted brine solution is pumped through the electrolytic cell. The cell consists of numerous dimensionally stable electrodes packed into an equal number of electrodes acting as anodes and cathodes. DC power is applied to the cell from a rectifier. Chemically, chlorine is evolved at the anode surface, while hydrogen is evolved at the cathode surface. The secondary reaction of chlorine, sodium and the hydroxyl ion results in sodium hypochlorite solution.

4. The hypochlorite solution flows into a storage tank.

5. A metering pump delivers the disinfectant to an ejection point in the well water treatment system.

The amount of sodium hypochlorite produced is a function of the amount of direct electrical current passed through the electrolytic cell. The net reaction in the electrolytic cell to produce sodium hypochlorite from sodium chloride and water is:

$$NaCl + H_2O \rightarrow NaOCl + H_2$$
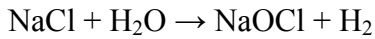
Principal reactions occurring in the electrolytic cell (Casson and Bess, 2003):

$$2Cl^- - 2e^- \rightarrow Cl_2 \dots\dots\dots\text{(principal reaction at the anode)}$$
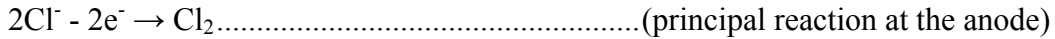
$$Cl_2 + 2H_2O \rightarrow HOCl + H^+ + Cl^- \dots\dots\dots\text{(principal reaction in the solution after}$$

the chloride generated at the anode is rapidly hydrolyzed into hypochlorous acid)

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \dots\dots\dots\text{(principal reaction at the cathode)}$$

$$HOCl \rightarrow H^+ + OCl^- \dots\dots\dots\text{(principal reaction at the cathode)}$$
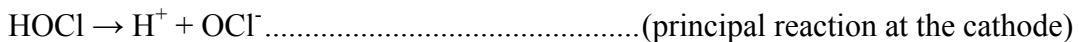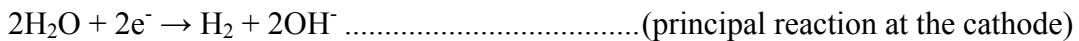
In addition to the principal reactions in the electrolytic cell, there are also parasitic reactions taking place in the cell that reduce the amount of hypochlorite produced in the system (Casson and Bess, 2003). Such as:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e\text{- }\dots\dots\dots\text{(parasitic reaction at the anode)}$$

$$6OCl^- + 3H_2O \rightarrow 2ClO_3^- + 6H^+ + 4Cl^- + 1.5O_2 + 6e\text{- (parasitic reaction at the anode)}$$

$$ClO^- + H_2O \rightarrow 2H^+ + Cl^- + O_2 + 2e\text{- }\dots\dots\dots\text{(parasitic reaction at the anode)}$$

$$OCl^- + H_2O + 2e\text{-} \rightarrow Cl^- + 2OH^- \dots\dots\dots\text{(parasitic reaction at the cathode)}$$

$$2HOCl + OCl^- \rightarrow ClO_3 + 2H^+ + 2Cl^- \dots\dots\dots\text{(parasitic reaction in the solution)}$$
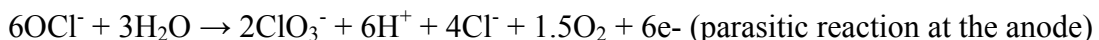
On-site hypochlorite is a dilute form of disinfectant compared to chlorine gas or concentrated commercial hypochlorite. As a result, handling, transportation and containment are easier and safer. The benefits of the process over chlorine gas and bulk hypochlorite

include: eliminating the bulk storage of chemicals; reducing risk to plant personnel; eliminating transportation liabilities; reducing the threat to public safety; creating a consistent solution concentration and increasing water quality; reducing overall disinfection costs (Casson and Bess, 2003).

2.1.3.4 Chlorine Dioxide

Chlorine dioxide (ClO_2) is another bactericide, equal to or greater than chlorine in disinfecting power. It is an effective disinfectant in both water and wastewater treatment systems. Although chlorine dioxide was first produced in 1811, it was not until the middle 1960s when its widespread use occurred due to changes in the manufacturing process. In the past, it did not receive much consideration as a wastewater disinfectant due to its high costs. Chlorine dioxide applications have typically been associated with medium-sized treatment facilities in the United States.

Chlorine dioxide is a neutral compound of chlorine in the +IV oxidation state. It disinfects by oxidation. It is a relatively small, volatile, and highly energetic molecule, and a free radical even while in dilute aqueous solutions. At high concentrations, it reacts violently with reducing agents. However, it is stable in dilute solution in a closed container in the absence of light (EPA 815-R-99-014, 1999).

Chlorine dioxide is an unstable and explosive gas and for this reason it must be generated on site. Generation of chlorine dioxide involves reacting sodium chlorite ($NaClO_2$) with chlorine to produce gaseous chlorine dioxide according to the following reaction:

$$2NaClO_2 + Cl_2 \rightarrow 2ClO_2 + 2NaCl$$
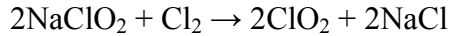
Recently, production of chlorine dioxide from sodium chlorate ($NaClO_3$) has been introduced as a generation method in which $NaClO_3$ is reduced by a mixture of concentrated hydrogen peroxide (H_2O_2) and concentrated sulfuric acid (H_2SO_4). Chlorate-based systems have traditionally been used in pulp and paper applications, but have recently been tested full-scale at two U.S. municipal water treatment plants (EPA 815-R-99-014, 1999). Chloric acid for the production of ClO_2 can also be obtained in an electrochemical cell from an alkali metal chlorate by selective migration of the chlorate ions through a diaphragm toward the anode, where they encounter H^+ ions and produce the acid (Rajeshwar & Ibanez, 1997).

The active disinfecting agent in a chlorine dioxide system is free dissolved chlorine dioxide (ClO_2). The complete chemistry of chlorine dioxide in an aqueous environment is not clearly understood. Chlorine dioxide has an extremely high oxidation potential which probably accounts for its potent germicidal powers. Possible bacteriocidal mechanisms may include inactivation of critical enzyme systems or disruption of protein synthesis.

Certain potentially toxic end products, chlorite and chlorate, can be formed with chlorine dioxide. The chlorine dioxide residuals and the end products are believed to degrade quicker than chlorine residuals, and therefore may not pose as serious a threat to aquatic life as the chlorine residuals. An advantage of using chlorine dioxide is that it does not react with ammonia to form the potentially toxic chloramines. It also does not have a tendency to form trihalomethanes in water treatment distribution systems or wastewater treatment outfalls.

The environmental impacts associated with the use of chlorine dioxide are less adverse than those associated with chlorination. However, dechlorination is required. Dechlorinating wastewater disinfected with chlorine dioxide can be achieved using sulfur dioxide.

2.1.4 Alternative Disinfection Technologies

Disinfection of wastewater effluents has been extensively studied in the U.S. since the early 1970s in response to the inclusion of a universal fecal coliform standard for wastewater discharges in the Clean Water Act of 1972, and the potentially adverse effects caused by the extensive use of chlorine (EPA 815-R-99-014, 1999). The search for effective alternatives to chlorine led to the evaluation of other halogens, ultraviolet radiation, and ozone as technically feasible processes. Ultraviolet radiation and ozone have been considered the most feasible alternatives to chlorination. Both have demonstrated effective reduction of pathogenic organisms in water and wastewater environments.

2.1.4.1 Ozone Disinfection

Ozone it is a very strong oxidant and virucide. Early application of ozone in the United States was primarily for non-disinfection purposes such as color removal or taste and odor control. However, since the implementation of the SWTR and proposal of the DBP rule, ozone usage for disinfection has augmented in the United States (EPA 815-R-99-014, 1999). It is generally used at medium to large sized plants after secondary treatment.

Although this technology has been widely accepted in Europe for decades, ozone disinfection is the least used method in the U.S. (WEF, 1996). It has the ability to achieve high

levels of disinfection but the capital costs as well as maintenance expenditures are not competitive with the existing alternatives.

Ozone (O_3) is produced when oxygen (O_2) molecules are dissociated by an energy source into oxygen atoms and these subsequently collide with other oxygen molecules. Most wastewater treatment plants generate ozone by imposing a high voltage alternating current (6 to 20 kilovolts) across a dielectric discharge gap that contains an oxygen-bearing gas. Ozone is generated onsite because it is unstable and decomposes to elemental oxygen in a short amount of time after generation (EPA 832-F-99-063, 1999).

The components of an ozone disinfection system include four basic modules: a gas feed system, an ozone generator, an ozone contactor, and an off-gas destruction system (EPA 832-F-99-063, 1999). The gas feed system provides a clean, dry source of oxygen to the generator; the ozone contactor transfers the ozone-rich gas into the water to be treated, and provides contact time for disinfection; and the off-gas destruction system, is required as ozone is toxic in the concentrations present in the off-gas.

Ozone generators are typically classified by the control mechanism (voltage or frequency unit), the cooling mechanism (water, air, or water plus oil), the physical arrangement of the dielectrics (vertical or horizontal), and the name of the inventor (EPA 815-R-99-014, 1999). The electrical discharge method is the most common energy source used to produce ozone. Extremely dry air or pure oxygen is exposed to a controlled, uniform high-voltage discharge at a high or low frequency.

Ozone decomposes spontaneously in water by a complex mechanism and generates hydroxyl (OH^-) and hydroperoxide (HO_2) free radicals, which also have a great oxidizing capacity (EPA 832-F-99-063, 1999). Hence, ozone can react by either or both modes in aqueous solution: direct oxidation of compounds by molecular ozone (O_{3aq}), or oxidation of compounds by the free radicals produced during the decomposition of ozone. It is generally believed that the bacteria are destroyed because of protoplasmic oxidation resulting in cell wall disintegration (cell lysis).

The effectiveness of ozone disinfection depends on the susceptibility of the target organisms, the contact time, and ozone concentration. Since ozone has limited solubility and decomposes rapidly in water, the ozone contactor must be well covered to ensure the ozone diffuses into the wastewater as effectively as possible (EPA 832-F-99-063, 1999).

The advantages of ozonation systems include the following (EPA 832-F-99-063, 1999): few safety problems associated with transportation and storage (onsite generation); more effective than chlorine in destroying viruses and bacteria; short contact time (approximately 10 to 30 minutes); less observed dependency on pH and temperature; no harmful residuals need to be removed after ozonation because ozone decomposes rapidly; ozonation elevates the dissolved oxygen concentration of the effluent; wastewater quality improvements (including effluent color, odor, and turbidity).

On the other hand, some of the disadvantages of ozone disinfection are (EPA 832-F-99-063, 1999): low dosage may not effectively inactivate some viruses, spores, and cysts; it is a

complex technology, requiring complicated equipment and efficient contacting systems; ozone is very reactive and corrosive, thus requiring corrosion-resistant materials; it is not economical for wastewater with high levels of suspended solids, biochemical oxygen demand, chemical oxygen demand, or total organic carbon; the cost is generally high in comparison with other disinfection techniques.

Table 5. Typical Cost Estimate of Ozone Disinfection

Items	Costs
Capital Costs	
Oxygen feed gas and compressor	$245,500
Contact vessel (500 gpm)	$4,000-5,000
Destruct unit	
Small (around 30 cfm)	$800
Large (around 120 cfm)	$1,000-1,200
Non-component costs	$35,000
Engineering	$12,000-15,000
Contingencies	30%
Annual O&M Costs	
Labor	$12,000
Power	90 kW
Other (filter replacements, compressor oil, spare dielectric, etc.)	$6,500

Source: Wastewater Technology Fact Sheet. EPA 832-F-99-063 (September 1999)

The overall cost for ozone disinfection systems is largely determined by the capital and O&M expenses. The annual operating costs include power consumption, supplies, miscellaneous equipment repairs, and staffing requirements. Table 5 shows a typical cost estimate for ozone disinfection systems used to disinfect one mgd of wastewater. The costs are based on the wastewater having passed through both primary and secondary treatment processes of properly designed system (the BOD content does not exceed 30 mg/L and the TSS

content is less than 30 mg/L). In general, costs are largely influenced by site-specific factors, and thus, the estimates that follow are typical values and can vary from site to site.

2.1.4.2 Ultraviolet Disinfection

Due to improvements in the Ultraviolet (UV) disinfection technology and advances in understanding the process, UV irradiation has become the most common alternative to chlorination for wastewater disinfection in the United States. Today, among all the US wastewater treatment plants more than 1000 have chosen UV irradiation for disinfection, and a significant fraction of them are large facilities (EPA 832-F-99-064, 1999).

UV irradiation inactivates organisms by absorption of the light which causes a photochemical reaction that alters molecular components essential to cell function. As UV rays penetrate the cell wall of the microorganism, the energy reacts with nucleic acids and other vital cell components, resulting in injury or death of the exposed cells. There is ample evidence to conclude that if sufficient dosages of UV energy reach the organisms, UV can disinfect water to whatever degree is required.

The effectiveness of a UV disinfection system depends on the characteristics of the wastewater, the intensity of UV irradiation, the amount of time the microorganisms are exposed to the radiation, and the reactor configuration (EPA 832-F-99-064, 1999). Disinfection success is directly related to the concentration of colloidal and particulate constituents in the wastewater. If the wastewater quality is poor, the ultraviolet light will be unable to penetrate the solids and the effectiveness of the process will decrease dramatically. Consequently, many

states limit the use of UV disinfection to facilities that can reasonably be expected to produce an effluent containing less than or equal to 30 mg/l of BOD and TSS.

The main components of a UV disinfection system are lamps, the reactor, and ballasts (EPA 815-R-99-014, 1999). The lamps typically used in UV disinfection consist of a quartz tube filled with an inert gas, such as argon, and small quantities of mercury. Producing UV radiation requires electricity to power UV lamps. Ballasts are transformers that control the power to the UV lamps.

The most conventional UV reactors are available in two types: closed vessel and open channel. Two different configurations may be used on both types: contact and noncontact, and wastewater can flow either perpendicular or parallel to the lamps (EPA 832-F-99-064, 1999).

In high-quality UV systems, the best lamps are those with a stated operating life of at least 7500 h that do not produce significant amounts of ozone of hydrogen peroxide (EPA 832-F-99-064, 1999). All surfaces between the UV radiation and the target organisms must be clean. Inadequate cleaning is one of the most common causes of a UV system's ineffectiveness. The quartz sleeves or Teflon tubes need to be cleaned regularly. Contact tanks must provide a minimum of 10 seconds of exposure time.

The average lamp life ranges from 8,760 to 14,000 working hours, and the lamps are usually replaced after 12,000 hours of use (EPA 832-F-99-064, 1999). Operating procedures should be set to reduce the on/off cycles of the lamps, since their efficacy is reduced with

repeated cycles. The ballast must be compatible with the lamps and should be ventilated to protect it from excessive heating, which may shorten its life or even result in fires. Although the life cycle of ballasts is approximately 10 to 15 years, they are usually replaced every 10 years. Quartz sleeves will last about 5 to 8 years but are generally replaced every 5 years.

Some advantages of UV disinfection systems include the following (EPA 832-F-99-064, 1999): very effective inactivating most viruses, spores, and cysts; it is a physical process rather than a chemical disinfectant, which eliminates the need to generate, handle, transport, or store toxic/hazardous or corrosive chemicals; there is no residual effect that can be harmful to humans or aquatic life; user-friendly for operators; UV disinfection has a shorter contact time when compared with other disinfectants; the necessary equipment requires less space than other methods.

Then again, some of the disadvantages of UV disinfection are (EPA 832-F-99-064, 1999): low dosage may not effectively inactivate some viruses, spores, and cysts; organisms can sometimes repair and reverse the destructive effects of UV; a preventive maintenance program is necessary to control fouling of tubes; turbidity and total suspended solids (TSS) in the wastewater can render UV disinfection ineffective; UV disinfection is not as cost-effective as chlorination.

The cost of UV disinfection systems depends on the manufacturer, the location, the capacity of the plant, and the characteristics of the wastewater to be disinfected. Total costs of UV disinfection can be competitive with chlorination when the dechlorination step is included.

Table 6 summarizes the costs of some of the lamps used in UV disinfection and Table 7 describes the typical capital and O&M costs associated with the system. This information was collected in a study conducted by the Water Environment Research Federation in 1995 (EPA 832-F-99-064, 1999).

Table 6. Lamp Costs for UV Disinfection Systems

Items	Range*	Typical*
UV lamps	($/lamp)	($/lamp)
1-5 mgd	397 - 1,395	575
5-10 mgd	343 - 594	475
19-100 mgd	274 - 588	400

*Costs are based on a 1993 Engineering News Record Construction Cost Index of 5,210.
Source: Wastewater Technology Fact Sheet. EPA 832-F-99-064 (September 1999)

Table 7. Typical Cost Estimate for UV Disinfection Systems

Items		Costs
Capital Costs		
Equipment		$120,000
Structural modifications		$64,000
Electrical		$20,000
Miscellaneous		$40,000
	Total	*$244,000*
Annual O&M Costs		
Energy		$3,300
Lamps and chemicals		$2,840
Cleaning		$1,180
Maintenance		$1,440
Process control		$6,210
Testing		$4,160
	Total	*$19,190*

Source: Wastewater Technology Fact Sheet. EPA 832-F-99-064 (September 1999)

The annual operating costs for UV disinfection include power consumption; cleaning chemicals and supplies; miscellaneous equipment repairs (2.5% of total equipment cost); replacement of lamps, ballasts and sleeves; and staffing requirements. Costs have decreased in

recent years due to improvements in lamp and system designs, increased competition, and improvements in the systems' reliability (EPA 832-F-99-064, 1999).

2.1.4.3 Peroxone (Ozone/Hydrogen Peroxide)

As stated before, hydroxyl radicals are produced during the spontaneous decomposition of ozone. By accelerating the ozone decomposition rate, the hydroxyl radical concentration is elevated, and therefore the oxidation rate of various compounds in the water is increased. Several methods have been used to increase ozone decomposition and produce high concentrations of hydroxyl radicals: ozone plus UV, ozone at high pH, hydrogen peroxide plus UV, and other combinations (EPA 815-R-99-014, 1999). One of the most common of these processes is known as *PEROXONE*, which involves adding hydrogen peroxide to ozonated water.

Disinfection in a peroxone system occurs due to two reactions (EPA 815-R-99-014, 1999): (1) direct oxidation of compounds by aqueous ozone ($O_{3(aq)}$), and (2) oxidation of compounds by hydroxyl radicals produced by the decomposition of ozone.

The main difference between the ozone and peroxone processes is that the ozone process relies heavily on the direct oxidation of aqueous ozone while peroxone relies primarily on oxidation with hydroxyl radical (EPA 815-R-99-014, 1999). In the peroxone process, the ozone residual is short lived because the added peroxide greatly accelerates ozone decomposition. However, the increased oxidation achieved by the hydroxyl radical greatly outweighs the reduction in direct ozone oxidation. The net result is that oxidation is more

reactive and much faster in the peroxone process compared to the ozone molecular process. The high reactivity of hydroxyl radicals creates a different effect in the reactions with water constituents and, thus, improves disinfection effectiveness.

Peroxone is one of the most potent and effective germicides used in water treatment. It is slightly more effective than ozone against bacteria, viruses, and protozoan cysts. It is effective in oxidizing difficult-to-treat organics, such as taste and odor compounds. Additional selected advantages of using peroxone as a disinfection method are (EPA 815-R-99-014, 1999): it have been shown to be effective in oxidizing halogenated compounds; it transforms organic carbon compounds to a more biodegradable form; pumps used to house peroxide are not very large, so space requirements are not significant; peroxone itself does not form halogenated DBPs.

The main drawback of this process is that peroxide is a also a strong oxidant and contact with personnel is extremely dangerous. Hydrogen peroxide is a hazardous material requiring secondary containment for storage facilities.

2.1.4.4 Bromine-Based Disinfectants

Bromine chloride is a promising alternative to chlorine-based disinfection. Its disinfection-related chemistry is very similar to that of Cl_2. It adsorbs on the microorganism and affects normal enzyme activity, hydrolyzes to produce HOBr and HCl, and reacts with ammonia to produce the three bromamines.

Advantages with respect to chlorine disinfection include the following: smaller contact times are required for similar disinfection results, bromamines are more effective than chloramines, brominated organic DBPs are more susceptible to hydrolysis and photolysis, and in general, the environmental effects are less dangerous that those related to chlorine disinfection. The main drawback seems to be the lack of an extensive research and database to support more widespread use (Rajeshwar & Ibanez, 1997).

2.1.4.5 Combinations of Disinfectants

Wastewater disinfection has become especially complicated by the growing number of end use applications that many treatment facilities must now accommodate. In addition to defending the public from acute risks of pathogen infection and avoiding negative impacts on the aquatic environment, some municipalities must now develop strategies that minimize DBP formation while also complying with other reuse and recharge standards (EPA 815-R-99-014, 1999).

For utilities with a single discharge point, the selection of a disinfection approach is fairly straightforward. However, for those facilities which optimize the use of their effluent via discharge of multiple end uses (such as: irrigation, reuse, groundwater recharge), selecting an appropriate disinfection strategy is challenging.

Multiple disinfectants, the sequential or simultaneous use of two or more disinfectants, have been used with increasing frequency in recent years (EPA 815-R-99-014, 1999). This trend is attributed to the fact that:

- Less reactive disinfectants, such as chloramines, have proven to be quite effective in reducing DBPs formed during disinfection.

- Regulatory and end users pressure to achieve high inactivation for various pathogens in water has pushed the industry towards more effective disinfectants.

- Recent research has shown that the application of sequential disinfectants is more effective than the added effect of the individual disinfectants.

Table 8. Disinfectant Combinations and Typical Applications in Water Treatment

Primary / Secondary	Typical application	Comment
Chlorine/Chlorine	Low THMFP raw water, low TOC, conventional treatment with optimal coagulation.	Most commonly used disinfection scheme. Effective system.
Chlorine/Chloramine	Moderate THM production situation, typically with conventional treatment.	Chlorine to provide disinfection and monochloramine to limit DBP formation.
Chlorine Dioxide/Chlorine Dioxide	High DBP production, require filter process to remove *Cryptosporidium*, low chlorine dioxide demand in treated water.	Primary and secondary usage requires a limit on chlorine dioxide dose to reduce residual chlorate/chlorite.
Chlorine Dioxide/Chloramine	High DBP production, require filtration to remove *Cryptosporidium*.	Primary chlorine dioxide dose limited to residual chlorate/chlorite. Stable, low reactive secondary disinfectant.
Ozone/Chlorine	Moderate DBP formation, direct or no filtration, low THMFP.	Highly effective disinfection to achieve high log inactivation; low THMFP to accept free chlorine.
Ozone/Chloramine	Moderate DBP formation, direct or no filtration, higher THMFP.	Highly effective disinfection to achieve high log inactivation, low THMFP to require combined chlorine residual.
UV/Chlorine	Requires membrane treatment to provide effective *Giardia* and *Cryptosporidium* removal. UV only for virus inactivation; ground water disinfection; low THMFP.	Rare application but feasible in special circumstances. Little *Giardia* and no *Cryptosporidium* inactivation.
UV/Chloramine	Requires membrane treatment to provide effective *Giardia* and *Cryptosporidium* removal. UV only for virus inactivation; ground water disinfection, moderate THMFP.	Rare application but feasible in special circumstances. No *Giardia* or *Cryptosporidium* inactivation.

Source: Alternative Disinfectants and Oxidants Guidance Manual. EPA 815-R-99-014, April 1999.

The process where two (or more) disinfectants produce a synergistic effect by either simultaneous or sequential application to achieve more effective pathogen inactivation is referred to as *interactive disinfection* and it is still considered an emerging technology.

The combinations of disinfectants that are viable options to meet the disinfection requirements are presented in Table 8. These combinations are shown for various treatment objectives. To meet DBP, and specifically, THM limits, several studies have evaluated the application of various primary/secondary disinfectants.

2.2 ELECTROCHEMICAL PROCESSES IN WATER AND WASTEWATER TREATMENT

Electrochemical (EC) processes are being successfully used today in solving pollution problems. These systems have proven to be able to cope with a variety of wastewaters. Among others, paper pulp mill waste, metal plating, tanneries, canning factories, steel mill effluent, slaughter houses, chromate, lead and mercury laden effluents, and domestic sewage have been treated using electrochemical technologies to yield clear, clean, odorless and reusable waters (Pletcher, D. 1992).

Many EC processes involve the direct reaction of species at electrode surfaces, while others involve production of active species at the electrode and subsequent reaction with the targeted pollutants (Chiang *et al.*, 1995). In *direct processes* an electrode transfer reaction to or from the undesired pollutant occurs at the surface of an electrode. Similarly, in *indirect*

processes a dissolved redox reagent either exists in or is generated from the electrolyte or from the electrode phase in order to participate in a targeted reaction. Figure 1 illustrates and compares the two types of approaches.

Pollutants capable of undergoing *direct electrolysis* (oxidation or reduction) at an inert electrode can be removed from water streams by the application of appropriate potentials without the involvement of other substances (Rajeshwar & Ibanez, 1997). Unfortunately, side reactions (particularly solvent breakdown) almost always occur. For instance:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$ ....(water oxidation)

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$ ....(water reduction)
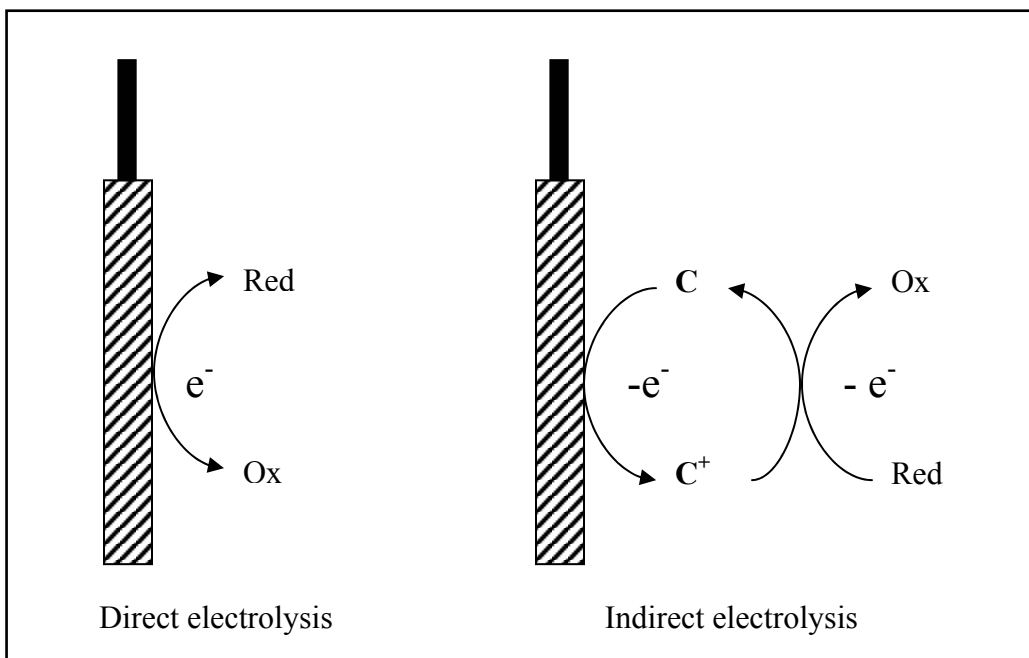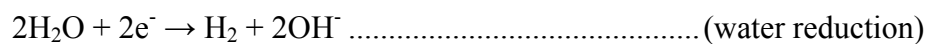
Figure 1. Electron-transfer schemes for direct and indirect processes.

These reactions might have a harmful effect on the overall process efficiency, however vivid schemes can be developed to exploit the production of gases as well as the pH changes

associated with them to bring about useful reactions. For example, the production of H_2 gas has been used to facilitate the flotation and removal of unwanted substances in the electrocoagulation-electroflotation process (Chen *et al.*, 2000). Likewise, the generation of hydroxyl ions serves to immobilize metals electrolytically generated in the form of hydroxides.

Many organic and inorganic pollutants are treated by *direct oxidation* at anodes of different materials. The main secondary reaction of this process in aqueous media is water oxidation. Therefore, to make this reaction to become very slow, researchers have developed electrodes with high overpotentials for oxygen production. One example is the boron-doped diamond electrode which makes possible the oxidation of substances with standard potentials higher than that for the oxidation of water (Fryda *et al.*, 2003).

Likewise, water reduction is the main secondary reaction in *direct reductions*. There are efforts to sell or utilize the hydrogen produced (high purity, electrolytic grade) in devices such as fuel cells to generate electricity (Ibanez, 2004). The electrochemical reduction processes that have reached the highest degree of maturity are those for metal ion recovery from their dissolved ions. Cadmium, copper, chromium, mercury, nickel, silver, lead, and aluminum ions have been reduced and recovered effectively in electrochemical reactors. Other toxic compounds amenable for direct reduction include: chlorinated hydrocarbons, organic acids, chromates, oxychlorinated species, and oxynitrogenated ions.

The main problems with direct electrolysis are the large amount of electrons required to complete oxidation of some substances and the large variety of intermediates formed

(Rajeshwar & Ibanez, 1997). Sometimes the intermediate is even worse than the original pollutant. Other times, intermediates polymerize and block the electron transfer surface. An alternative to evade these problems is to use *indirect processes* which provide oxidizing or reducing agents at the anode or cathode, respectively. These redox reagents can be electrochemically generated either in a reversible or irreversible manner.

In *indirect electrolysis* the agents (C in Figure 1) are the ones that oxidize or reduce the pollutants. Among the most popular redox reagents are (Ibanez, 2004):

- *Metallic ions* in higher than normal oxidation states (reversible reagents). For example, doubly charged silver cation is an excellent oxidizer for organophosphorous, organosulfur, and chlorinated compounds. Triply charged iron cation is an oxidizer that can be used in successful cases of degradation of grease, cellulose derivatives, urea, meat packing wastes, sewage, and carbonaceous fuels. Cerium ions are well known oxidants used in organic synthesis reactions. Triply charged manganese cation and insoluble metallic oxides such as bismuth oxide and cobalt oxide can also oxidize pollutants.

- *Hydrogen peroxide*, *ozone, hypochlorite, or chlorine* (irreversible reagents). The electrolytic generation of these killer agents can be used as a disinfection tool.

Recent investigations have demonstrated the unique chemical and physical advantages of boron-doped diamond electrodes; they have shown outstanding properties in indirect oxidation of organic and inorganic compounds (Haenni *et al.*, 2001). This reactivity can be associated with the production of hydroxyl radicals, which may also be responsible for the

production of chlorine, ozone, persulfates and hydrogen peroxide. Substances that have been treated by this technique include: phenols, aromatic amines, halogenated compounds, nitrated derivatives, fecal wastes, dyes, aldehydes, carboxylic acid anions, and cyanide. In the process, these organic molecules are oxidized to CO_2 without major amounts of other detectable byproducts (Fryda *et al.*, 2000).

Indirect electrolytic processes can be viewed as chemical on-off switches, since they stop when the current supply is discontinued. A listing of reagents that can be electrolytically generated for pollutant destruction, including its corresponding standard reduction potentials (ORP relative to the normal hydrogen electrode: V vs. NHE) are presented in Table 9. The standard potential values are all fairly positive attesting to the ability of these reagents for oxidizing a wide variety of organic substrates.

Table 9. Reagents that can be electrolytically generated for the anodic treatment of pollutants and the corresponding standard potentials (Rajeshwar & Ibanez, 1997).

Reagent	Standard Reduction Potential V vs. NHE
Hydroxyl radical (OH·)	2.80
Atomic oxygen [O]	2.42
Ozone (O_3)	2.07
Hydrogen peroxide (H_2O_2)	1.78
Perhydroxyl radical (HO_2^-)	1.70
Chlorine (Cl_2)	1.36

An important advantage to the electrolytic generation of these reagents is that it can be done in situ. Hence, these dangerous chemicals need not be transported over long distances. Further, many of the reagents listed on Table 9 are unstable on long-term storage. It is

interesting to note that the electrogeneration in situ of these species is having a rebirth thanks to the availability of new electrode materials.

According to Tatapudi and Fenton (1994), the electrochemical synthesis of **ozone** responds to the following reactions at the anode:

(1) $3\ H_2O\ \rightarrow\ O_3 + 6\ H^+ + 6e^-$ ....$E° = 1.51$ V vs NHE

(2) $H_2O\ + O_2 \rightarrow\ O_3 + 2\ H^+ + 2e^-$ ....$E° = 2.07$ V vs NHE
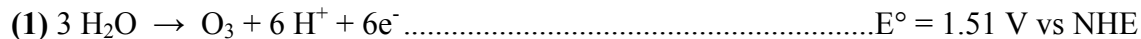
However, up to now from a practical point of view only the process represented by equation (1) has been considered in the literature (da Silva *et al.*, 2003).

The evolution of oxygen will occur preferentially over ozone evolution as it is a lower potential process (Tatapudi and Fenton, 1994):

(3) $2\ H_2O\ \rightarrow\ O_2 + 4\ H^+ + 4e^-$ ....$E° = 1.23$ V vs NHE

In addition, the ozone produced at the anode probably participates in the following reactions (Patermarakis and Fountoukidis, 1990):

(4) $O_3 + H_2O \rightarrow HO_3^+ + OH^-$

(5) $HO_3^+ + OH^- \rightarrow 2HO_2$

(6) $O_3 + 2HO_2 \rightarrow OH\cdot + 2O_2$
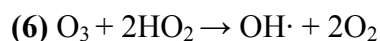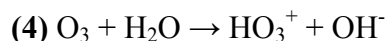
In order to obtain ozone at reasonable concentration the evolution of oxygen must be inhibited by using high oxygen overvoltage anodes. Other requirements for practical generation of ozone include: electrolytes whose anions and cations engage in no competitive

oxidation or reduction reactions, anodes kinetically resistant to further oxidation, and anodes stable in highly acidic environments produced by the anodic decomposition of water. The majority of laboratory investigations on the anodic evolution of ozone used Pt and PbO_2 electrode materials and H_2SO_4, $HClO_4$, or H_3PO_4 electrolytes (Tatapudi and Fenton, 1994).

According to the EPA publication 815-R-99-014, the electrochemical synthesis of the **hydroxyl radical** (OH·) responds to the following reaction at the anode:

(7) $OH^- \rightarrow OH\cdot + e^-$ ....$E° = 2.80$ V vs NHE

Active oxygen atoms [O] are produced at the anode by the following reaction (Patermarakis and Fountoukidis, 1990), and also participate in oxygen gas formation:

(8) $2OH^- \rightarrow H_2O + [O] + 2e^-$ ....$E° = 2.42$ V vs NHE

(9) $2[O] \rightarrow O_2$
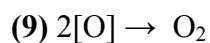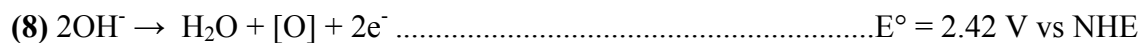
The oxygen gas formed at the anode migrates by simple diffusion, and/or by means of the movement of the water in the cell toward the cathode, and is then reduced when in contact with the cathode according to the following (Porta *et al.*, 1986):

(10) $O_2 + 2H_2O + 4e^- \rightarrow 4\ OH^-$..$E° = 0.401$ V vs NHE

(11) $O_2 + H_2O + 2e^- \rightarrow HO_2^- + OH^-$ ....$E° = -0.08$ V vs NHE

(12) $HO_2^- + H_2O + 2e^- \rightarrow 3OH^-$ ....$E° = 0.88$ V vs NHE
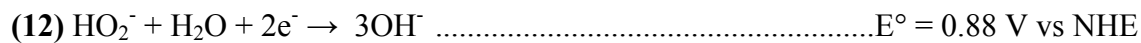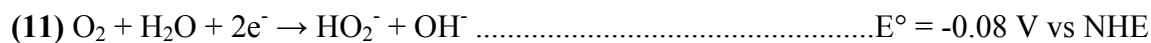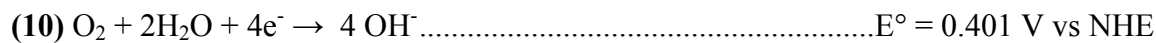
Hydrogen peroxide can be produced at the cathode, being the product of a two electron transfer to oxygen:

(13) $O_2 + 2\ H^+ + 2e^- \rightarrow H_2O_2$ ....$E° = 0.68$ V vs NHE

or at the anode by the half cell reaction:

(14) $2\ H_2O \rightarrow H_2O_2 + 2\ H^+ + 2e^-$ ....$E° = 1.78$ V vs NHE

Therefore, hydrogen peroxide solutions decompose to water and oxygen ($H_2O_2 \rightarrow 2H_2O + O_2$). These reactions can be catalyzed d by trace metal ions (Tatapudi and Fenton, 1994).

According to Malik *et al.* (2001), hydrogen peroxide is responsible for free radical (OH·) production in the case of electrical discharges in water:

(15) $H_2O_2 + e^- \rightarrow OH· + OH^-$ ....$E° = 0.09$ V vs NHE
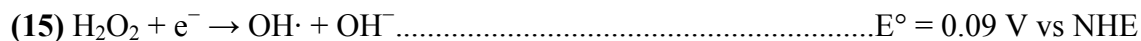
Which course oxygen reduction takes depends upon the electrolyte media, its composition, and the electrode used. Kinetic and mechanistic studies have been performed in both acidic and alkaline media, using different metals as well as various types of carbon electrodes. Significant production of hydrogen peroxide has been found using carbon cathodes in alkaline electrolytes (Tatapudi and Fenton, 1994).

The **perhydroxyl ion** (HO_2^-) is formed at the cathode in reactions (5), (11), and by hydrogen peroxide dissociation:

(16) $H_2O_2 \rightarrow H^+ + HO_2^-$
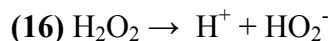
This radical is a very active decontamination agent, but very unstable and short-lived. In effect, these species can be ultimately reduced according to reaction (12), or might be

decomposed to form active oxygen according to the following (Porta *et al.*, 1986; Patermarakis and Fountoukidis, 1990):

(17) $HO_2^- \rightarrow OH^- + 1/2O_2$

(18) $HO_2^- \rightarrow OH^- + [O]$
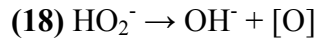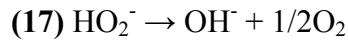
The electrochemical synthesis of **chlorine** takes place through the electrolysis of aqueous sodium chloride, according to electrode reactions (Tatapudi and Fenton, 1994):

(19) $2Cl^- \rightarrow Cl_2 + 2e^-$ ....$E° = 1.36$ V vs NHE

(20) $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ ....$E° = -0.83$ V vs NHE
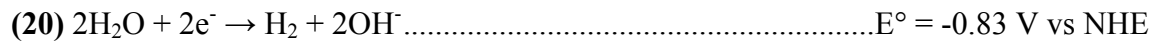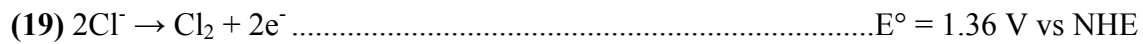
To produce chlorine and hypochlorite electrochemically, the cathode material is usually stainless steel, a nickel alloy, or titanium. Graphite, lead dioxide, platinized titanium, and dimensionally stable anode are some of the materials that have been used as an anode. The cells are operated between a current density of $0.1 - 0.5$ A/cm^2, and the majority of the cells used utilize the parallel plate type geometry (Tatapudi and Fenton, 1994).

2.2.1 Advantages and Disadvantages of Electrochemical Processes

Electrolytic generation of reagents in a pollutant treatment reactor has the virtue of precise process controllability (because of its electrical nature), and the extent of reagent generation can be profitably coupled to the demand imposed by the degree of pollution of the process stream (Rajeshwar & Ibanez, 1997).

In general, electrochemical processes offer many distinctive advantages relative to the other technologies. The following list summarizes some of the positive features of electrochemical approaches to pollution control (Rajeshwar & Ibanez, 1997):

1. Environmental compatibility: The main reagent used is the electron, which is a clean reagent, and usually there is no need for adding extra chemicals.

2. Versatility: Electrochemical processes involving direct or indirect oxidation and reduction can generate neutral, positively, or negatively charged inorganic, organic, or biochemical species. They can also deal with solid, liquid, or gaseous pollutants and can induce the production of precipitates, gaseous species, pH changes, or charge neutralization. The products from the electrolysis of pollutants often are even useful. In addition, a plethora of reactor and electrode materials, shapes and configurations can be utilized. Frequently, the same reactor can be used for different electrochemical reactions with only minor changes. In addition, point-of-use production of chemicals is facilitated by electrochemical techniques (e.g., for water disinfection). Finally, volumes of fluid from microliters to millions of liters can be treated.

3. Energy efficiency: Electrochemical processes often have lower temperature and pressure requirements than those of equivalent nonelectrochemical counterparts (e.g., incineration, supercritical oxidation). The applied potentials can be controlled and electrodes and cells can be designed to minimize power losses due to poor current distribution and voltage drops.

4. Safety: Electrochemical processes are safe because of the mild conditions usually employed, and the small quantity and innocuous nature of the added chemicals.

5. Selectivity: The applied potential in many cases can be controlled to selective attack specific bonds and thus avoid production of by-products.

6. Amenability to automation: The electrical variables used in electrochemical processes are particularly suited for facilitating data acquisition, process automation, and control.

7. Cost effectiveness: The required equipment and operations are normally simple and, if properly designed, can also be made relatively inexpensive.

In spite of these advantages, there are also some challenges to be faced (Ibanez, 2004):

1. Electrode materials may be prone to erosion, complexation, oxidation, wearing, or inactivation.

2. Since most of the electrochemical processes are performed in aqueous solutions, solvent decomposition (water oxidation/reduction) is often hard to avoid and thus there is a concomitant energy waste.

3. The production of gases from the above decomposition (hydrogen and oxygen) may form explosive mixtures.

4. The best electrode materials in terms of durability and inertness frequently involve precious metals, and this increases costs.

5. The cost of electricity in many areas is prohibitive.

6. Initial capital investment may be large.

7. The lack of knowledge or understanding of electrochemistry is perhaps the greatest barrier for its utilization.

2.2.2 Electroflotation, Electrocoagulation, and Electroflocculation

Electroflotation involves the electrolytic production of gases (O_2, H_2) that can be used to attach pollutants, such as fats and oils, to the gas bubbles and carry them up to the top of the solution where they can be more easily collected and removed. *Electrocoagulation* refers to the electrochemical production of destabilization agents that bring about charge neutralization for pollutant removal. *Electroflocculation* is the electrochemical production of agents that promote particle bridging or coalescence (Rajeshwar & Ibanez, 1997).

In the electrocoagulation process contaminated water is forced to flow between sacrificial electrodes while alternating or direct current electricity is applied to the system. In most cases the sacrificial electrodes are made of iron or aluminum, therefore, hydrogen gas is produced on the cathodes and Fe^{n+} or Al^{3+} ions results from the oxidation of the anode. These ions can react with the OH^- ions produced at the cathode and yield insoluble hydroxides that will precipitate, absorbing pollutants out of the solution and also will contribute to coagulation-flocculation processes (see Figure 2).

The reactions that take place during electrocoagulation using aluminum electrodes are presented below (Donini *et al.*, 1994):

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^- \quad \text{..(Anode reaction)}$$

$$3\,H_2O + 3e^- \rightarrow 1.5\,H_{2(g)} + 3\,OH^- \quad \text{.......................................(Cathode reaction)}$$

$$Al_{(s)} + 3H_2O \rightarrow Al(OH)_{3(s)} + 1.5\,H_{2(g)} \quad \text{...................................(Chemical reaction)}$$
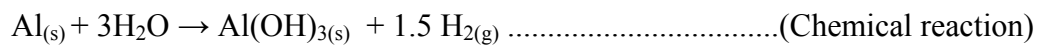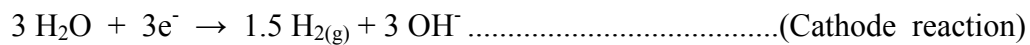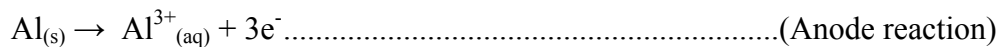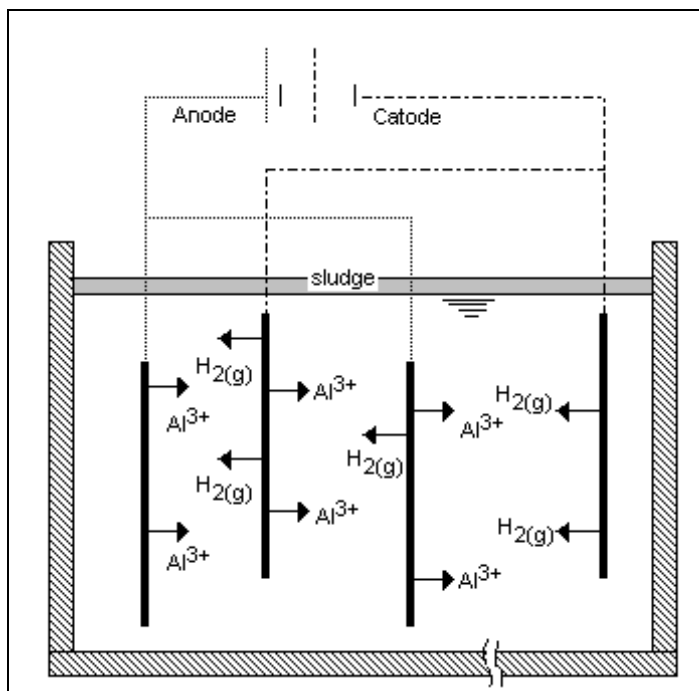
Figure 2. Electrocoagulation Process using Aluminum electrodes (after Vik E. *et al*, 1984)

In the same approach, the reactions that take place during electrocoagulation using iron electrodes are presented below (Rajesh *et al*., 2003):

$4\ Fe \rightarrow\ 4\ Fe^{2+} + 8e^{-}$..(Anode reaction)

$8\ H^{+} + 8e^{-} \rightarrow\ 4\ H_2$...(Cathode reaction)

$4\ Fe^{2+} + 10\ H_2O + O_2 \rightarrow 4\ Fe(OH)_3\ + 8\ H^{+}$..........................(Chemical reaction)
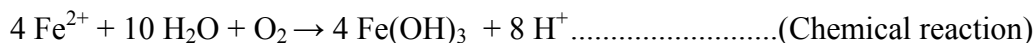
The sludge produced by electrochemical treatment is more hydrophobic, leading to more compact residues and shorter decantation times. In addition, the resulting solid is a low-density waste due to the flotation action by the gas, which facilitates its separation from the aqueous phase (Ibanez, 2004).

These electrocoagulation-electroflotation processes have proven to be as good as the combined chemical precipitation-air flotation processes, both can remove simultaneously and successfully oil and heavy metals from wastewaters (Chen *et al*., 2000). Opportunities for the electroflotation-electrocoagulation-electroflocculation processes include: cleanup of oil-water emulsions, dye removal, phosphorus removal, and the treatment of waters containing food and protein wastes, synthetic detergents, and fluorides.

Electrocoagulation offers several advantages (Rajeshwar & Ibanez, 1997), such as: removal of the smallest charged colloids, it reduces the amount of required chemicals and avoids the need for mechanical agitation, the durability of the electrodes translates to low down times for maintenance or replacement, effective organic matter removal, coagulant dosing as well as required overpotentials can be easily calculated and controlled, the observed pH increase aids in the removal of heavy metal ions by their precipitation as hydroxides or by adsorption into other flocs or precipitates, operating costs are much lower when compared with most of the conventional technologies.

The major challenges for these processes are: slight increased concentration of aluminum or iron ions in the effluent; insoluble hydroxides may agglomerate between the electrodes, hampering their further production; anode passivation and sludge deposition on the electrodes.

A considerable amount of work was done on electrolytic wastewater treatment from 1900 to 1930. This work resulted in the establishment of several electrolytic municipal waste

plants, but all were eventually abandoned because of the high cost of operation and questionable efficiency (Miller and Knipe, 1965).

2.2.3 Fenton's Reaction

Many metals have special oxygen transfer properties which improve the utility of hydrogen peroxide. By far, the most common of these is iron which, when used in the prescribed manner, results in the generation of highly reactive hydroxyl radicals ($\cdot$OH). The reactivity of this system was first observed in 1894 by its inventor H.J.H. Fenton, but its utility was not recognized until the 1930's once the mechanisms were identified.

The Fenton reaction involves the following sequence of major steps (Rajeshwar & Ibanez, 1997):

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \cdot OH$$

$$Fe^{3+} + \cdot OH \rightarrow Fe^{3+} + OH^-$$

$$H_2O_2 + \cdot OH \rightarrow \cdot HO_2 + H_2O$$

$$Fe^{2+} + \cdot HO_2 \rightarrow Fe^{3+} + HO_2^-$$
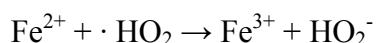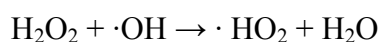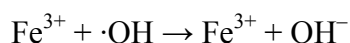
Most of the early investigations on the Fenton reaction were motivated by possibilities in preparing organic chemistry. Today, Fenton's Reagent is used to treat a variety of industrial wastes containing a range of toxic organic compounds (phenols, formaldehyde, BTEX, and complex wastes derived from dyestuffs, pesticides, wood preservatives, plastics additives, and rubber chemicals). The process may be applied to wastewaters, sludge or contaminated soils,

with the effects being: organic pollutant destruction, toxicity reduction, biodegradability improvement, BOD and COD removal, odor and color removal.

2.3 ELECTROCHEMICAL DISINFECTION OF WATER

Electro-disinfection as a technology to sanitize wastewater dates back to the 1800s. Originally, the development of electrochemical sewage treatment had as primary interest the electrolytic generation of chlorine for deodorizing and disinfecting wastewater. Eugene Hermite received two British and French patents in 1887 which described a method of treating sewage by mixing it with a proportion of seawater and electrolyzing (Vik, E.A. *et al*., 1984). Two treatment plants utilizing these patents were built in 1889 in England and operated for 10 years. Iron electrodes were used and seawater was added as a chlorine source for disinfection.

In the U.S. electrolytic sludge treatment plants were in operation as early as 1911 in Santa Monica, California and Oklahoma City, Oklahoma. Both aluminum and iron were used together as anodes which corroded during electrolysis. Steel electrodes alternatively connected to the positive and negative terminals of a DC power supply with sewage flowing in demonstration plants were built and all were praised for their high quality effluent and lack of odor. However, operation costs were high since sludge from the settling tanks had to be hauled away. Eventually, all plants were abandoned in 1930 (Vik, E.A. *et al*., 1984).

Electro-disinfection as a modern technology was subsequently developed in the 1980's by several vendors (especially in Europe) to disinfect drinking water, process waters, and wastewaters including the removal of fecal coliform bacteria from final effluent sewage

discharges. Treatment is achieved by generating an intense electric field in a reactor through which water passes. It is claimed that the process is as effective as chlorination with the environmental benefits of UV treatment. However, only a few data are published due to several problems including commercial interests and analysis complexity.

For electrochemical disinfection, direct current (DC), as well as alternating current (AC) of low and high frequency (0.5-800 Hz) has been used (Patermarakis and Fountoukidis, 1990). A variety of electrode types have been utilized including graphite fibers in a polymer matrix, carbon-cloth, stainless steel, platinum, titanium, diamond, and silver. Sometimes additives such as NaCl and NaBr have been added to increase the effectiveness of the process.

The water quality, nature of the electrodes, energy input, and other operational condition may all influence the effectiveness of EC disinfection. Experiments have demonstrate that the electro-disinfection process can generate a high disinfection efficiency within a short contact time for potable water, raw water supply, milk and liquid foodstuffs, and treated wastewater effluent (Li $et\ al.$, 2002).

Microorganisms can be electrochemically inactivated either directly or via the generation of very active chemical species, such as free radicals and other ions (OH·, [O], HO$_2$·, Cl$_2$, OCl⁻, etc). Electric fields are themselves harmful to cells (Drees $et\ al.$, 2003), but it has been demonstrated that death does not occur by disruption of the cell wall (Allen and Soike 1996). Direct inactivation involves the electrosorption of bacteria and the like on the electrode surface and their subsequent destruction (Matsunaga $et\ al.$, 1994).

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The direct and indirect routes are not always distinguishable, and it is possible that in many of the studies done to date, both processes play a significant role. Electro-disinfection is actually quite complex and there are several killing mechanisms that may be in play. Some hypotheses on the various means of disinfective action of the process are as follows (Patermarakis and Fountoukidis, 1990):

1. If low voltage (5-15V) is used the kill may be achieved by the formation of species such as chlorine gas, hypochlorite, hypochlorous acid, chlorine dioxide or bromine species (if Cl- or Br- ions are present).

2. Electrocution of bacteria: the electrical field directly causes the destruction of bacteria. This is due to the electrochemical oxidation of intracellular Coenzyme A (CoA), which leads to decreased respiration and consequent cell death (Matsunaga *et al.*, 1992).

3. It is also likely that the formation of radicals (active oxygen atoms produced at the anode, as well as HO_2^-, OH^-, and ozone) may be responsible for some of the kill if the right frequency and voltage are used. The hydroperoxide ions, hydroxyl radicals and ozone are very active disinfective agents but are very unstable and short-lived.

4. The carbonate and sulphate ions present in the water could be oxidized at the anode to form percarbonate or persulphate which are excellent oxidizing agents for bacteria.

5. Alternatively dissolution of the electrode material into the solution may be responsible for disinfection (especially transition metal ions as copper and silver).

Figure 3 summarizes most of the proposed modes of microorganism deactivation by electrochemical processes.
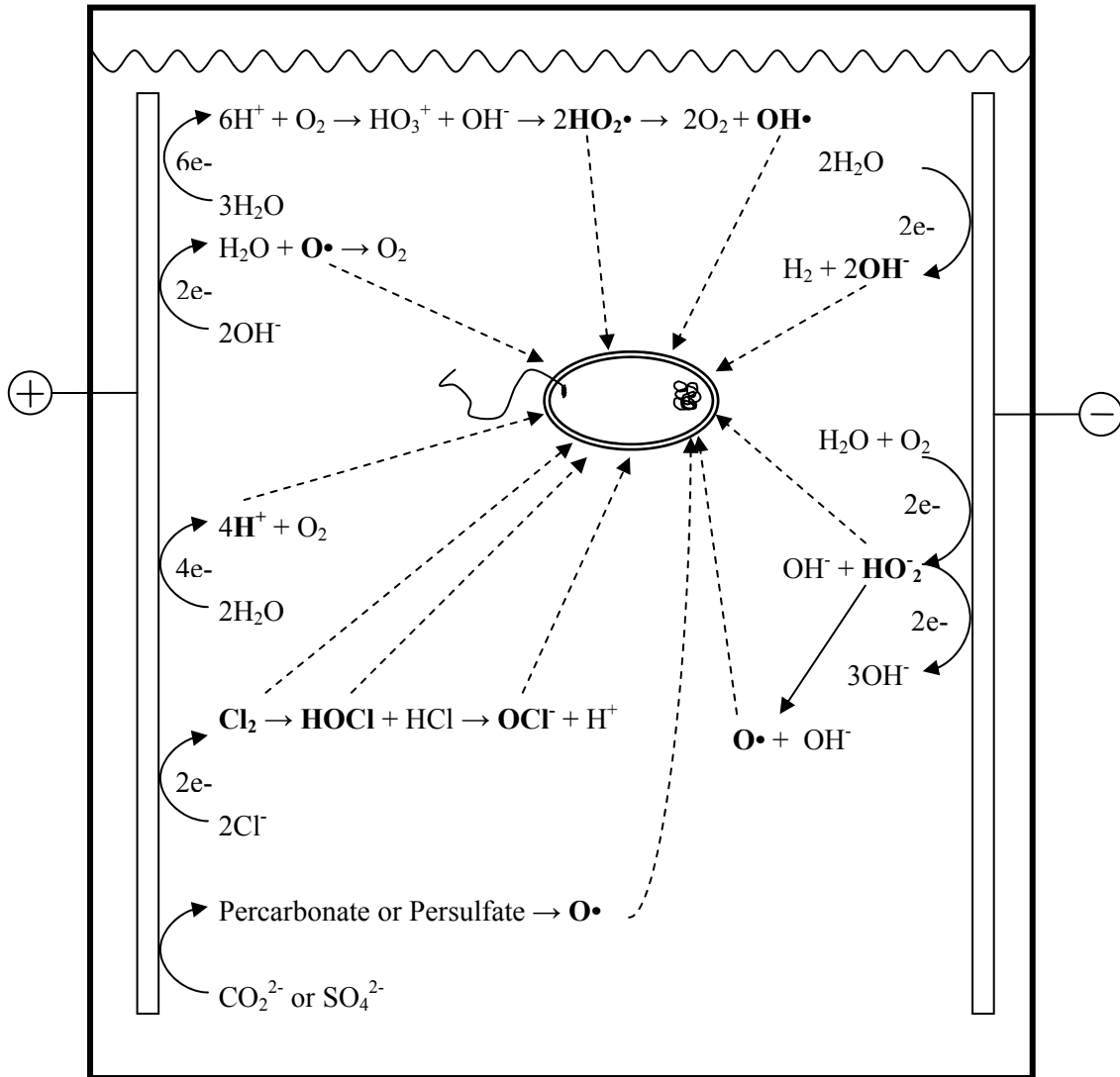
Figure 3. Electrolytic generation of microorganism deactivators.
(Rajeshwar & Ibanez, 1997)

As can be seen, the inactivation of bacteria and yeast cells by electrochemical means has been well documented. Drees *et al.* (2003) proved that the inactivation is primarily due to the disinfectant properties of active oxygen compounds produced at the electrodes. These

oxygen compounds help to reduce the formation of unwanted disinfection byproducts such as THM as they are formed during the disinfection with conventional chlorine dosing. The hydroxyl radicals are highly reactive, non-selective electrophilic reagents that serve as a precursor to the oxidative breakdown of organic molecules, such as halogenated hydrocarbons into smaller, less toxic organic compounds and mineralized acids (Trujillo *et al*., 2005). Indeed, advanced oxidation processes (AOP) are a class of emerging technologies in drinking water treatment that utilizes hydroxyl radicals to oxidize DBP precursors.

2.3.1 Electrochemical Disinfection of Drinking Water and Recent Commercial Applications

Matsunaga *et al*. (1994) studied a novel electrochemical reactor employing activated carbon fiber (ACF) electrodes to disinfect bacteria in drinking water. They reported that E. coli cells adsorbed onto the ACF were killed electrochemically without noticeable production of chlorine species. They even claim that this reactor may be used for the clean and safe treatment of drinking water with additional separation systems for nonbacterial pathogens.

Even though various patented devices exist, the direct disinfection of water by electrolysis has not yet found a broad application in the drinking water treatment industry (Bergmann *et al*., 2002). New studies have been reported and some authors - Fryda *et al*., 2003; Ferro *et al*., 2000; Haenni *et al*., 2001 - consider diamond electrodes to be a promising alternative to traditional electrode materials, such as activated titanium.

It has also been reported that bacteriophage are able to tolerate greater direct current magnitudes and greater durations of exposure to direct current than bacteria (Drees *et al.*, 2003). Therefore, use of this technology in fields that affect human health (such as drinking water disinfection) must ensure the destruction of viruses, not just bacteria, in order to consider the treated medium safe.

In parallel to this investigation several companies, especially in Europe, are developing a range of advanced electro-chemical industrial scale water and wastewater treatment processes that offer a rapid, effective and low cost alternative or enhancement to physical, chemical and biological treatment systems for the removal of toxic, organics, colloids, solids, heavy metals, colors, inorganics, odor and disinfection for potable, municipal and industrial wastewater and recreational waters.

There are various electro-disinfection patented processes that are claimed to be as effective as chlorination with the environmental benefits of UV treatment. These commercial applications are primarily in the field of drinking water treatment, disinfection of swimming pools, cooling towers and process waters.

The following are examples of companies that offer electro-disinfection patented equipment:

1. AXONICS® (United Kingdom, http://www.axonics.co.uk)

    Patented Process: **ELECTRAdeck™.**

    The Axonics® disinfection device is a low power system which disinfect water by electrification of microorganism and viruses using specially developed inert electrodes and closed loop fuzzy logic control. "ELECTRAdeck™ is an energy efficient, low cost, environmentally friendly process that can be used for the combined treatment and separation of suspended solids, colloids, dissolved inorganic and organic pollutants, heavy metals and for disinfection."

2. NEWTEC® (Germany, http://www.newtec-berlin.de)

    Patented Process: **e-disinfector.**

    The e-disinfector can be applied in most fields of water disinfection. Through setting of the operational parameters it is easy to comply with appropriate technical requirements and guide lines. According to NEWTEC®, several hundred systems are used worldwide.

3. CSEM (Switzerland, http://www.csem.ch/fs/environmental.htm)

    Patented Process: **DiaCell®.**

    DiaCell® is a product based on boron doped diamond electrodes for water disinfection with remaining action such as micro-organisms inactivation in the drinking water, swimming pool water, process water, and ballast water treatment. The company claims that E-Coli inactivation is at least 3 times faster with DiaCell® than with chlorine.

2.3.2 Electrode Materials for Electrochemical Treatment

The selection of electrode materials for electrochemical treatment must take into account issues such as cost, accessibility, stability at the required potentials, selectivity, composition and pH of the reaction medium, nature of intermediates substances and products, and environmental compatibility. Care has to be taken in proper selection, since most electrodes are useful in only a limited range of potential and pH.

With conventional metal electrodes, electrochemical treatments are unsuitable because of the low stability of the anodes and the poor current efficiency (Fryda *et al*., 2000). Regarding stability at the required potentials, the selected electrode material must be such that it will not corrode under the application of the needed potentials. It must be noted that the majority of organic and inorganic substances require high potentials for their oxidation, often higher than that for the oxidation of water. Consequently, oxidized noble metal surfaces (for example: Pt, Ir, Ru) are usually necessary for the oxidation of organic substances, although their cost poses a major restriction for their widespread use. Some cheaper substitutes such as oxidized nickel and lead can be used in aqueous media (Rajeshwar & Ibanez, 1997).

As explained before, there are two important classes of electrochemical reactions occurring at the electrodes in aqueous solutions under externally applied current:

1. Oxidation of the solid metal into solution (in the case of reactive anodes):

$$Metal \rightarrow Metal(^{n+}) + ne^- \text{ (where n = number of charges)}$$
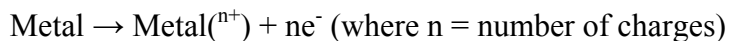
(secondary chemical reactions may follow depending upon the metal ion)

2. Production of gases, according to equations (3), (19) and (20):

$$2\ H_2O\ \rightarrow\ O_2 + 4\ H^+ + 4e^-$$

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
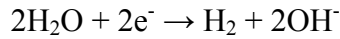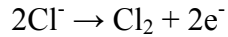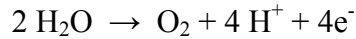
For all but a few very specialized anodes, chlorine gas production will dominate over oxygen gas production (Ashworth and Booker, 1986).

Electrode materials for the electro-disinfection process vary widely. Cathode materials include stainless steel, copper, graphite, carbon cloth, and reticulated vitreous carbon; anode materials include platinized titanium or niobium, tantalum, graphite, carbon, metal oxides, silver, copper, nickel, monel, dimensionally stable anodes, and combinations thereof. Electrocatalytic materials can be incorporated into electrodes, for example, in the form of coatings, such as ruthenium oxide (RuO_2), mixed iridium oxide (MIO), and/or titanium oxide (TiO_2) (Ibanez, 2004).

Three-dimensional electrodes have also been successfully used because they offer high surface areas per unit volume (Ibanez, 2004). Additionally, the passage of the solution through these electrodes produces local turbulence, which is beneficial for mass-transfer processes. Commercially available high surface area anodes include graphite, reticulated vitreous carbon, titanium, stainless steel, nickel, and Ebonex (a Ti-based ceramic).

2.3.2.1 Types of Anode materials

Electrode materials can be classified in four different types based upon their reactive behavior under electric current application (Ashworth and Booker, 1986):

1. *Fully consumable metals and alloys*: These are metals such as magnesium, zinc, aluminum and iron that dissolve under applied current. Faraday's law can be used to describe the relationship between current density (A/cm^2) and the amount of metal that goes into solution (Vik, E.A. *et al.*, 1984):

$w = (i \cdot t \cdot M \cdot area) / (Z \cdot F)$ where,
i = current density (A/cm^2)
w = metal dissolving (g)
M = molecular weight of the metal
F = Faraday's Constant (96500)
Z = number of electrons involved in the oxidation/reduction reaction

2. *Bulk non-metallic conductors*: Graphite and magnetite anodes fall into this category of anode materials. The primary reaction at the anode is chlorine and oxygen gas evolution. Electrode dissolution occurs via secondary chemical reactions with the electrolyte products near the anode. The rate of anode dissolution for this kind of electrode is about a factor of hundred less than that of fully consumable metal anodes.

3. *Partially passive metals and alloys*: This includes lead and high silicon iron alloy anodes. Resistance to direct dissolution of the anode is achieved by the formation of an electrically conductive thick oxide film over the surface of the metal. Conduction through this type of thick oxide film is from micropores or by metal alloy atoms imbedded in the oxide

film. The rate of dissolution is less than that of fully consumable metal anodes by a factor of ten to a hundred.

4. Fully passive anodes: Platinum is the most common metal in this category of anode. On platinum anodes an electrically conductive thin film a few atomic layers thick forms on the surface of the metal. The film itself is both conductive and nonreactive. The only reaction at the anode is gas evolution. The DSA™ (Dimensionally Stable Anode) composed of titanium with a thin film coating of RuO_2 and IrO_2 is also in this category. The residual rate of dissolution is roughly one millionth of that of fully consumable metal anodes.

2.3.2.2 Characteristics of Specific Electrode Materials

As stated before, noble metals and oxide-covered lead and titanium substrates are more commonly used for electrochemical applications, due in part to their high resistance to severe conditions and the high oxygen evolution overpotentials of the oxide-covered materials (Rajeshwar & Ibanez, 1997). Some relevant details of various electrode materials used in electrochemical processes are presented below (Ashworth and Booker, 1986):

1. Ferrous metals:

This electrode material has the serious problem of very rapid usage rate. The theoretical rate of dissolution is about 1 kg / kiloamp-hour. The reason why this type of electrode might be considered for electrochemical processes is due to its easy and cheap availability as scrap material.

2. Aluminum:

This shares the rapid dissolution problem that ferrous metals have. The dissolution products though are more chemically benign. The use of aluminum in electrochemical applications is not very common for economic reasons.

3. Magnetite:

This is a naturally occurring mineral composed of iron and oxygen in a non stoichiometric crystal lattice. Manufacture is by melting and casting at 1540°C. Magnetite electrodes have the disadvantage of being mechanically fragile and having low electrical conductivity compared to metal anodes. The dissolution rate at about 2×10^{-4} kg / amp-hour is very low compared to conventional metal anodes. Magnetite is claimed to have an oxygen production overvoltage lower than for chlorine gas production which will be advantageous in minimizing chlorine gas byproducts.

4. Carbon:

Carbon in the form of graphite is one of the most commonly used anode materials. Graphite is highly porous and gas production in the pores at high current densities can result in mechanical deterioration of the anode. The dissolution reactions are not direct oxidation reactions but chemical reactions with the electrolyte. In low chloride ion environments oxidation of the carbon into carbon dioxide is the dominant reaction. In sea water anode dissolution is caused by more complex reactions involving reactions with chlorine gas and chloride ions. The dissolution rate is dependent upon current density. In sea water, at current

densities of 4 to10 amps / meter^2, the measured dissolution rate is about 0.005 kg / kiloamp-hour.

Carbonaceous materials (carbon felt, reticulated vitreous carbon, glassy carbon) are known to have surface oxygenated functional groups that facilitate electron exchange with organic substances and are safe from an environmental point of view. However, composite conductive carbon materials are expensive to produce as high temperature carbonization and graphitization stages are necessary to transform polymer compositions into conductive carbon electrodes (Rajeshwar & Ibanez, 1997).

Three-dimensional carbonaceous cathodes made of partially graphitized amorphous carbon and graphite felts have proven to be immune from deterioration (attack by radical species or intercalation of ions or molecules between its basal planes causing fractures). The graphitization ensures sufficient reactivity enhancement, whereas the amorphous structure provides cross-linking between planes.

5. High silicon composition steel alloys:

These are steel alloys that contain up to 18% silicon. The theory of operation of these anodes is that the initial corrosion of these anodes leaves a surface film of porous, metal ion doped silicon dioxide that can conduct electricity but suppresses dissolution of the inner metal anode material. The exact nature of this surface passivation mechanism is a matter of dispute among researchers. These are very hard brittle alloys shapeable only by casting and grinding. The major advantage of this type of anode is its good balance between cost and resistance to

dissolution. The dissolution rate under impressed current flow of an optimized alloy was given as 0.02 kg / kiloamp-hour.

6. *Lead and lead alloys:*

Lead has a complex electrochemistry when used as an anode material. Pure lead at low current densities dissolves into Pb^{2+} ions. The measured dissolution rate for pure lead under these conditions is 5 kg / kiloamp-hour. At higher current densities in sea water, lead chloride ($PbCl_2$) forms at the surface. Lead chloride is an insulator that drops power efficiency radically as it thickens due to the IR voltage drop that occurs across the $PbCl_2$ film. Under special conditions however a thin film layer of lead oxide (PbO_2) can be formed over the surface of the anode. PbO_2 is an electrical conductor that can passivate the surface against both dissolution and lead chloride formation. A lead oxide covered lead anode can have a dissolution rate as low as 0.001 kg / kiloamp-hour.

Lead can be conditioned to form oxide films by alloying and by embedded surface microelectrode arrays. Alloying with silver and antimony produces a surface with localized silver grains that forms nucleation sites for PbO_2 to form and spread over the entire surface. A similar effect has been observed with lead anodes with platinum microelectrodes (0.5 mm diameter) inserted into the surface. A lower cost method of embedding microelectrodes was accomplished by embedding particles of magnetite in lead. Such surface passivated lead alloy anodes were rated by some authors to be a factor of 8 more economical than that of silicon steel.

7. Platinum:

Platinum electrodes resist dissolution not only because of its position in the galvanic series as a noble metal, but also because it forms an electrically conductive passivating thin surface film. The dissolution rate of platinum anodes in sea water is rated as about 2×10^{-6} kg / kiloamp-hour. The high expense of platinum combined with its very low rate of wear has lead to it being primarily used as a thin film plating over less expensive metals. The most cost effective combination has been platinum applied over titanium. Niobium and tantalum are other metals which have been used successfully as substrate metals for manufacturing platinum anodes.

Titanium has a critically important characteristic as a base metal in that it forms a nonconducting oxide over any breaks in the platinum thin film when operating as an anode. This anodic inert oxide formation by the substrate metal is very important for the successful use of platinum as a thin film anode. If platinum were applied over magnesium for example, any breaks in the platinum thin film would lead to a concentration of current flow to the break in the thin film with a subsequent rapid corrosion of the less noble magnesium substrate propagating from that point.

Platinum is most commonly applied to the substrate metal by electrodeposition in a plating bath. Coatings from 1 to 15 microns are commonly used. These platinum thin films have some restrictions in the conditions of operation if long operating life is to be maintained. Electrical ripple in the power supply will couple through the passivating thin film and rapidly corrodes the electrode. The DC current source must be well filtered. Also operation of a

platinum coated electrode as a cathode causes rapid platinum coating loss due to hydrogen ingress into the titanium substrate. This can be very important in that any direct metallic contact between magnesium and a platinum coated electrode in an electrolyte will result in the platinum electrode acting as a cathode. This also disqualifies platinum coated electrodes from operating as both an anode and a cathode for alternating polarity.

8. Diamond Coated Electrodes:

Diamond coated electrodes have undergone intensive investigation over the past number of years. The most important electrochemical properties are the very high corrosion stability in electrochemical applications and the extremely high overvoltage for water electrolysis, providing the possibility of producing strong oxidizing solutions with extremely high efficiency (Fryda *et al*, 2003).

Boron doped diamond films have been deposited on silicon, siliconcarbide and different industrial electrode materials, like niobium, tantalum, titanium, tungsten, zirconium and graphite on areas up to 40cm x 60cm (Fryda *et al*., 2000). The Fraunhofer IST in cooperation with CSEM in Switzerland has further developed a technology for large area production of diamond coatings on areas up to 50 x 100 cm (Fryda *et al*, 2003). Utilizing this technology diamond coated electrodes may be produced on a variety of base materials and geometries for many processes in sufficient quantities.

Diamond coated electrodes are chemically, mechanically and thermally very resistant and show no significant corrosion even under high electrochemical load (Fryda *et al.*, 2000).

Its electrochemical activity remains constant in contrast to other conventional carbon electrodes: as diamond electrodes are both stable as anodes and cathodes, it is possible to reverse polarity in order to prevent limestone build up on the electrode surface from calcium and magnesium ions in water (Fryda *et al.*, 2003).

These electrodes show high overpotentials for water electrolysis (hydrogen, as well as oxygen evolution) and present no surface redox processes as known from other carbon electrodes. This electrochemical window is large enough to produce hydroxyl radicals with high efficiency, capable of oxidize organics completely to carbon dioxide (Fryda *et al.*, 2003). Depending on the presence of other reactants in aqueous solutions different species with a high oxidizing potential could also be produced. All of these reactants contribute to the complete, indirect oxidation of pollutants (Fryda *et al.*, 2000).

The number of environment-related investigations, papers, and symposium topics in electrochemistry and materials-related journals and conferences is on the upswing, and this trend is likely to continue in the following years. This leads to the possibility to manufacture low cost water electro-disinfection systems in the near future.

CHAPTER 3

EXPERIMENTAL PHASE

3.1 EXPERIMENTAL DESIGN AND SETUP

Several experiments have been done at the University of New Orleans since January 2004 to evaluate the kinetics of the electro-disinfection process. In the beginning, a pilot scale treatment plant located adjacent to the Engineering Building at the University of New Orleans was used to reveal the influence of important parameters such as contact time and power consumption on the process performance.

This first experimental set up consisted of three reaction chambers in parallel, formed by 2 concentric, vertical, seamless aluminum pipes connected to a power supply. The outer pipe on each chamber was 89 mm (3.5 in) in diameter, 1.82 m (6 ft) long and the internal concentric pipe was 63.5 mm (2.5 in) in diameter, 2.44 m (8 ft) long. A plastic cone supported the inner pipe and sealed the center opening, therefore, a 13 mm (0.51 in) annular space was provided between the pipes for water to flow from bottom to top. The total anode/cathode/water contact area on each chamber was 0.78 m^2 (8.4 ft^2) and it could handle continuous flow rate up to 4.5 L/min (1.2 gal/min). Figure 4 shows a diagram of the unit.

The electrodes were connected to the positive and negative outputs of a 40-volt, 20-amp direct current rectifier that takes alternate current (AC) and transforms it into direct current (DC). The power supplier had automatic polarity reversal every two minutes and the

DC output was adjustable by varying either the current or the voltage. Reversing polarity minimized the formation of polarized layers and distributed the aluminum electrode consumption. It also allowed the required voltage and the power consumed to be maintained at a lower level.
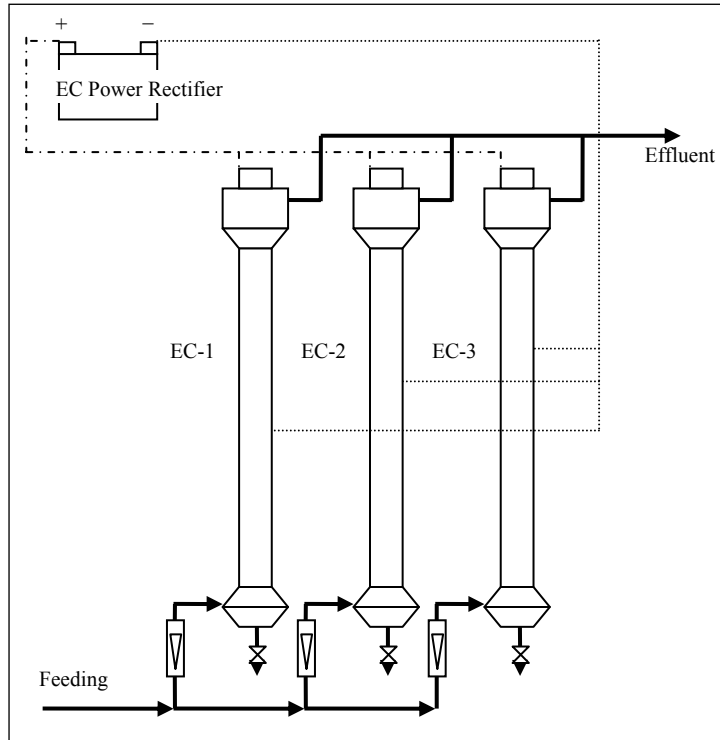
Figure 4. Diagram of the Pilot-Scale Electro-Disinfection Unit

Few experiments were performed with this tentative system because many difficulties were experienced and some parameters were extremely complex to control, particularly the flow rate and energy consumption. In addition, a significant amount of sludge was produced and it was difficult to remove it from the effluent with this particular system configuration. Conductivity, pH, ORP and temperature of influent and effluent samples were monitored. Total

coliform count, total COD, total suspended solids and total aluminum concentrations in each sample were determined.

Nevertheless, coliform removal efficiencies between 60% (0.4 log removal) and 96.5% (1.5 log removal) were observed. It was also determined that for better coliform removals the power consumption must be increased, and that as the power is raised more aluminum suspends into the water from the electrodes, thus generating larger quantities of sludge.

These preliminary tests demonstrated the usefulness of this technology for wastewater disinfection. However, further examination of the technology was required to find out if chlorine disinfecting species are produced or if electrocution and/or free radical and oxygen species are the major coliform death causes. The successful preliminary results warranted the development of carefully controlled experiments to optimize the electro-disinfection technology, as presented below.

To further confirm the disinfective effectiveness of the system, four bench scale batch electrochemical cells were assembled and operated in the UNO Schlieder Urban Environmental Systems Center Analytical Laboratory. Based on previous researches and available resources, the electrode materials selected where: aluminum, stainless steel, and titanium. The first electro-disinfection reactor was set with aluminum electrodes, the second with standard 316 stainless steel electrodes, the third one with titanium electrodes, and the fourth one was assembled with a standard 316 stainless steel cathode and a titanium anode.

Each cell is cylindrical in shape, consisting of a tube-shaped column as the outer electrode, and a similar thinner pipe placed in the center surrounded concentrically. A plastic section supports both pipes and seals the center opening, providing an annular space between the pipes to place the water sample. Dimensions of the pipes for each cell, as well as the total anode/cathode/water contact area utilized on each case, are presented in Table 10. Figures 3 and 4 illustrate, respectively, a basic diagram of the electrochemical reactor and a photo of the laboratory unit (aluminum electrodes).

Table 10. Dimensions of the Electrochemical Cells

		Aluminum		Titanium		Stainless Steel	
		cm	in	cm	in	cm	in
Inner Pipe							
	Inside Diameter	5.26	2.07	5.54	2.18	5.26	2.07
	Outside Diameter	6.03	2.37	6.07	2.39	6.05	2.38
	Thickness	0.40	0.16	0.28	0.11	0.40	0.16
	Length	71.00	27.95	71.00	27.95	71.48	28.14
Outer Pipe							
	Inside Diameter	7.74		8.31	3.27	7.81	3.07
	Outside Diameter	8.89	3.50	8.95	3.52	8.94	3.52
	Thickness	0.55	0.21	0.31	0.12	0.55	0.21
	Length	66.00	25.98	62.90	24.76	62.40	24.57
Anode/Cathode/Water Contact Area		1828 cm^2		1044 cm^2		1742 cm^2	

Again, the rectifier had automatic polarity reversal capabilities. The reversal of polarity among the system facilitates electrochemical reactions at the average electrochemical potentials set by the equilibrium between surface groups and the electrolytic solution. In addition, a self-cleaning effect occurs due to the periodic reversal of current, which changes the nature of the substances produced at each electrode, thus preventing deposits and other undesired cumulative effects.
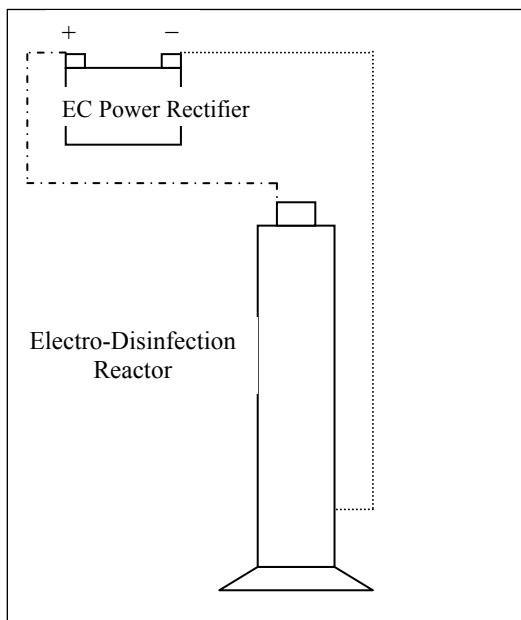
Figure 5. Diagram of the batch Electro-Chemical Cell

The DC output was adjustable by varying either the current in the range of 0 - 40 amp or the voltage in the range of 0 - 20 v. A multimeter (AMPROBE®, model ACDC-400) was used to read the current values.
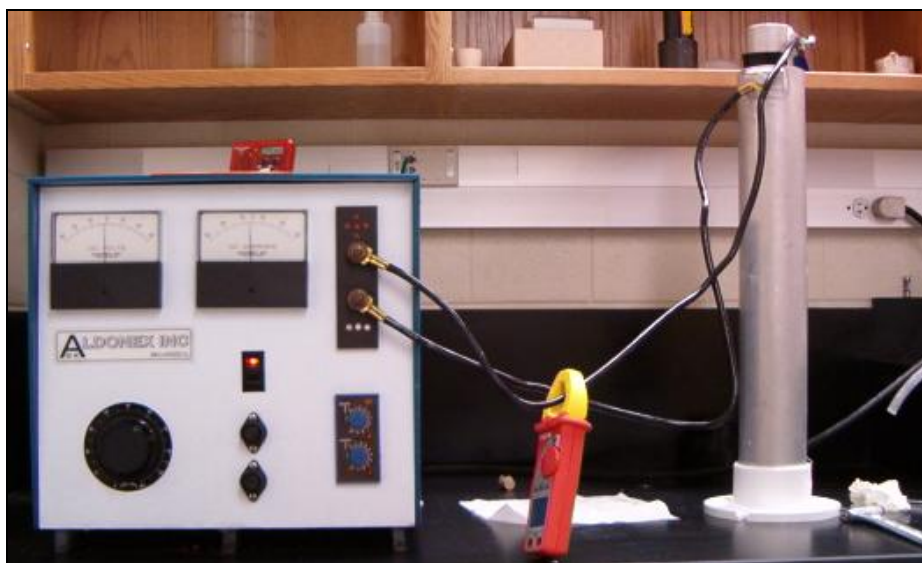
Figure 6. Electro-Chemical Cell connected to the Power Supply.

The chemical composition of the standard 316 stainless steel electrodes is presented in Table 11. Aluminum and titanium electrodes were 100% pure.

Table 11. Typical chemical composition for 316 stainless steel alloys

Element	%
Iron	62.00 - 69.00
Carbon	<0.08
Manganese	2.00
Phosphorus	0.045
Sulfur	0.03
Silicon	1.00
Chrome	16.00 - 18.00
Nickel	10.00 - 14.00
Molybdenum	2.00 - 3.00

3.2 OPERATIONAL PROCEDURES. WASTEWATER SAMPLES

Wastewater effluent samples were collected from the secondary clarifier after activated sludge treatment at the East Bank Wastewater Treatment Plant. Immediately after collection, the samples were taken to the Schlieder Urban Environmental Systems Center Analytical Laboratory to be disinfected in the electrochemical cells. During the course of the experiments over approximately 5 months, the quality of treated effluent was reasonably consistent. The main water quality characteristics are summarized in Table 12. Salinity of the water (chloride concentration) was raised in some of the tests with the addition of sodium chloride.

To evaluate the disinfection efficiency of each electrochemical cell, an orthogonal array experimental design method was used to study the three main factors (in addition to electrode material) thought to influence the disinfection efficiency of the system: current density,

chloride concentration and contact time. Full-factorial design allows to experiment on many

factors simultaneously and to reveal interactions among them.

Table 12. Main Characteristics of the Wastewater Effluent

Parameter	Average Value	Range
Coliforms (MPN/100ml)	4.81×10^6	$1.68 \times 10^6 - 7.13 \times 10^6$
COD (mg/l)	70	$46 - 105$
TSS (mg/l)	15	$4 - 41$
Cl$^-$ Concentration (mg/l)	137	$118 - 165$
pH	7.13	$6.88 - 7.44$
Temperature (˚C)	21.1	$17.2 - 25.0$

The first unit evaluated was the aluminum electrodes reactor. Table 13 shows the actual

high and low levels of each factor used to design the experiment with this cell.

Table 13. Factors and Levels for the Experimental Design (Aluminum Electrodes)

Factor	Units	Low Level	High Level
Current Density	mA/cm^2	1.5	5.5
Contact Time	min	5	15
Cl$^-$ Concentration	mg/L	~ 130	~ 1000

Twelve runs were conducted according to the experimental design obtained with the

software *Design-Ease*[®] *6.0* from Stat-Ease[®]. The design matrix, showing all the operating

conditions tested (including two center points and replicates) is presented on Table 14. The

runs were performed in randomized order to offset any lurking variables such as sampling

time, temperature, humidity or the like. Each experiment was repeated three times to account

for variability and to decrease experimental errors.

Table 14. Experimental Design Layout for the Aluminum Electrodes Reactor

Run	Current Density (mA/cm^2)	Contact Time (min)	Chlorides (mg/l)	Date
1	5.5	5	~ 130	Jan 24, 2005
2	5.5	15	~ 130	Jan 26, 2005
3	3.5	10	500	Jan 31, 2005
4	1.5	5	~ 130	Feb 11, 2005
5	1.5	15	~ 130	Feb 16, 2005
6	5.5	5	1000	Feb 21, 2005
7	1.5	5	1000	Mar 1, 2005
8	1.5	15	1000	Mar 2, 2005
9	5.5	15	1000	Mar 7, 2005
10	5.5	5	~ 130	Mar 10, 2005
11	3.5	10	500	Mar 15, 2005
12	5.5	15	~ 130	Mar 22, 2005

The evaluation of the aluminum electrodes reactor demonstrated that the factor "chloride concentration" does not affect the disinfection efficiency of system, at least for the range of contact time and current densities studied. Therefore, to evaluate the succeeding reactors only two variables were examined (current density and contact time). Table 15 presents the six runs performed with the stainless steel electrodes reactor, again each experimental condition was repeated three times.

Table 15. Experimental Design Layout for the Stainless Steel Electrodes Reactor

Run	Current Density (mA/cm^2)	Contact Time (min)	Date
1	7.5	15	19-Apr-05
2	3.5	5	21-Apr-05
3	7.5	5	25-Apr-05
4	5.5	10	3-May-05
5	3.5	15	4-May-05
6	1.5	10	4-May-05

It can be seen that with the stainless steel reactor higher current densities were tried, keeping the same contact times tested with the aluminum reactor. In the case of the titanium electrodes reactor, due to the fact that titanium is not a very good electrical conductor, lower

current densities and longer contact times were experimented. Table 16 shows the ten experiments performed with this reactor.

With the titanium cell it was difficult to maintain a constant current density because the thickness of a thin oxide film (TiO_2) increases slowly with time of current passage and therefore, additional voltage is needed in order to establish a constant current. Current densities reported on Table 16 are average values. In this case each experiment was done only once. In some of the runs chloride concentration was increased to augment the conductivity of the water and as a result achieve the desired current densities.

Table 16. Experimental Design Layout for the Titanium Electrodes Reactor

Run	Current Density (mA/cm^2)	Contact Time (min)	Chlorides (mg/l)	Date
1	2.59	5	~ 1000	Apr 5, 2005
2	1.99	5	~ 1000	Apr 5, 2005
3	2.45	5	~ 1000	Apr 5, 2005
4	1.00	15	~ 130	May 9, 2005
5	0.84	15	~ 130	May 9, 2005
6	0.78	15	~ 130	May 9, 2005
7	1.41	15	~ 1000	May 11, 2005
8	1.10	15	~ 1000	May 11, 2005
9	1.06	25	~ 1000	May 11, 2005
10	1.05	25	~ 1000	May 11, 2005

Finally, the fourth reactor was assembled with two different materials: the internal pipe was titanium (acting as the anode), and the outer pipe was stainless steel (acting as the cathode). Short retention times were experimented with this cell and no reversal of polarity was made, because the titanium electrode was selected as the anode for this experiment. Table 17 shows the four runs performed with this reactor; once more, each experimental condition was repeated three times.

Table 17. Experimental Design Layout for the Stainless Steel-Titanium Reactor

Run	Current Density (mA/cm^2)	Contact Time (min)	Date
1	3.5	5	May 18, 2005
2	1.5	5	May 18, 2005
3	3.5	2.5	May 23, 2005
4	1.5	2.5	May 23, 2005

At each combination of these experimental settings, the water was analyzed before and after disinfection for total coliform bacteria, total chlorine, chlorides, total COD, total suspended solids, and (depending on the electrodes used) aluminum or iron concentration. In addition, the following operational parameters were monitored in each experiment: pH, oxidation reduction potential (ORP), temperature, conductivity, dissolved oxygen, DC voltage and amperage applied. In the experiments with the stainless steel and titanium reactors, disinfected water was also tested for ozone.

3.3 LABORATORY ANALYSES

Except for the total coliform count, all the analytical procedures followed the methods stated in the Standard Methods for the Examination of Water and Wastewater 20th Edition (AWWA, 1998) or in the Analytical Procedures Manual of the HACH Direct Reading Spectrophotometer DR/2010 (HACH Company, 1999).

For simplicity and to save time, total coliform bacteria were used as the indicator microorganisms for the disinfection study, and were enumerated using the *3M Petrifilm™ E.Coli/Coliform Count Plates* (a method validated by the Association of Analytical Communities). After each run, a sample of around 200 ml was dechlorinated with excess

$Na_2S_2O_3$ to eliminate possible killing by residual chlorine prior to the enumeration. The concentration of total coliform bacteria in the original sample was determined taking into account the dilution factors.

The TSS test was performed according to Method 2540 D of the Standard Methods for the Examination of Water and Wastewater (AWWA, 1998). This parameter quantifies the amount of solid matter suspended in the samples.

Total residual chlorine, chlorides, ozone, aluminum, iron and the chemical oxygen demand concentration were measured with a portable datalogging spectrophotometer (DR/2010, HACH). Method 8167 (DPD Method, Powder Pillows) was used to determine total residual chlorine (this procedure is equivalent to USEPA method 330.5 for wastewater and Standard Method 4500-CL G for drinking water). Chloride concentrations were measured utilizing Method 8113 (Mercuric Thiocyanate Method). Ozone concentrations were measured using Method 8311 (Indigo Method). Method 8000 (Reactor Digestion Method) was used to determine COD (this method is approved by the USEPA for reporting wastewater analysis). Total aluminum and total iron were measured following Methods 8012 and 8008 respectively (both adapted from the Standard Methods for the Examination of Water and Wastewater).

CHAPTER 4

RESULTS AND DISCUSSION

The results and discussion of the various experiments conducted along the course of this investigation are presented in this chapter, and are grouped according to the electrode materials used in the batch reactors, namely: aluminum, stainless steel, titanium, and stainless steel-titanium.

4.1 ALUMINUM ELECTRODES

Even though aluminum falls in the category of fully consumable metals and might be unsuitable for economic reasons, this electrode material was selected because it was already available and because it has proved to be successful for electrocoagulation and electroflotation of wastewaters (Vik *et al*., 1984; Chen *et al*., 2000; Jiang *et al*., 2002; among others).

The aluminum electrodes reactor was the first one to be tested and served to observe the effects of three critical operational parameters, contact time, current density and salinity of the wastewater, on disinfection efficiency. To evaluate three variables at the same time, two levels of each variable were selected (see Table 13); as shown on Figure 7 and Table 14, a total of 12 runs were performed. The first two experimental conditions were repeated because the initial total coliform concentration of the wastewater was somewhat lower than the rest of the days. Also the center point conditions were carried out twice.
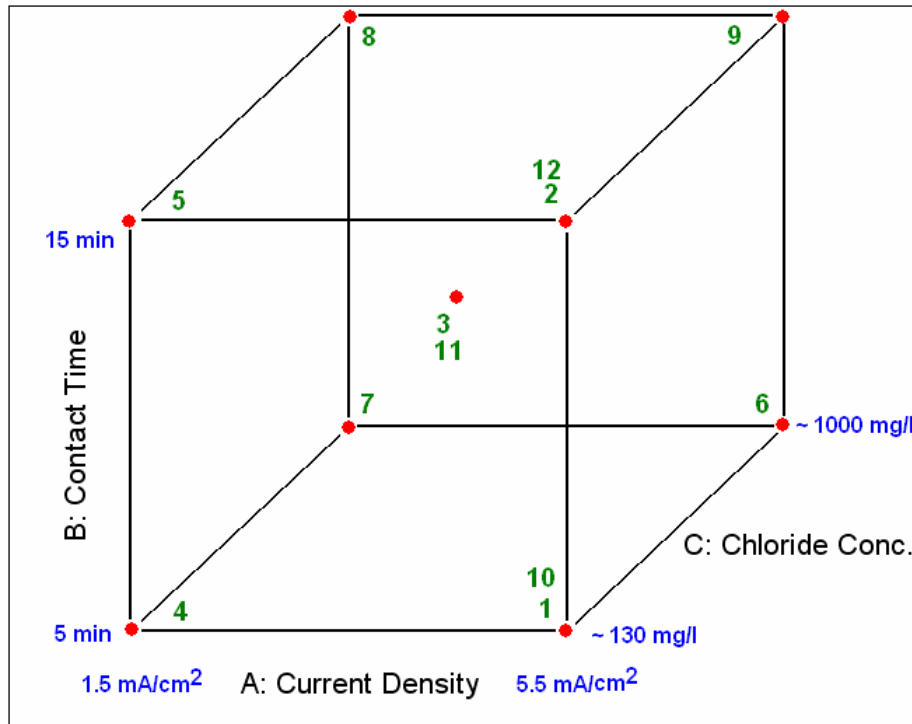
Figure 7. Experimental conditions of each run performed with the aluminum electrodes reactor.

Despite the large amount of sludge generated, the results obtained with this reactor provide evidence that a total coliform bacteria killing efficiency of 45 % or higher could be achieved with a contact time of less than 15 min in combination with the appropriate current input (see Figure 8). As it was expected, according to Li *et al.* (2004), the bactericidal efficiency generally increased with the current density and contact time, and the impact of these factors was much larger than that of salinity.

Log removal efficiencies were calculated and are presented in Table 18 along with COD removal efficiencies and total residual chlorine measured at the end of the disinfection process. The table contains average values of the three experiments performed at each set of conditions. Log removal values were used to evaluate the effect of the three variables (contact

time, current density and salinity) on the system utilizing the software *Design-Ease® 6.0* from

Stat-Ease®.
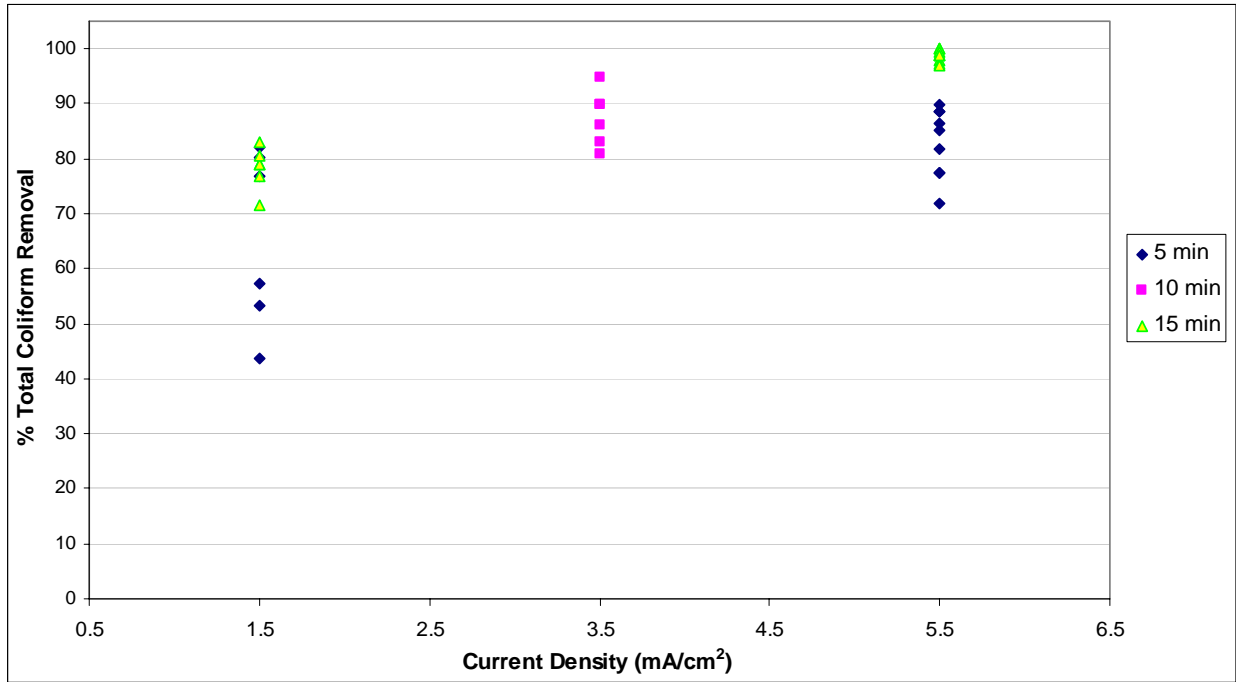
Figure 8. Coliform removal efficiencies as a function of current density and contact time (aluminum electrodes).

Table 18. Average experimental results using aluminum electrodes.

Run	Current Density (mA/cm²)	Contact Time (min)	Chlorides (mg/l)	Coliform Log Removal	% COD Removal	Total Residual Chlorine (mg/l)
1	5.5	5	139	0.61	-	0.35
2	5.5	15	137	2.18	61.4%	0.92
3	3.5	10	583	0.97	60.4%	0.78
4	1.5	5	140	0.31	67.4%	0.32
5	1.5	15	129	0.62	78.5%	0.53
6	5.5	5	868	0.90	62.2%	0.43
7	1.5	5	1005	0.69	59.3%	0.34
8	1.5	15	1025	0.72	65.6%	0.15
9	5.5	15	1075	1.74	65.9%	1.01
10	5.5	5	123	0.85	49.5%	0.41
11	3.5	10	580	0.84	75.2%	0.36
12	5.5	15	162	1.79	76.4%	0.61

A half-normal plot (Figure 9) was created to determine which factors or which combinations of factors affect statistically more drastically the disinfection efficiency of the system. On this plot, the y-axis displays the normal cumulative probability of getting a result at or below any given point. The x-axis presents, on an absolute value scale, the interaction effect of each variable. These effects are calculated averaging the responses obtained (log removal efficiencies) at its respective high and low levels, and determining the difference among them. Mathematically, the calculation of an effect is expressed as follows:

$$\text{Effect} = (\sum Y_{\text{high level}}/n) - (\sum Y_{\text{low level}}/\, n)$$

where, Y = response at the desired level

n = number of responses at given level
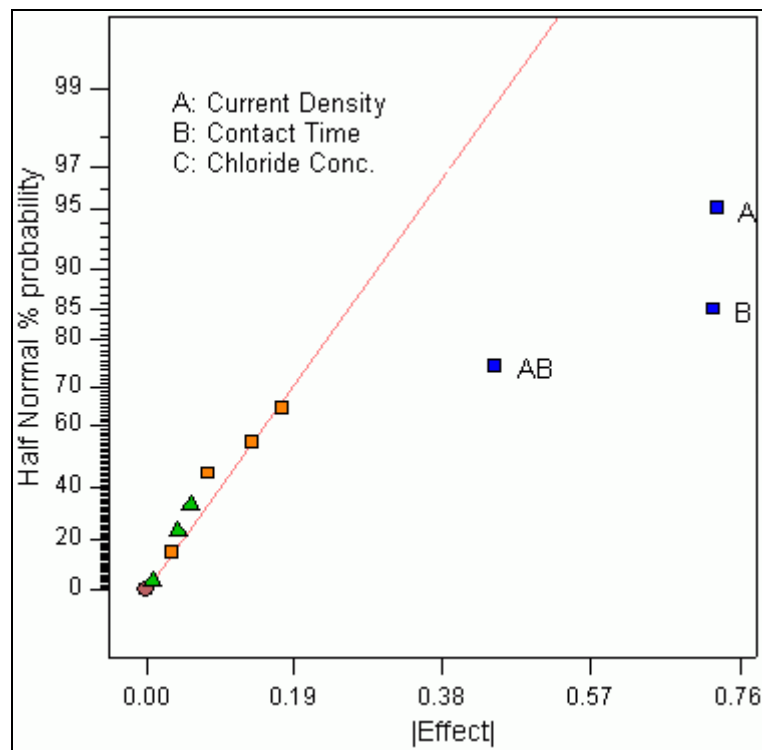
Figure 9. Half-normal plot of effects for log removal efficiency
(created with *Design-Ease*® *6.0*)

It can be seen that three points fall at a significant distance from the remainder, which indicates that these three factors (or combinations of factors) influence significantly the coliform removal efficiencies. The effects that fall on the line represent the normal scatter, so it can be assumed that they vary only due to normal causes and therefore are insignificant. According to this graph, it can be stated that the chloride concentration has very little effect on disinfection efficiency and, therefore the investigation should focus on the factors current density and contact time.

To verify the importance of the three larger effects (A, B, and AB on Figure 6), they were incorporated in a "model equation" for predicting the log removal efficiency response and an analysis of variance (ANOVA) was performed. The ANOVA results for the selected factorial model are tabulated in Table 19. The calculated mean square for the experimental error is only 1.10, which indicates that the analysis results of this factorial experimental design can be regarded as reliable.

Table 19. ANOVA results for the experimental design (Log Removal response).

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	3.31	3	1.10	30.92	0.0002
A	1.39	1	1.39	38.85	0.0004
B	0.99	1	0.99	27.84	0.0012
AB	0.54	1	0.54	15.07	0.0060
Residual	0.25	7	0.04		
Cor Total	3.57	11			

On the basis of the calculated F values, the current density and the contact time are statistically inferred to have significant influences on the disinfection efficiency, while the chloride concentration can be assumed to be insignificant. The actual F value of 30.92 exceeds

the critical values for 0.1% risk (18.77). Therefore, it can be said that the probability of getting an F as high as that observed, due to chance alone, is less than 0.1%. In other words, it can be stated with more than 99.9% confidence that the coliform removal efficiency is significantly affected by one or more of the effects chosen for the model.

The following mathematical equation is the "model equation" obtained by the program, in terms of actual factors:

$$\text{Log Removal} = 0.485 - 0.046667 * CD - 0.0185 * CT + 0.023667 * CD * CT$$

where, $\quad CD$ = Current Density (mA/cm^2)
$\qquad\quad CT$ = Contact Time (min)

Figure 10 shows log removal efficiencies predicted with this equation compared with the log removal efficiencies measured in the laboratory. The correlation found was relatively good ($R^2 = 0.91$), so the model can be trusted at the range of experimental conditions tested.
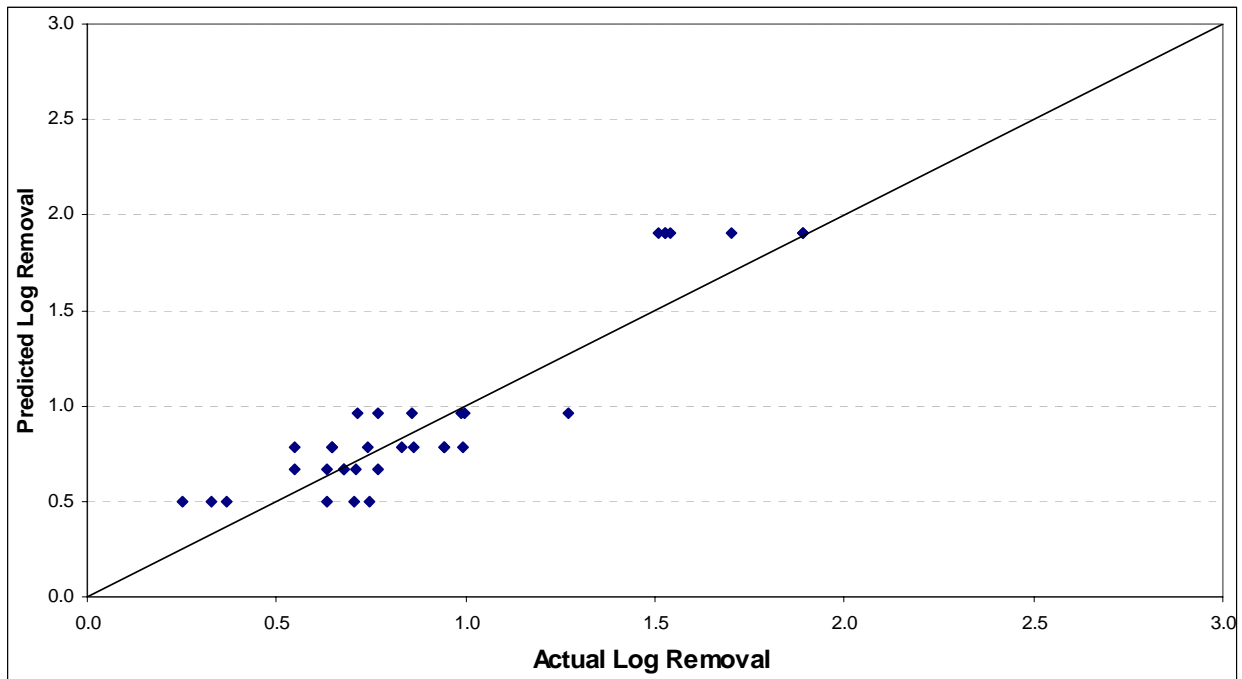
Figure 10. Relationship between predicted and actual values of log removal efficiencies.

The interaction between contact time and current density and their effect on coliform log removal efficiency is illustrated in Figure 11. Two lines appear on the plot, bracketed by least significant difference (LSD) bars at either end. It can be observed that in the tests where contact time was low (5 min), the change in log removal when current density changed was small. However, when the contact time was high (15 min), the log removal increased considerably, indicating a strong positive effect due to the augmented current density. It can also be seen that when the current is set at its low level (1.5 mA/cm^2) the LSD bars overlap at this end of the interaction graph, which implies that there is not significant difference in log removal when the current density is low.
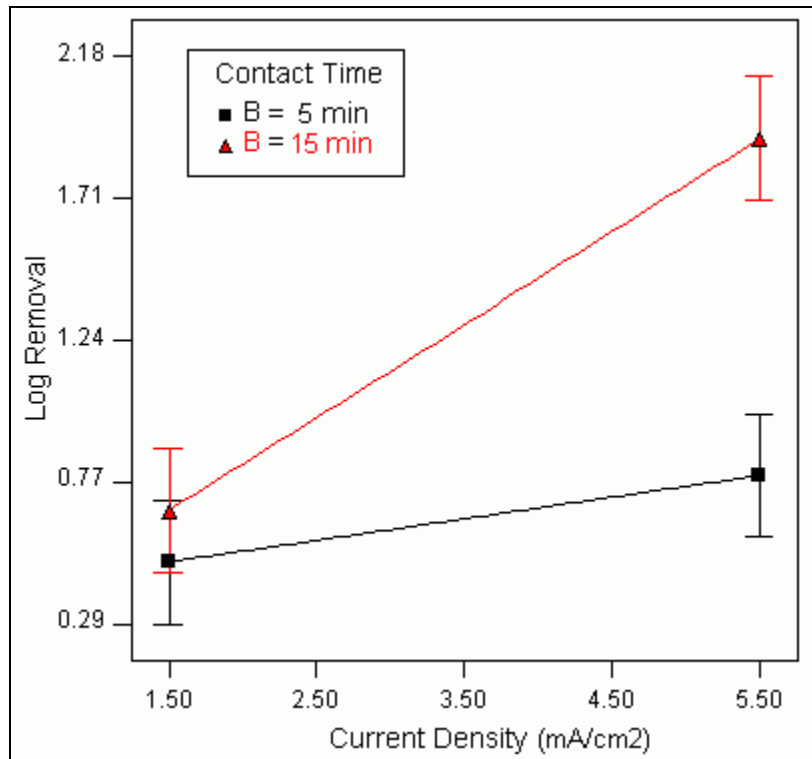
Figure 11. Interaction of current density vs. contact time on log removal efficiency.

The interaction of these two factors can be also appreciated in Figure 12, which depicts a contour graph for the system. This two-dimensional representation of the log removal response as a function of current density and contact time depicts factor levels outside the boundaries of the experiment. However, it could be used as a practical tool to estimate optimal contact time-current density combinations. For instance the use of a current density of 5 mA/cm^2 in combination with 25 min of residence time will cause a major bacteria killing achieving approximately 3 log removal efficiency. These conditions are suitable to be implemented in a wastewater treatment plant.
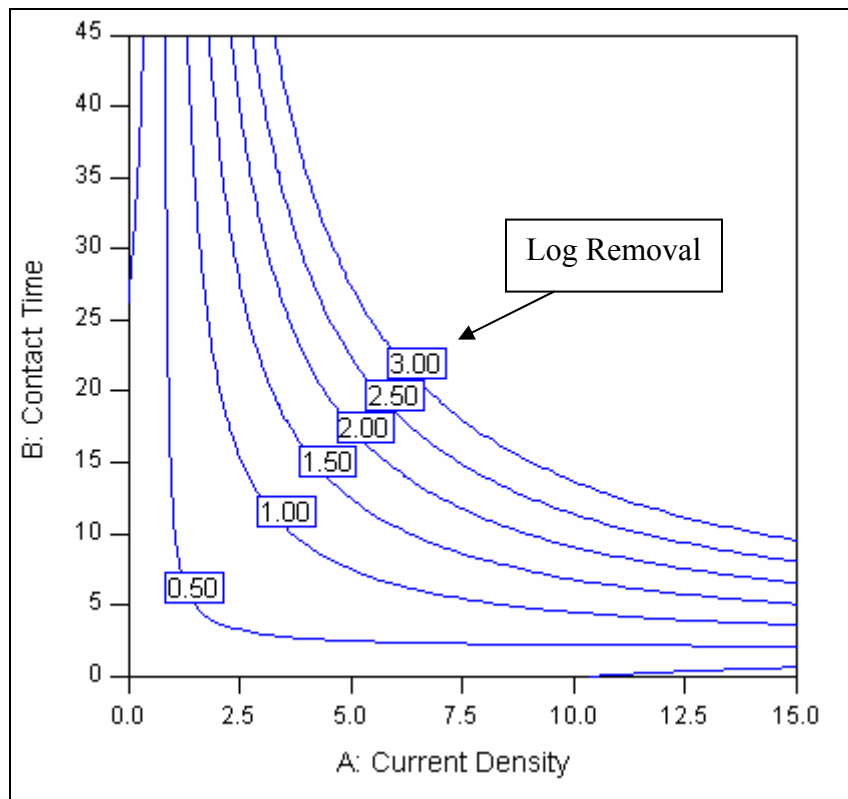
Figure 12. Interaction of current density vs. contact time on log removal efficiency
(created with *Design-Ease*® *6.0*)

Immediately after each experimental run, total residual chlorine was measured in the samples to verify that during the electro-disinfection process chloride ions were oxidized to form chlorine gas and hypochlorite ions at the anode (average values are presented in Table 18). The time elapsed between grabbing the sample and the analysis of chlorine was not exactly the same among all the experiments. However, values presented on Table 18 and Figure 10 demonstrate that total residual chlorine was present in the effluent samples; in general, as the operating current density increased the chlorine/hypochlorite production improved. This experimental evidence is consistent with the assumption that some of the lethal species are chlorine gas, hypochlorite, and hypochlorous acid.
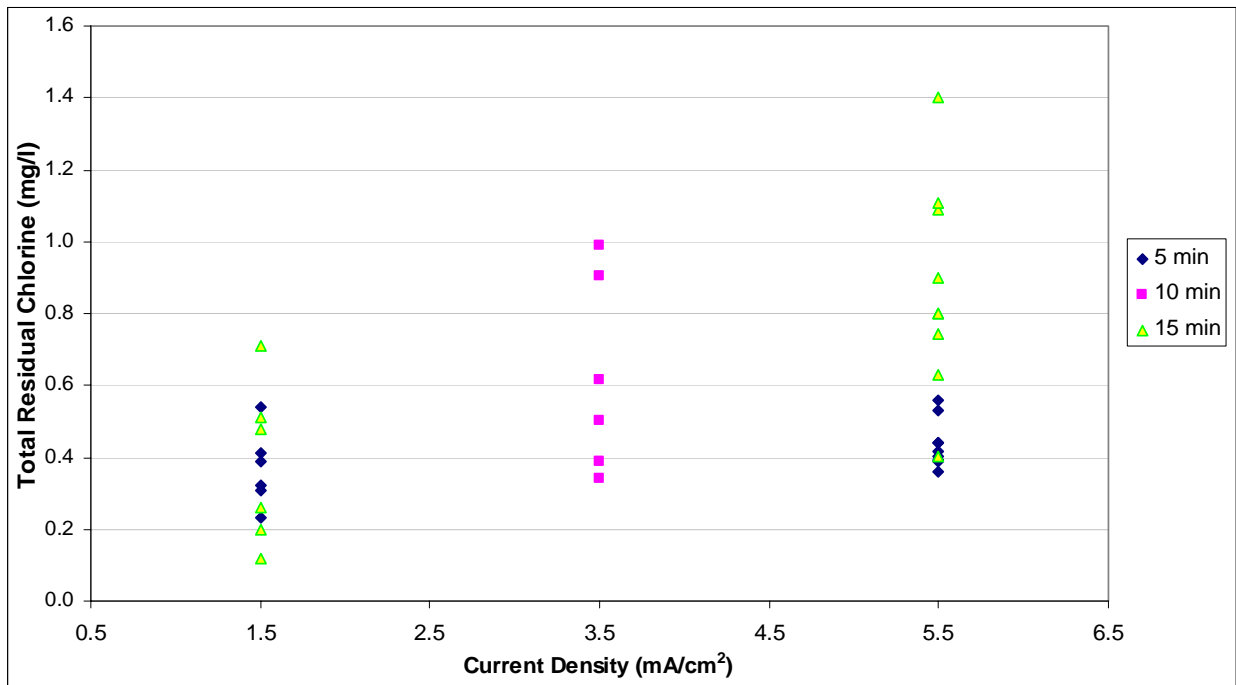
Figure 13. Total residual chlorine in the effluent samples as a function of current density and contact time.

Water samples were analyzed for total COD before and after treatment (effluent samples were analyzed after sludge sedimentation/flotation) and it was observed that the

electro-disinfection process using aluminum electrodes removes COD up to 76% (average values are presented in Table 18). In effect, this behavior was expected because some authors have demonstrated that electrocoagulation performs better than conventional coagulation for COD and suspended solids removal (Baklan and Kolesnikova, 1996). This is mainly attributed to the indirect oxidation effect of species being generated during the process and coagulation/absorption by the aluminum hydroxide floc.

In these experiments, the current used was 2-10 amps corresponding to current densities of 1.5-5.5 mA/cm^2 and the voltage demand was approximately 2-14 volts respectively. The energy consumption rate was calculated on each case using the formula $P = (I \cdot V \cdot t)/Vol$ in kWh/m^3, where I is the current in amps, V is the voltage applied in volts, t is the contact time in hours, and Vol is the sample volume in liters.
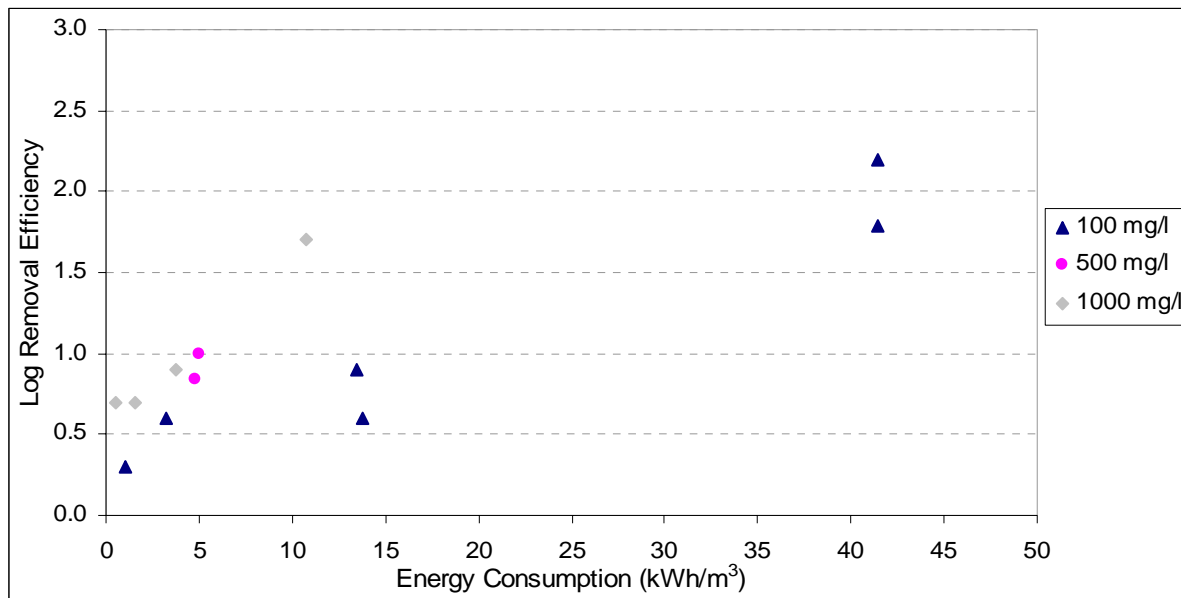
Figure 14. Log removal efficiencies as a function of energy consumption and chloride concentration on the influent water.

Log removal efficiencies are plotted as a function of energy consumption and chloride concentration in the influent water in Figure 14. It can be recognized that the energy requirements were very high on the two cases that the best disinfection efficiencies were obtained. But it is also clear that the addition of salts (such as sodium chloride) decreases the energy consumption of the process. This allows a system improvement from the energy requirement point of view.

As mentioned in Section 2.3.2.1, Faraday's law can be used to describe the relationship between current density (A/cm2) and the amount of aluminum that goes into solution. During the course of the investigation, the total aluminum concentration of the effluent in mg/l was measured before and after complete sedimentation. Table 20 shows the average values for total aluminum and TSS, before and after settling. The theoretically calculated amount of aluminum dissolved utilizing Faraday's Law was compared with measured values on Figure 15. Error bars are showed in the graph to illustrate the magnitude of experimental errors on each case.

Table 20. Total Aluminum and TSS after electro-disinfection.

Run	Current Density (mA/cm^2)	Contact Time (min)	Total Aluminum (mg/l) Before settling	Total Aluminum (mg/l) Super Natant	TSS (mg/l) Before settling	TSS (mg/l) Super Natant
1	5.5	5	678	-	1679	< 4
2	5.5	15	1145	-	6587	< 4
3	3.5	10	1023	1.4	2927	< 4
4	1.5	5	167	4.9	363	< 4
5	1.5	15	409	6.1	1111	< 4
6	5.5	5	801	15.8	2292	< 4
7	1.5	5	194	4.0	484	< 4
8	1.5	15	551	9.5	1411	< 4
9	5.5	15	3197	8.4	5951	< 4
10	5.5	5	876	20.0	1977	< 4
11	3.5	10	808	>8.0	2538	< 4
12	5.5	15	1548	17.0	5756	< 4
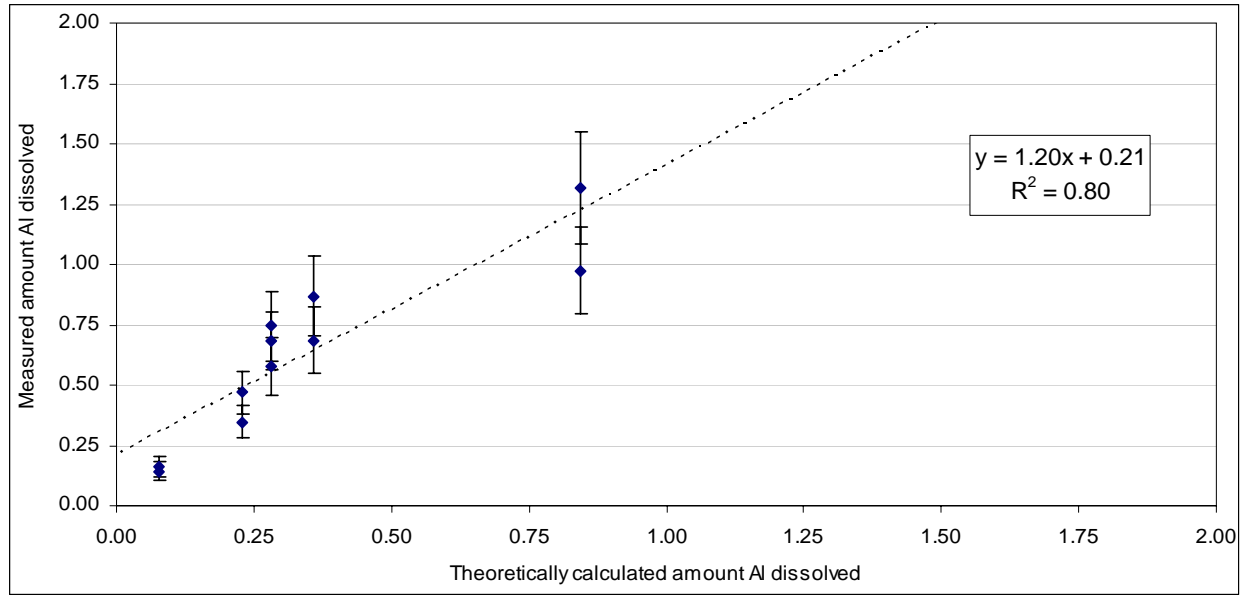
Figure 15. Relationship between theoretically calculated and practical dissolution of aluminum.

TSS as well as total aluminum concentration (before clarification) increases considerably due to the aluminum sludge produced in the process. At optimal conditions this sludge is easily removed by sedimentation/flotation leaving a super natant suitable to discharge from any wastewater treatment plant. Figure 16 compares electro-disinfected water at three different conditions after sedimentation /flotation.

As shown in Figure 15, there is around 20 % more aluminum dissolving into the water than the predicted by Faraday's law. Several possibilities could explain the atypical Faradaic yields of dissolved aluminum species: anomalous pitting corrosion behavior of aluminum has been reported; rapid dissolution of the oxide film formed on the surface of the electrode; *Jiang et al.* (2002) reported that apparent current efficiencies for Al anode dissolution and Al cathode dissolution are greater that unity for three-electron oxidation processes producing Al(III) species.

Figure 16. Treated water at three different current conditions after sedimentation /flotation.

In addition to the results presented herein, in each experiment water samples were monitored before and after the disinfection process for changes on pH, oxidation reduction potential (ORP), temperature, conductivity, TDS, and dissolved oxygen. These results are presented on the Appendix. In general, the pH rises on average 1.5 units, sometimes up to a pH of 9, due to the hydrogen gas evolution at the anodes and reduction of oxygen at the cathodes. Conductivity and TDS were found to decrease slightly after electro-disinfection (5% reduction at the lowest level experimented and 35% at the highest), and the change is directly proportional to the current density and residence time applied.

Although oxidant species are produced at the anode during the process (being the ones killing the bacteria), the average ORP in the water after treatment becomes more negative because the pass of electric current introduces loads of electrons into the water and creates a

strong reducing environment. As presented on Appendix A, the ORP is reduced noticeably in all the experiments (17% reduction at the lowest level experimented and 66% at the highest).

4.2 STAINLESS-STEEL ELECTRODES

Fewer experiments were done with the stainless steel reactor, because this time salinity of the wastewater was not included as a variable. The same contact time levels used with the aluminum reactor and a high range of current densities were used in this case, and the results are presented in Table 15. Stainless steel electrodes were selected because they have been used in previous researches (Li *et al.*, 2002), and have proved to be useful for electrochemical disinfection.

Electrochemical disinfection was highly effective for the treatment of wastewater effluents with this cell. Again, the efficiency of coliform reduction was a function of both contact time and current density. Killing efficiencies higher than 99.5 % were achieved with contact times equal or greater than 5 minutes (see Table 21). Log removal efficiencies were calculated and are presented in the same table along with COD removal efficiencies and total residual chlorine measured at the end of the disinfection process. During the first two runs it was not possible to measure total residual chlorine because oxidant species were interfering with the DPD method and the required reactives were not available.

Figure 17 shows how disinfection efficiency increases with both contact time and current density in a manner similar to that observed with the aluminum reactor. However,

stainless steel is markedly more efficient, and even with a current density of 1.5 mA/cm^2 log

removals greater than 2 were achieved.

Table 21. Experimental results using stainless steel electrodes.

Run	Current Density (mA/cm^2)	Contact Time (min)	% Coliform Removal	Coliform Log Removal	% COD Removal	Total Residual Chlorine (mg/l)	Residual Ozone (mg/l)
1	7.5	15	100.00	2.59	68.15	-	-
			100.00	2.59	69.43	-	-
			99.66	2.46	76.43	-	-
2	3.5	5	99.66	2.47	97.09	-	-
			100.00	2.09	91.27	-	-
			98.66	1.87	98.55	-	-
3	7.5	5	100.00	3.68	78.63	1.23	0.08
			100.00	3.68	82.44	1.15	0.03
			100.00	3.68	83.21	1.04	0.04
4	5.5	10	99.97	3.51	83.03	1.17	-
			100.00	4.63	90.30	2.50	-
			99.90	2.99	84.85	0.81	-
5	3.5	15	100.00	5.76	81.13	1.11	0.15
			100.00	5.76	69.06	0.64	0.12
			99.99	4.24	81.13	0.47	0.05
6	1.5	10	99.99	4.16	54.96	0.49	-
			99.79	2.67	45.80	0.27	-
			99.51	2.31	72.52	0.50	-

Similar to aluminum, this electrode material has the problem of very rapid usage rate.
However, stainless steel has the ability to form a thin layer of protection called the passive
film, which forms on the outside surface in the presence of oxygen. Contact with oxygen is
needed for the passive film to exist, and once formed it prevents further oxidation or
corrosion from occurring. Even if chipped or scratched, a new passive film on stainless steel
will form.
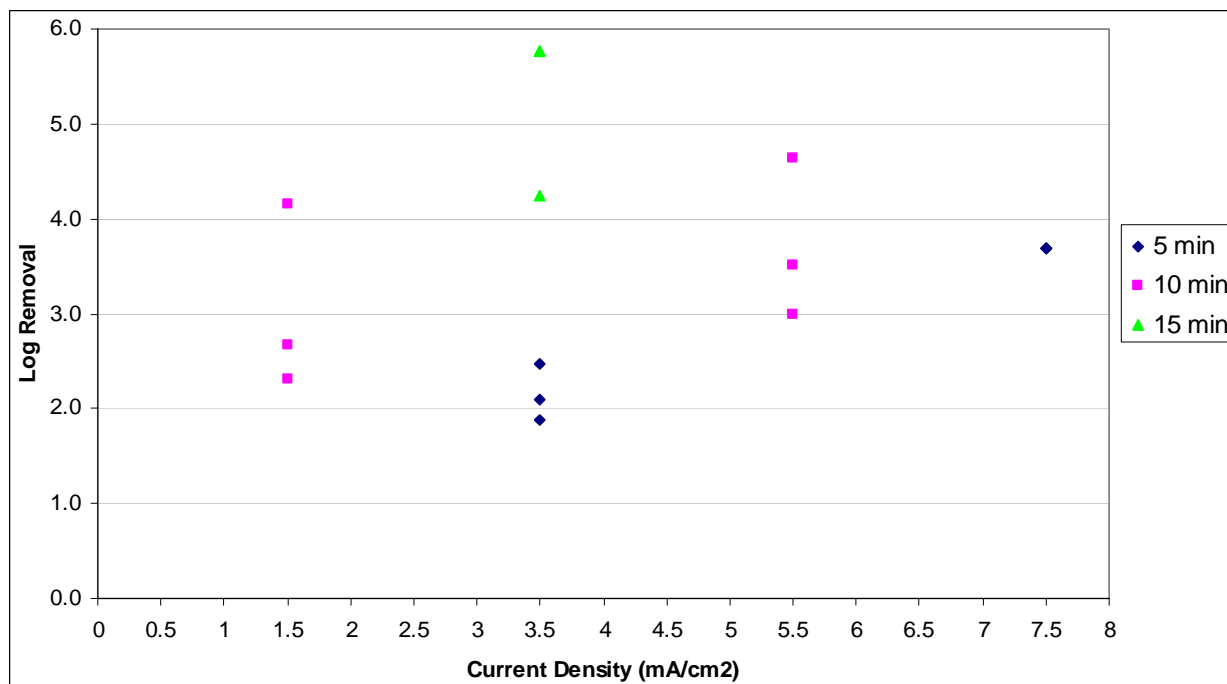
Figure 17. Log removal efficiencies as a function of current density and contact time
(stainless steel electrodes).

It can be observed that during the first run (7.5 mA/cm^2 current density, and 15 min
contact time) the reactor behaved differently from the rest of the experiments: more iron
leached into the water and a large amount of sludge was generated (see Table 22). Most
likely the passive film was formed during this first run. The rate of dissolution of the passive
film is less than that of the fully consumable metal by a factor of ten to a hundred (Ashworth
and Booker, 1986).

It is important to mention than in addition to iron, possibly other constituents of the
stainless steel are being dissolved in the water. Chromium (16.00-18.00%) and Nickel
(10.00-14.00%) are of special concern, because presence of these pollutants in the effluent
may have the potential to cause toxic conditions in the receiving stream. Effluent limitations

established in the LPDES indicate that the maximum amounts allowed for chromium and nickel are 10 μg/l and 40 μg/l respectively.

Table 22. Total Iron and TSS after electro-disinfection.

Run	Current Density (mA/cm^2)	Contact Time	Total Iron (mg/l) Before settling	Total Iron (mg/l) Super Natant	TSS (m/l) Before settling	TSS (m/l) Super Natant
1	7.5	15	1550.0	1.85	3376	
			950.0	0.78	2956	< 4
			1080.0	3.90	3212	
2	3.5	5	97.6	4.17	300	
			117.6	2.10	280	4
			52.6	1.76	168	
3	7.5	5	46.5	0.44	88	
			48.0	0.29	109	2
			42.0	0.30	131	
4	5.5	10	59.6	0.98	217	
			48.6	0.51	156	0
			84.1	0.44	302	
5	3.5	15	40.6	0.45	100	
			55.6	0.40	158	4
			73.7	0.30	230	
6	1.5	10	27.1	0.63	78	
			35.6	0.52	120	< 4
			29.6	0.74	122	

4.3 TITANIUM ELECTRODES

The choice of titanium was based on the fact that it exhibits an unusually high resistance to corrosion. This material is especially known for its outstanding resistance to chlorides and other halides generally present in most process streams. Its resistance is greater in the presence of oxidizing conditions, thus when Ti becomes anode (highly oxidizing conditions) there is no danger of corrosion and unwanted consumption of the material.

Moreover, it is not a harmful element to human health and it is not attacked by alkali hydroxides and acids which are produced to some extent during the electrolysis of natural water (Patermarakis and Fountoukidis, 1990).

Titanium falls in the category of partially passive metals and alloys and has been used successfully in previous electrochemical disinfection researches. When it is coated with lead dioxide (PbO_2), ruthenium oxide (RuO_2) and/or mixed iridium oxide (MIO) it is upgraded into the fully passive metals category or the so called Dimensionally Stable Anodes (DSA).

Ten experiments were performed with this reactor and good disinfection efficiencies were obtained considering that only current densities below 2.6 mA/cm^2 were employed. Table 23 presents the results obtained with this reactor. It can be observed that less or almost none sludge was produced. Fewer chlorine species were detected after experiments with the titanium cell and it was not possible to detect ozone in the treated water. Nonetheless, the applied voltage was very high, increasing power supply investment.

Similar to stainless steel, resistance to direct dissolution of the anode is achieved by the formation of an electrically conductive oxide film over the surface of the metal. The composition of this film varies from TiO_2 at the surface to Ti_2O_3 to TiO at the metal interface (Pjescic *et al.*, 2000). It is produced with the pass of current and oxidizing conditions promote the formation of TiO_2.

Table 23. Experimental results using titanium electrodes.

Run	Current Density (mA/cm²)	Contact Time (min)	% Coliform Removal	Coliform Log Removal	% COD Removal	Total Residual Chlorine (mg/l)	TSS (m/l) Before settling
1	2.59	5	50.66	0.31	43.92	0.10	28
2	1.99	5	40.79	0.23	50.68	0.18	16
3	2.45	5	42.76	0.24	42.57	0.28	16
4	1.00	15	63.21	0.43	23.42	0.06	36
5	0.84	15	77.86	0.65	47.51	0.08	30
6	0.78	15	90.36	1.02	40.09	0.22	24
7	1.41	15	98.80	1.92	31.80	0.14	46
8	1.10	15	92.17	1.11	45.57	0.16	64
9	1.06	25	98.47	1.82	50.82	0.14	78
10	1.05	25	100.00	2.21	70.49	0.16	108

The oxide film formed on titanium is more protective than that on stainless steel, and it often performs well in media that cause pitting and crevice corrosion in the latter -e.g., seawater, wet chlorine, organic chlorides- (Pjescic *et al.*, 2000). Since the thickness of the thin oxide film increased slowly with time, additional voltage increase was needed in order to establish a constant current density; consequently a larger quantity of energy was consumed.

It has been demonstrated that this TiO_2 film allows anodic electrochemical reactions to take place (Patermarakis and Fountoukidis, 1990). Following this assertion and the evidence of less chlorine being detected, it could be assumed that with this cell more reactive species such as H_2O_2, [O], ·OH, and ·HO_2 are being generated in comparison with the other reactors. Which electrochemical reactions are taking place depend on factors such as the half-cell potential, the concentrations of the ions present in the water, and the physical state of the electrolysis products (Liu *et al.*, 1997). The lower the half-cell potential of the reaction, the easier for the reaction to take place. It is also known that the amount of electrochemical products is proportional to the amount of electric charge available (Liu *et al.*, 1997).

4.4 STAINLESS STEEL CATHODE, TITANIUM ANODE

Four additional experimental conditions were tried with a cell consisting of a titanium anode and a stainless steel cathode. Both electrodes were previously tested, so the passive film was already starting to appear on both of them and consequently a smaller amount of solids leached into the water treated (see Table 25).

This time lower contact times were experimented and superior disinfection efficiencies were obtained as presented on Table 24. Practically, all coliform bacteria were killed leaving the water suitable for discharge. Figure 18 shows a picture of the 3M Petrifilm™ coliform count plates, before and after electrodisinfection taken on Run 3 (Contact Time: 2.5 min; Current Density: 3.5 mA/cm2; Energy Consumption: 1.6 kwh/m^3).

Table 24. Experimental results using titanium anode, stainless steel cathode.

Run	Current Density (mA/cm^2)	Contact Time (min)	% Coliform Removal	Coliform Log Removal	% COD Removal	Total Residual Chlorine (mg/l)	Residual Ozone (mg/l)
1	3.5	5	100	5.78	37.83	1.82	0.06
			100	5.78	37.83	0.72	0.05
			100	5.78	38.58	0.68	0.02
2	1.5	5	100	5.78	18.98	0.50	0.03
			100	5.78	34.31	0.57	0.09
			100	5.78	24.82	0.70	0.01
3	3.5	2.5	100	5.98	22.90	0.82	-
			100	5.98	33.59	0.62	0.00
			100	5.98	43.51	0.67	-
4	1.5	2.5	96.91	1.51	23.66	0.30	0.01
			96.66	1.48	26.72	0.39	0.00
			96.51	1.46	29.77	0.33	-

Figure 18. 3M Petrifilm™ coliform count plates before and after electro-disinfection.

Before Electro-Disinfection
Dilution 1000:1

After Electro-Disinfection
Dilution 10:1
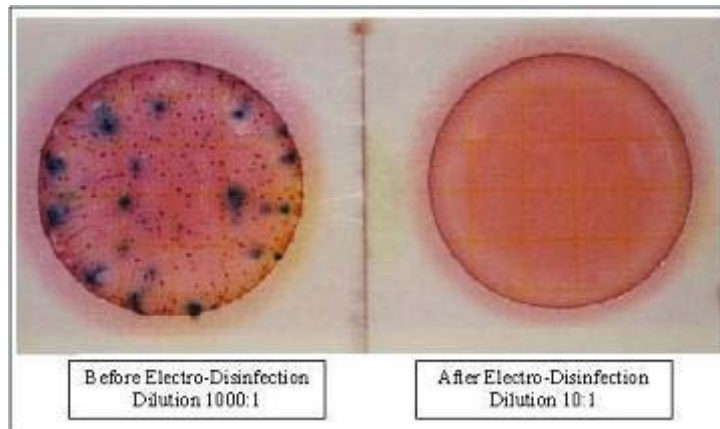
Analogous to the stainless steel reactor, this time higher amounts of residual chlorine were measured on the effluent samples and some ozone residual traces were detected. In fact, one of the paths that have evolved for generating ozone electrolytically uses a cell whose anodic section is made of titanium and the cathodic section of stainless steel at current densities between 0.5 and 2 A/cm^2 (Tatapudi and Fenton, 1994).

Table 25. Total Iron and TSS after electro-disinfection (SS/Ti electrodes).

Run	Current Density (mA/cm²)	Contact Time	Total Iron (mg/l) Before settling	Total Iron (mg/l) Super Natant	TSS (m/l) Before settling	TSS (m/l) Super Natant
1	3.5	5	29.04	1.25	21	0
			26.54	1.19	22	0
			44.06	1.54	30	0
2	1.5	5	11.52	2.58	16	0
			7.01	2.68	18	0
			8.51	2.37	16	0
3	3.5	2.5	4.66	4.15	13	0
			5.06	3.86	11	0
			4.81	3.76	13	0
4	1.5	2.5	2.20	1.86	8	0
			2.60	1.73	8	0
			1.90	1.62	5	0

4.5 COMPARISON OF ELECTRODE MATERIALS

Based on earlier findings, as presented on *Section 2.2*, the electrode material strongly affects the production of reactive species such as Cl_2, OCl^-, H_2O_2, ozone, $\cdot OH$, and $\cdot HO_2$, affecting consequently the disinfection efficiency of the process (Chiang *et al.*, 1995). In agreement with this statement, Figures 19 and 20 illustrate coliform removals efficiencies and log removal efficiencies as a function of energy consumption rate and the electrode materials tested on this investigation.
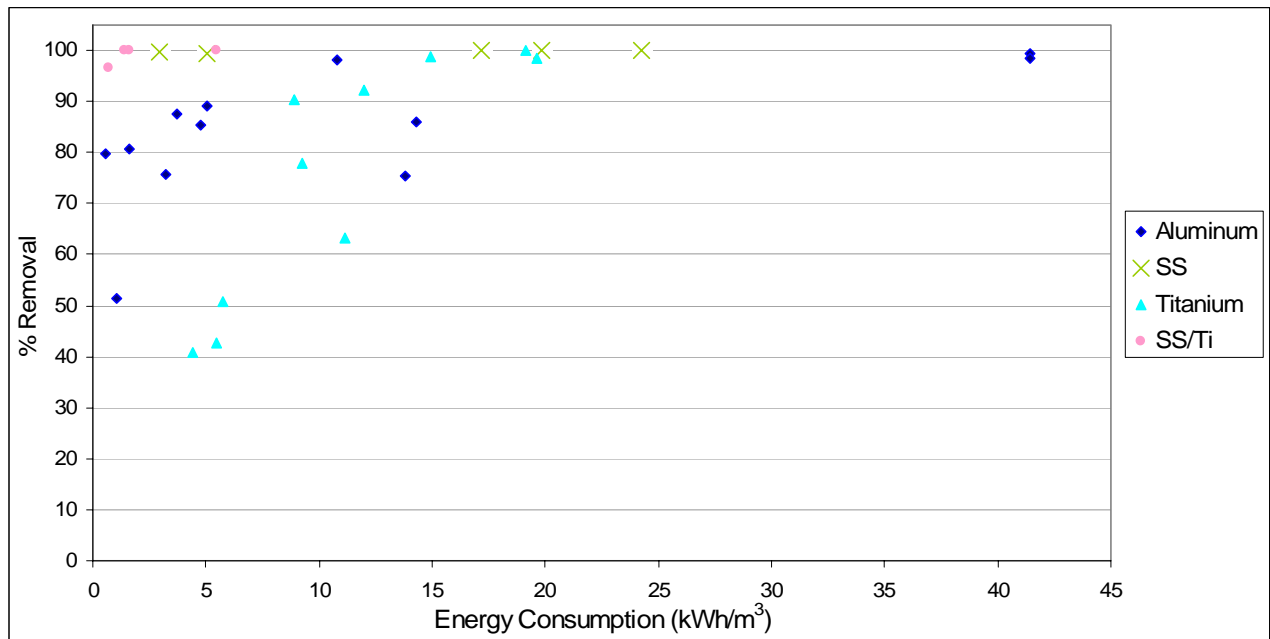
Figure 19. Coliform removal efficiencies as a function of energy consumption rate and electrode material

As it was expected, there is a remarkable difference in energy efficiency between the metals tested. It can be observed that the stainless steel reactor as well as the titanium/steel cell gave much better removal efficiencies than the other two reactors, at least for the range of current densities and contact time experimented on this research.
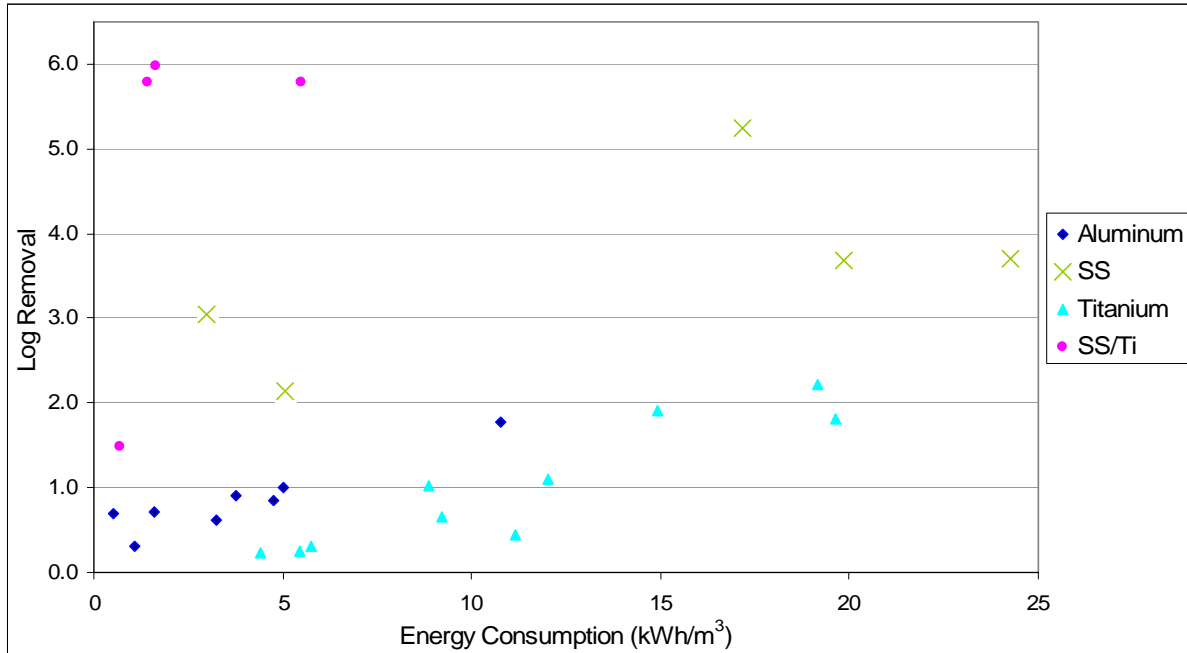
Figure 20. Log removal efficiencies as a function of energy consumption rate and electrode material.

Total chlorine residual was measured in the effluent samples on all the experiments performed and also ozone analyses were carried out after the tests with stainless steel, titanium and the stainless/titanium reactors. Even when ozone was detected only in a few tests, the results obtained demonstrate that indeed these disinfecting species with residual capacity were produced during the process. It is important to mention that the local concentration of active disinfective species when the current is on can exceed the average concentration found in the fluid emerging from the cell by one or two orders of magnitude (Stoner, 1982). Figure 21 compares total residual chlorine production for all the reactors tested. However, it was not possible to ascertain whether chlorine or ozone are the major causes of bacterial killing.

From the technological point of view this residual disinfection capacity is an attractive result since application of the method for a continuous water flow could ensure that only part

of the flowing water should require contact with the electrodes and then be mixed with the remaining flowing volume of water. However, further investigations are needed to find out if halogenated hydrocarbons are produce in the process.
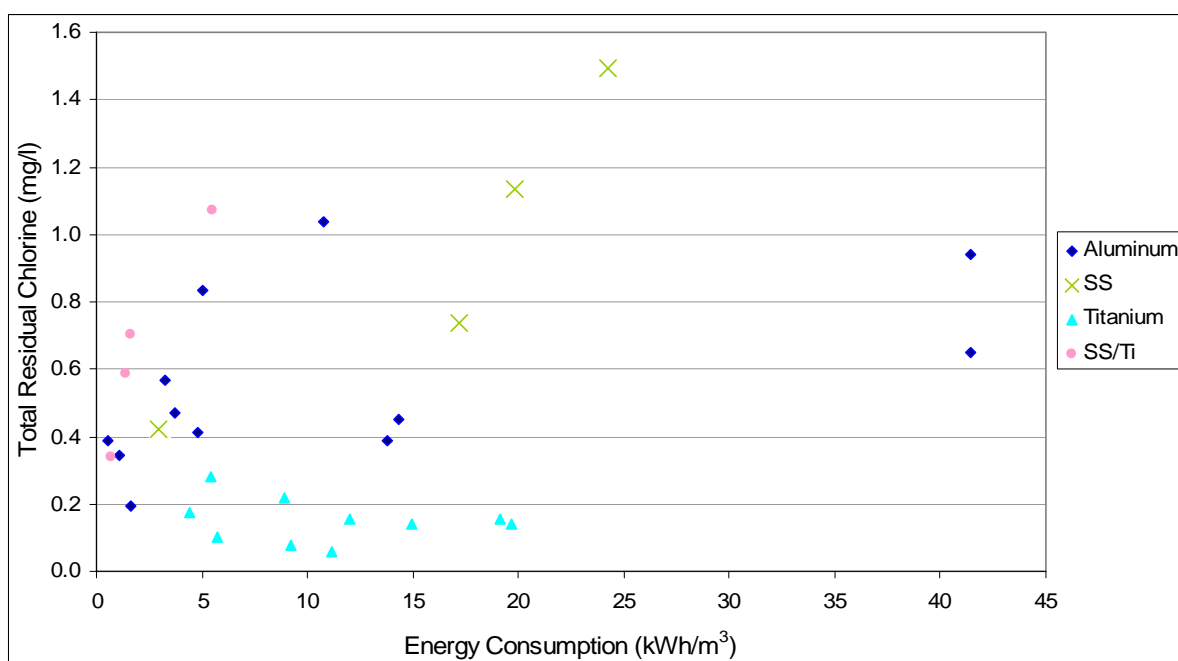
Figure 21. Total residual chlorine in the effluent samples as a function of energy consumption rate and electrode material.

It is possible that other oxidant species were produced by the electrochemical reactions presented on S*ection 2.2.* Since hydroxyl radicals, atomic oxygen, hydrogen peroxide and perhydroxyl radicals are very unstable and short-lived it was not feasible to monitor them. Nonetheless, it is likely that all of them were present in the water while the current was on. In addition to kill the bacteria, it is known that these powerful oxidizing agents are capable of degrading organic pollutants, so the process shows promise as a technique to reduce DBPs.

Hydroxyl radicals (·OH) are much more reactive than chlorine and various researchers have reported that these active radicals are involved in the principal mechanism that cause the death of microorganisms by electrochemical treatment (Mills, 2000; Feng *et al*., 2004; Patermarakis and Fountoukidis, 1990; among others). The mechanism of formation of hydroxyl radicals at an oxide anode (MO_x) was described by Feng *et al.* (2005). Water is electrolyzed by anodic catalysis to produce adsorbed hydroxyl radicals, as given in the following equation:

$$H_2O + MO_x \rightarrow MO_x[·OH] + H^+ + e^-$$

Regardless of the selected material, unfortunately, electrochemical reactions normally occur in a rather unselective manner and most of the energy from the power source is spent on side reactions and heat generation (Rajeshwar & Ibanez, 1997). The rate of an electrochemical reaction can be either activation-controlled or mass transport-controlled (Rudd E.J., 1995). Therefore, it is evident that to enhance the rate of these reactions it is important to: (1) provide electrodes with high surface area, and (2) promote turbulent conditions in the electrolyte through agitation, movement of the electrode itself, or turbulence promoters in the cell.

The ideal electrode material would be one totally stable that allows the generation of oxidants efficiently at a low overpotential. The region of potential in which the selected reaction occurs is important since its relationship to the electroxidation of the wastewater will determine the overall current efficiency of the process. The evolution of oxygen (at the anode) and hydrogen (at the cathode) are competing reactions and simultaneously produce protons (O_2

evolution) and hydroxyl ions (H_2 evolution). These reactions may be inhibited by the particular electrode material and/or by additives to the electrolyte.

The potential of the system would be the sum of the potential applied by the external power supply, plus the overpotential required for the reactions, plus the heat loss from resistances ($E = IR$), plus the sum of all the half cell reactions in the predominant direction of the overall reactions. Since this is not an ideal cell, and the activity, concentration and purity of each compound that is present is not known, it is essentially impossible to balance the equations and know the actual potential voltage of the system and current use efficiency.

As can be observed on Figure 22, sludge generation was a major problem only with the aluminum electrodes reactor. The other three materials tested did not corrode as much as aluminum and offered much better coliform removal efficiencies. Final effluent characteristics after electro-disinfection and settling (except for residual chlorine values, which were taken before clarification) are presented on Table 26 for the best experience obtained with each cell; the best run corresponds to the experiment with the highest log coliform removal.

In general, in all the experiments COD, TDS and conductivity of the water decreased (these values are presented on the appendix tables). This decrease was due to the electric field neutralizing the surface charges of the colloid particles contained in the water, resulting in their agglomeration and sedimentation (Drogui *et al*., 2001). Removal of turbidity and TDS is beneficial for the process; it may enhance the disinfection of microorganisms because disinfection is hampered by high turbidity (Drogui *et al*., 2001).
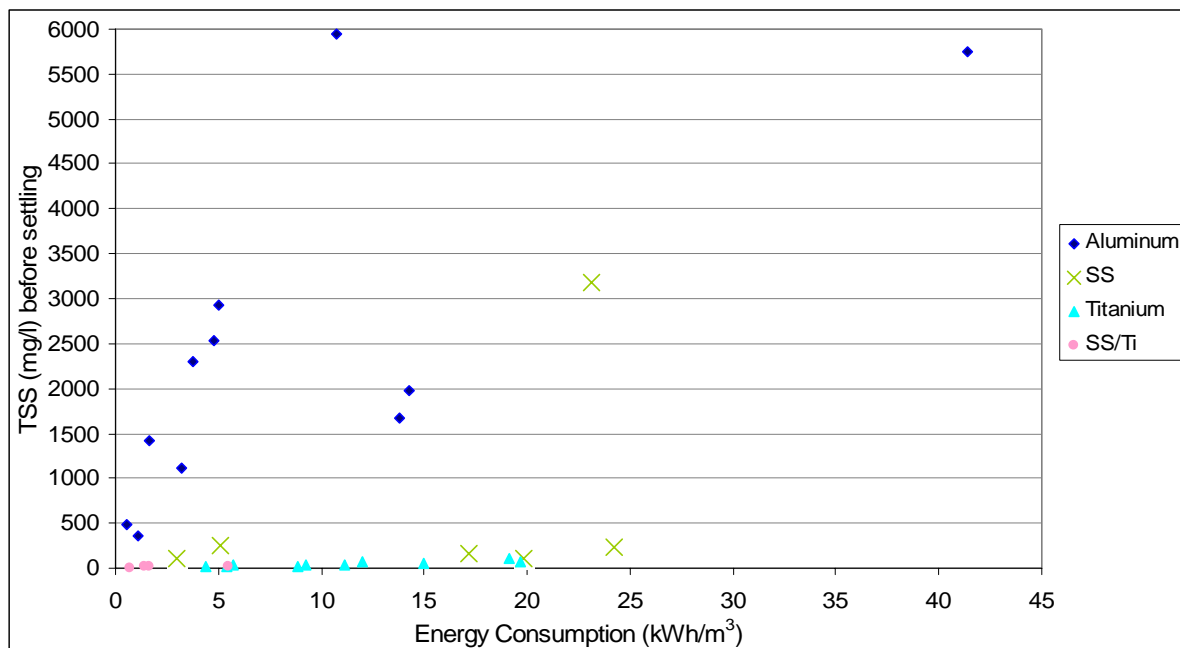
Figure 22. TSS in the effluent samples (before settling) as a function of energy consumption rate and electrode material.

Table 26. Final effluent characteristics, after electro-disinfection and settling

Material/Run	Current Density (mA/cm^2)	Contact Time (min)	Energy Consumption (kWh/m^3)	pH	COD (mg/l)	TSS (mg/l)	Coliforms (MPN/100ml)	TRC (m/l) Before Settling
Aluminum Run 12	5.5	15	41.42	8.99	13.2	< 4	60,000	0.65
Stainless Steel Run 5	3.5	15	17.18	7.44	15.17	4	111	0.74
Titanium Run 10	1.06	25	19.41	8.50	30.2	8	50,000	0.15
SS/Ti Run 3	3.5	2.5	1.64	7.22	43.67	0	0	0.70

This research is a preliminary study on the subject of electro-disinfection for wastewater effluents with very small volumes so the implications for water treatment are not conclusive. Nonetheless, the results are highly positive and demonstrate the need to examine this process more closely.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be derived from the research presented in this dissertation:

1. The electrochemical process is highly effective for the disinfection of wastewater effluents after secondary treatment, especially when stainless steel or titanium oxide electrodes are employed.

2. It was demonstrated that the electrode material strongly affects the production of oxidant species such as Cl_2, OCl^-, H_2O_2, ozone, $\cdot OH$, and $\cdot HO_2$, affecting consequently the disinfection efficiency of the process

3. A bactericidal efficiency of 98.7 % or higher were achieved within a contact time of less than 15 min and a current density lower than 7.5 mA/cm^2 when stainless steel electrodes were used, and a contact time of less than 5 min and a current density lower than 3.5 mA/cm^2 when the stainless steel/titanium cell was utilized.

4. The bactericidal efficiency of the process generally increased with the current density and contact time, and the impact of these factors was much larger than that of salinity.

5. Due to the fact that less chlorine was detected when titanium electrodes were utilized, electrochlorination does not seem to be the predominant disinfective means of the process. Production of other short lived and more powerful killing substances such as H_2O_2, [O], $\cdot OH$, and $\cdot HO_2$ takes place and provide the strong disinfecting

action of the system within a short contact time (100% coliform removal was obtained with 2.5 min of contact time).

6. After electro-disinfection the effluent pH rises on average 1.5 units, conductivity, TDS and COD were found to decrease, and the average ORP becomes more negative because the electric current introduces loads of electrons into the water and creates a strong reducing environment.

7. This preliminary study on electro-disinfection revealed that this process could be a feasible alternative to chlorination for wastewater effluents. It is an effective process, cheaper and more environmentally friendly than conventional disinfection techniques.

Based on the experience of this research project, and the results obtained, the following items are suggested for further investigation:

1. The disinfective mechanism of action of this electrochemical process is complex and additional investigation is needed for its elucidation.

2. There are several important aspects of this process which need to be studied further before its application in large scale wastewater treatment plants. The process need to be improved from the technological and economical point of view.

3. Since chlorine/hypochlorite species are produced during the process, chlorinated organic compounds may be generated as by-products. More investigations should be conducted to elucidate if active oxygen compounds truly prevent its formation.

4. It is necessary to investigate if toxic species leach into the water when consumable electrodes, such as stainless steel, are employed.

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APPENDIX

Table A1. Results Experiment # 1 - Aluminum Electrodes Reactor

EXPERIMENT # 1
Date: Jan 24, 2005

OPERATION PARAMETERS:

Contact Time, minutes	5		**Power Consumption**	
Sample Volume, mL	850		Volts :	14
Current Density (mA/cm^2)	5.5		Amps :	10.06
Cl$^-$ Concentration (mg/L)	130		kWh/m^3 :	13.8

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	1012	667	6.97	-10.2	16.7	8.33	0.20
Influent End	966	638	6.92	-8.7	17.7	8.35	0.20
Influent Avg	**989**	**653**	**6.95**	**-9.5**	**17.2**	**8.34**	**0.20**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	811	524	8.50	-99.0	26.7	5.29	0.10
Effluent B	801	528	8.66	-106.5	26.0	5.56	0.09
Effluent C	741	483	8.53	-101.0	26.5	4.47	0.10
Effluent Avg	**784**	**512**	**8.56**	**-102.2**	**26.4**	**5.11**	**0.10**

LAB ANALYSES   Coliform dilution =   Feed 500   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start									
Influent 1	0.05	142.4	69.5	0.15	-	8.0	36	1.80E+04	1.80E+06
Influent 2	0.04	141.4	66.5	0.14	-	-	46	2.30E+04	2.30E+06
Influent 3	0.05	143.4	64.5	0.13	-	-	42	2.10E+04	2.10E+06
Influent End									
Influent 1	0.05	136.3	57.4	0.03	-	-	-	-	-
Influent 2	0.03	133.3	58.4	0.02	-	-	-	-	-
Influent 3	0.04	134.3	55.4	0.02	-	-	-	-	-
Influent Avg	**0.04**	**138.5**	**62.0**	**0.08**	**-**	**8.0**	**41.3**	**2.07E+04**	**2.07E+06**
Effluent A									
Effluent A1	0.36	177.4	46.3	611.5	-	1613	11	5.50E+03	5.50E+05
Effluent A2	0.48	174.4	54.4	621.6	-	-	10	5.00E+03	5.00E+05
Effluent A3	0.34	176.4	48.4	611.5	-	-	14	7.00E+03	7.00E+05
Effluent A Avg	**0.39**	**176.1**	**49.7**	**614.9**	**-**	**1613**	**12**	**5.83E+03**	**5.83E+05**
Effluent B									
Effluent B1	0.38	180.5	55.4	852.1	-	1645	6	3.00E+03	3.00E+05
Effluent B2	0.46	178.4	54.4	711.8	-	-	11	5.50E+03	5.50E+05
Effluent B3	0.40	185.5	50.4	782.0	-	-	11	5.50E+03	5.50E+05
Effluent B Avg	**0.41**	**181.5**	**53.4**	**782.0**	**-**	**1645**	**9**	**4.67E+03**	**4.67E+05**
Effluent C									
Effluent C1	0.40	191.5	69.5	651.6	-	1769	9	4.50E+03	4.50E+05
Effluent C2	0.33	181.5	71.5	621.6	-	-	10	5.00E+03	5.00E+05
Effluent C3	0.34	190.5	75.6	641.6	-	-	9	4.50E+03	4.50E+05
Effluent C Avg	**0.36**	**187.8**	**72.2**	**638.3**	**-**	**1769**	**9**	**4.67E+03**	**4.67E+05**
Effluent Avg	**0.39**	**181.8**	**58.4**	**678.4**	**-**	**1676**	**10**	**5.06E+03**	**5.06E+05**

Table A2. Results Experiment # 2 - Aluminum Electrodes Reactor

EXPERIMENT # 2
Date: Jan 26, 2005

OPERATION PARAMETERS:

Contact Time, minutes	15		**Power Consumption**	
Sample Volume, mL	850		Volts :	14
Current Density (mA/cm^2)	5.5		Amps :	10.06
Cl$^-$ Concentration (mg/L)	120		kWh/m^3 :	41.4

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	970	642	6.89	-9.6	20.2	7.69	0.19
Influent End	970	639	6.97	-14.1	20.1	7.06	0.19
Influent Avg	**970**	**641**	**6.93**	**-11.85**	**20.2**	**7.38**	**0.19**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	657	429	8.85	-126.8	41.5	1.52	0.06
Effluent B	706	452	8.66	-114.0	47.0	1.52	0.06
Effluent C	677	432	8.83	-123.5	43.0	1.02	0.06
Effluent Avg	**680**	**438**	**8.78**	**-121.4**	**43.8**	**1.35**	**0.06**

LAB ANALYSES   Coliform dilution =   Feed 500   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start									
Influent 1	0.03	122.3	42.3	0.00	-	4.0	34	1.70E+04	1.70E+06
Influent 2	0.03	136.3	48.4	0.00	-	-	35	1.75E+04	1.75E+06
Influent 3	0.02	135.3	43.3	0.00	-	-	32	1.60E+04	1.60E+06
Influent End									
Influent 1	0.03	143.4	50.4	0.12	-	-	-	-	-
Influent 2	0.02	144.4	49.4	0.11	-	-	-	-	-
Influent 3	0.02	139.3	44.3	0.10	-	-	-	-	-
Influent Avg	**0.03**	**136.8**	**46.3**	**0.06**	**-**	**4.0**	**34**	**1.68E+04**	**1.68E+06**
Effluent A									
Effluent A1	1.00	166.4	26.2	1167.3	-	5881	0	0.00E+00	0.00E+00
Effluent A2	1.22	158.4	34.3	1207.5	-	-	0	0.00E+00	0.00E+00
Effluent A3	1.04	163.4	27.2	1288.0	-	-	0	0.00E+00	0.00E+00
Effluent A Avg	**1.09**	**162.7**	**29.2**	**1220.9**	**-**	**5881**	**0**	**0.00E+00**	**0.00E+00**
Effluent B									
Effluent B1	0.66	196.5	11.1	1046.5	-	6750	0	0.00E+00	0.00E+00
Effluent B2	0.56	201.5	10.1	1066.6	-	-	0	0.00E+00	0.00E+00
Effluent B3	0.66	190.5	6.0	1006.3	-	-	0	0.00E+00	0.00E+00
Effluent B Avg	**0.63**	**196.2**	**9.1**	**1039.8**	**-**	**6750**	**0**	**0.00E+00**	**0.00E+00**
Effluent C									
Effluent C1	1.20	182.5	13.1	1207.5	-	6999	0	0.00E+00	0.00E+00
Effluent C2	0.96	171.4	19.1	1187.4	-	-	2	1.00E+03	1.00E+05
Effluent C3	1.16	172.4	14.1	1127.0	-	-	0	0.00E+00	0.00E+00
Effluent C Avg	**1.11**	**175.4**	**15.4**	**1174.0**	**-**	**6999.0**	**1**	**3.33E+02**	**3.33E+04**
Effluent Avg	**0.94**	**178.1**	**17.9**	**1144.9**	**-**	**6543.3**	**0**	**1.11E+02**	**1.11E+04**

Table A3. Results Experiment # 3 - Aluminum Electrodes Reactor

EXPERIMENT # 3
Date: Jan 31, 2005   Note: Addition of NaCl

OPERATION PARAMETERS:

Contact Time, minutes	10		**Power Consumption**	
Sample Volume, mL	850		Volts :	4
Current Density (mA/cm^2)	3.5		Amps :	6.4
Cl$^-$ Concentration (mg/L)	600		kWh/m^3 :	5.0

	Conductivity (mS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	2	1620	7.40	-39.2	18.8	7.64	0.17
Influent End	2	1604	7.48	-43.4	19.6	7.50	0.16
Influent Avg	**2**	**1612**	**7.44**	**-41.30**	**19.2**	**7.57**	**0.16**

	Conductivity (mS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	2	1434	8.91	-124.5	24.1	2.75	0.08
Effluent B	2	1421	9.01	-130.4	24.3	1.59	0.07
Effluent C	2	1417	9.07	-134.2	25.0	2.43	0.06
Effluent Avg	**2**	**1424**	**9.00**	**-129.7**	**24.5**	**2.26**	**0.07**

LAB ANALYSES   Coliform dilution =   Feed [500]   Effluent [500]

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.04	561.4	61.0	0.02	-	21.0	105	5.25E+04	5.25E+06
Influent 2	0.04	626.6	62.0	-	-	-	111	5.55E+04	5.55E+06
Influent 3	0.08	601.5	57.0	-	-	-	101	5.05E+04	5.05E+06
Influent End									
Influent 1	0.04	571.4	58.0	0.02	-	-	-	-	-
Influent 2	0.04	586.5	63.0	-	-	-	-	-	-
Influent 3	0.08	551.4	56.0	-	-	-	-	-	-
Influent Avg	**0.05**	**583.1**	**59.5**	**0.02**	**-**	**21.0**	**106**	**5.28E+04**	**5.28E+06**
Effluent A									
Effluent A1	1.00	516.3	26.0	1122.8	1.9	2820	6	3.00E+03	3.00E+05
Effluent A2	0.90	496.2	22.0	-	-	-	6	3.00E+03	3.00E+05
Effluent A3	1.06	-	26.0	-	-	-	5	2.50E+03	2.50E+05
Effluent A Avg	**0.99**	**506.3**	**24.7**	**1122.8**	**1.9**	**2820**	**6**	**2.83E+03**	**2.83E+05**
Effluent B									
Effluent B1	1.08	591.5	27.0	1162.9	2.0	2876	16	8.00E+03	8.00E+05
Effluent B2	0.78	596.5	25.0	-	-	-	19	9.50E+03	9.50E+05
Effluent B3	0.84	-	30.0	-	-	-	19	9.50E+03	9.50E+05
Effluent B Avg	**0.90**	**594.0**	**27.3**	**1162.9**	**2.0**	**2876**	**18**	**9.00E+03**	**9.00E+05**
Effluent C									
Effluent C1	0.70	466.2	26.0	782.0	0.4	3061	8	4.00E+03	4.00E+05
Effluent C2	0.58	496.2	17.0	782.0	-	-	14	7.00E+03	7.00E+05
Effluent C3	0.56	-	13.0	-	-	-	10	5.00E+03	5.00E+05
Effluent C Avg	**0.61**	**481.2**	**18.7**	**782.0**	**0.4**	**3061.0**	**11**	**5.33E+03**	**5.33E+05**
Effluent Avg	**0.84**	**527.1**	**23.6**	**1022.6**	**1.4**	**2919.0**	**11**	**5.72E+03**	**5.72E+05**

Table A4. Results Experiment # 4 - Aluminum Electrodes Reactor

EXPERIMENT # 4
Date: Feb 11, 2005

OPERATION PARAMETERS:

Contact Time, minutes	5		**Power Consumption**	
Sample Volume, mL	850		Volts :	4
Current Density (mA/cm^2)	1.5		Amps :	2.74
Cl$^-$ Concentration (mg/L)	140		kWh/m^3 :	1.1

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	1050	690	7.07	-22.6	18.1	7.29	0.18
Influent End	1040	686	7.00	-19.1	18.2	7.24	0.19
Influent Avg	**1045**	**688**	**7.04**	**-20.85**	**18.2**	**7.27**	**0.19**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	952	627	7.61	-52.9	20.5	6.52	0.15
Effluent B	954	629	7.46	-44.4	19.9	7.11	0.16
Effluent C	950	627	7.64	-54.8	20.2	4.43	0.15
Effluent Avg	**952**	**628**	**7.57**	**-50.7**	**20.2**	**6.02**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed: 1000   Effluent: 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.03	139.0	94.0	0.01	-	26.0	52	5.20E+04	5.20E+06
Influent 2	0.02	136.0	89.0	-	-	-	53	5.30E+04	5.30E+06
Influent 3	-	143.0	-	-	-	-	54	5.40E+04	5.40E+06
Influent End									
Influent 1	0.03	137.0	81.0	0.02	-	-	-	-	-
Influent 2	0.03	140.0	88.0	-	-	-	-	-	-
Influent 3	-	147.0	-	-	-	-	-	-	-
Influent Avg	**0.03**	**140.3**	**88.0**	**0.02**	**-**	**26.0**	**53.0**	**5.30E+04**	**5.30E+06**
Effluent A									
Effluent A1	0.22	139.0	33.0	170.5	4.0	338	46	2.30E+04	2.30E+06
Effluent A2	0.24	135.0	21.0	-	-	-	51	2.55E+04	2.55E+06
Effluent A3	-	142.0	-	-	-	-	52	2.60E+04	2.60E+06
Effluent A Avg	**0.23**	**138.7**	**27.0**	**170.5**	**4.0**	**338**	**50**	**2.48E+04**	**2.48E+06**
Effluent B									
Effluent B1	0.40	145.0	32.0	160.5	5.7	376	49	2.45E+04	2.45E+06
Effluent B2	0.38	147.0	35.0	-	-	-	60	3.00E+04	3.00E+06
Effluent B3	-	160.0	-	-	-	-	70	3.50E+04	3.50E+06
Effluent B Avg	**0.39**	**150.7**	**33.5**	**160.5**	**5.7**	**376**	**60**	**2.98E+04**	**2.98E+06**
Effluent C									
Effluent C1	0.44	135.0	34.0	170.5	4.8	374	41	2.05E+04	2.05E+06
Effluent C2	0.38	135.0	17.0	-	-	-	44	2.20E+04	2.20E+06
Effluent C3	-	134.0	-	-	-	-	51	2.55E+04	2.55E+06
Effluent C Avg	**0.41**	**134.7**	**25.5**	**170.5**	**4.8**	**374.0**	**45**	**2.27E+04**	**2.27E+06**
Effluent Avg	**0.34**	**141.3**	**28.7**	**167.2**	**4.9**	**362.7**	**52**	**2.58E+04**	**2.58E+06**

Table A5. Results Experiment # 5 - Aluminum Electrodes Reactor

EXPERIMENT # 5
Date: Feb 16, 2005

OPERATION PARAMETERS:

			Power Consumption	
Contact Time, minutes	15		Volts :	5
Sample Volume, mL	850		Amps :	2.74
Current Density (mA/cm^2)	1.5		kWh/m^3 :	3.6
Cl$^-$ Concentration (mg/L)	128.8			

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	988	652	6.99	-18.5	21.3	6.52	0.18
Influent End	982	648	7.05	-22.0	21.0	6.51	0.18
Influent Avg	**985**	**650**	**7.02**	**-20.25**	**21.2**	**6.52**	**0.18**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	786	518	8.10	-82.0	24.2	5.64	0.12
Effluent B	752	495	8.46	-102.5	24.3	6.17	0.10
Effluent C	756	497	8.51	-105.2	24.5	4.94	0.09
Effluent Avg	**765**	**503**	**8.36**	**-96.6**	**24.3**	**5.58**	**0.10**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 250

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.02	132.1	90.0	0.00	-	18.0	66	6.60E+04	6.60E+06
Influent 2	0.04	108.1	93.0	-	-	-	64	6.40E+04	6.40E+06
Influent 3	-	-	-	-	-	-	66	6.60E+04	6.60E+06
Influent End									
Influent 1	0.03	115.1	116.0	0.02	-	-	-	-	-
Influent 2	0.04	160.1	120.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.03**	**128.8**	**104.8**	**0.01**	**-**	**18.0**	**65**	**6.53E+04**	**6.53E+06**
Effluent A									
Effluent A1	0.52	146.1	25.0	371.9	4.5	1093	64	1.60E+04	1.60E+06
Effluent A2	0.50	156.1	29.0	-	-	-	74	1.85E+04	1.85E+06
Effluent A3	-	143.1	-	-	-	-	84	2.10E+04	2.10E+06
Effluent A Avg	**0.51**	**148.4**	**27.0**	**371.9**	**4.5**	**1093**	**74**	**1.85E+04**	**1.85E+06**
Effluent B									
Effluent B1	0.44	130.1	26.0	472.4	5.7	1067	45	1.13E+04	1.13E+06
Effluent B2	0.52	131.1	29.0	-	-	-	64	1.60E+04	1.60E+06
Effluent B3	-	123.1	-	-	-	-	56	1.40E+04	1.40E+06
Effluent B Avg	**0.48**	**128.1**	**27.5**	**472.4**	**5.7**	**1067**	**55**	**1.38E+04**	**1.38E+06**
Effluent C									
Effluent C1	0.76	124.1	12.0	381.9	7.9	1171	56	1.40E+04	1.40E+06
Effluent C2	0.66	119.1	14.0	-	-	-	63	1.58E+04	1.58E+06
Effluent C3	-	118.1	-	-	-	-	63	1.58E+04	1.58E+06
Effluent C Avg	**0.71**	**120.4**	**13.0**	**381.9**	**7.9**	**1171.0**	**61**	**1.52E+04**	**1.52E+06**
Effluent Avg	**0.57**	**132.3**	**22.5**	**408.7**	**6.1**	**1110.3**	**63**	**1.58E+04**	**1.58E+06**

Table A6. Results Experiment # 6 - Aluminum Electrodes Reactor

EXPERIMENT # 6
Date: Feb 21, 2005

OPERATION PARAMETERS:

Contact Time, minutes	5		**Power Consumption**	
Sample Volume, mL	850		Volts :	4
Current Density (mA/cm^2)	5.5		Amps :	10.06
Cl$^-$ Concentration (mg/L)	870.00		kWh/m^3 :	3.7

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	3890	2570	7.11	-25.3	22.0	6.07	0.18
Influent End	3860	2550	7.43	-43.3	22.1	6.34	0.16
Influent Avg	**3875**	**2560**	**7.27**	**-34.30**	**22.1**	**6.21**	**0.17**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	3650	2400	8.71	-116.7	25.9	3.36	0.08
Effluent B	3620	2380	8.75	-120.3	26.7	1.80	0.08
Effluent C	3610	2370	8.78	-121.3	26.5	3.06	0.08
Effluent Avg	**3627**	**2383**	**8.75**	**-119.4**	**26.4**	**2.74**	**0.08**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.05	850.0	55.0	0.00	-	9.0	72	7.20E+04	7.20E+06
Influent 2	0.04	890.0	60.0	-	-	-	71	7.10E+04	7.10E+06
Influent 3	-	900.0	-	-	-	-	71	7.10E+04	7.10E+06
Influent End									
Influent 1	0.05	860.0	58.0	0.00	-	-	-	-	-
Influent 2	0.04	850.0	60.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.05**	**870.0**	**58.3**	**0.00**	**-**	**9.0**	**71**	**7.13E+04**	**7.13E+06**
Effluent A									
Effluent A1	0.44	710.0	20.0	804.0	17.1	2187	21	1.05E+04	1.05E+06
Effluent A2	0.44	730.0	21.0	-	-	-	10	5.00E+03	5.00E+05
Effluent A3	-	-	-	-	-	-	18	9.00E+03	9.00E+05
Effluent A Avg	**0.44**	**720.0**	**20.5**	**804.0**	**17.1**	**2187**	**16**	**8.17E+03**	**8.17E+05**
Effluent B									
Effluent B1	0.42	700.0	16.0	783.9	15.1	2319	14	7.00E+03	7.00E+05
Effluent B2	0.46	680.0	22.0	-	-	-	15	7.50E+03	7.50E+05
Effluent B3	-	-	-	-	-	-	20	1.00E+04	1.00E+06
Effluent B Avg	**0.44**	**690.0**	**19.0**	**783.9**	**15.1**	**2319**	**16**	**8.17E+03**	**8.17E+05**
Effluent C									
Effluent C1	0.54	720.0	25.0	814.1	15.1	2354	19	9.50E+03	9.50E+05
Effluent C2	0.52	780.0	28.0	-	-	-	21	1.05E+04	1.05E+06
Effluent C3	-	-	-	-	-	-	23	1.15E+04	1.15E+06
Effluent C Avg	**0.53**	**750.0**	**26.5**	**814.1**	**15.1**	**2354.0**	**21**	**1.05E+04**	**1.05E+06**
Effluent Avg	**0.47**	**720.0**	**22.0**	**800.7**	**15.8**	**2286.7**	**18**	**8.94E+03**	**8.94E+05**

Table A7. Results Experiment # 7 - Aluminum Electrodes Reactor

EXPERIMENT # 7
Date: March 1, 2005

OPERATION PARAMETERS:

			Power Consumption	
Contact Time, minutes	5			
Sample Volume, mL	850		Volts :	2
Current Density (mA/cm^2)	1.5		Amps :	2.74
Cl$^-$ Concentration (mg/L)	1005		kWh/m^3 :	0.54

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	3930	2570	7.19	-23.4	19.2	7.64	0.18
Influent End	3830	2520	7.63	-47.9	19.6	6.80	0.16
Influent Avg	**3880**	**2545**	**7.41**	**-35.65**	**19.4**	**7.22**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	3790	2480	8.02	-72.4	21.2	6.43	0.13
Effluent B	3760	2470	8.25	-85.7	21.0	6.43	0.12
Effluent C	3770	2480	8.27	-87.3	21.1	6.74	0.12
Effluent Avg	**3773**	**2477**	**8.18**	**-81.8**	**21.1**	**6.53**	**0.12**

LAB ANALYSES   Coliform dilution = Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.04	1020	71.0	0.02	-	14.0	47	4.70E+04	4.70E+06
Influent 2	0.07	1010	75.0	-	-	-	49	4.90E+04	4.90E+06
Influent 3	-	-	-	-	-	-	46	4.60E+04	4.60E+06
Influent End									
Influent 1	0.06	1000	71.0	0.02	-	-	-	-	-
Influent 2	0.04	990	73.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.05**	**1005.0**	**72.5**	**0.02**	**-**	**14.0**	**47**	**4.73E+04**	**4.73E+06**
Effluent A									
Effluent A1	0.32	1070	30.0	190.5	3.2	444	12	6.00E+03	6.00E+05
Effluent A2	0.32	1060	32.0	-	-	440	27	1.35E+04	1.35E+06
Effluent A3	-	-	-	-	-	-	17	8.50E+03	8.50E+05
Effluent A Avg	**0.32**	**1065**	**31.0**	**190.5**	**3.2**	**442**	**19**	**9.33E+03**	**9.33E+05**
Effluent B									
Effluent B1	0.32	1060	26.0	190.5	4.2	496	20	1.00E+04	1.00E+06
Effluent B2	0.30	1040	30.0	-	-	496	22	1.10E+04	1.10E+06
Effluent B3	-	-	-	-	-	-	24	1.20E+04	1.20E+06
Effluent B Avg	**0.31**	**1050**	**28.0**	**190.5**	**4.2**	**496**	**22**	**1.10E+04**	**1.10E+06**
Effluent C									
Effluent C1	0.54	1050	28.0	200.5	4.7	512	16	8.00E+03	8.00E+05
Effluent C2	0.54	1020	31.0	-	-	516	16	8.00E+03	8.00E+05
Effluent C3	-	-	-	-	-	-	19	9.50E+03	9.50E+05
Effluent C Avg	**0.54**	**1035**	**29.5**	**200.5**	**4.7**	**514.0**	**17**	**8.50E+03**	**8.50E+05**
Effluent Avg	**0.39**	**1050**	**29.5**	**193.8**	**4.0**	**484.0**	**19**	**9.61E+03**	**9.61E+05**

Table A8. Results Experiment # 8 - Aluminum Electrodes Reactor

EXPERIMENT # 8
Date: March 2, 2005

OPERATION PARAMETERS:

Contact Time, minutes	15		**Power Consumption**	
Sample Volume, mL	850		Volts :	2
Current Density (mA/cm^2)	1.5		Amps :	2.74
Cl$^-$ Concentration (mg/L)	1025.00		kWh/m^3 :	1.61

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	3860	2550	7.27	-28.4	19.0	6.12	0.18
Influent End	3810	2520	7.35	-33.3	19.3	6.61	0.17
Influent Avg	**3835**	**2535**	**7.31**	**-30.85**	**19.2**	**6.37**	**0.17**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	3660	2400	8.60	-106.8	22.0	6.22	0.10
Effluent B	3610	2380	8.82	-117.6	22.2	6.16	0.08
Effluent C	3620	2370	8.82	-119.0	22.0	4.82	0.08
Effluent Avg	**3630**	**2383**	**8.75**	**-114.5**	**22.1**	**5.73**	**0.09**

LAB ANALYSES   Coliform dilution =   Feed **1000**   Effluent **500**

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.08	1010	76.0	0.01	-	20.0	51	5.10E+04	5.10E+06
Influent 2	0.03	1010	81.0	-	-	-	47	4.70E+04	4.70E+06
Influent 3	-	-	-	-	-	-	90	4.50E+04	4.50E+06
Influent End									
Influent 1	0.03	1030	79.0	0.01	-	-	-	-	-
Influent 2	0.03	1050	84.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.04**	**1025.0**	**80.0**	**0.01**	**-**	**20.0**	**63**	**4.77E+04**	**4.77E+06**
Effluent A									
Effluent A1	0.20	1090	27.0	541.4	7.5	1402	20	1.00E+04	1.00E+06
Effluent A2	0.20	1100	29.0	-	-	-	20	1.00E+04	1.00E+06
Effluent A3	-	-	-	-	-	-	-	-	-
Effluent A Avg	**0.20**	**1095**	**28.0**	**541.4**	**7.5**	**1402**	**20**	**1.00E+04**	**1.00E+06**
Effluent B									
Effluent B1	0.26	1060	24.0	611.5	9.0	1422	17	8.50E+03	8.50E+05
Effluent B2	0.26	1050	30.0	-	-	-	14	7.00E+03	7.00E+05
Effluent B3	-	-	-	-	-	-	18	9.00E+03	9.00E+05
Effluent B Avg	**0.26**	**1055**	**27.0**	**611.5**	**9.0**	**1422**	**16**	**8.17E+03**	**8.17E+05**
Effluent C									
Effluent C1	0.12	1100	24.0	501.3	11.8	1402	15	7.50E+03	7.50E+05
Effluent C2	0.12	1080	31.0	-	-	-	18	9.00E+03	9.00E+05
Effluent C3	-	-	-	-	-	-	23	1.15E+04	1.15E+06
Effluent C Avg	**0.12**	**1090**	**27.5**	**501.3**	**11.8**	**1402.0**	**19**	**9.33E+03**	**9.33E+05**
Effluent Avg	**0.19**	**1080**	**27.5**	**551.4**	**9.5**	**1408.7**	**18**	**9.17E+03**	**9.17E+05**

Table A9. Results Experiment # 9 - Aluminum Electrodes Reactor

EXPERIMENT # 9
Date: March 7, 2005

OPERATION PARAMETERS:

Contact Time, minutes	15		**Power Consumption**	
Sample Volume, mL	850		Volts :	3.7
Current Density (mA/cm^2)	5.5		Amps :	10.04
Cl$^-$ Concentration (mg/L)	1075.00		kWh/m^3 :	10.78

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	3990	2620	7.20	-31.2	20.5	5.28	0.17
Influent End	3890	2560	7.31	-37.6	21.3	5.21	0.17
Influent Avg	**3940**	**2590**	**7.26**	**-34.40**	**20.9**	**5.25**	**0.17**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	3560	2340	8.93	-131.0	29.8	3.18	0.06
Effluent B	3560	2320	9.10	-140.5	30.7	2.75	0.05
Effluent C	3560	2340	9.20	-145.3	31.2	2.32	0.05
Effluent Avg	**3560**	**2333**	**9.08**	**-138.9**	**30.6**	**2.75**	**0.05**

LAB ANALYSES Coliform dilution = Feed 1000 Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.03	1060	61.0	0.01	-	15.0	51	5.10E+04	5.10E+06
Influent 2	0.03	1070	67.0	-	-	-	47	4.70E+04	4.70E+06
Influent 3	-	-		-	-	-	58	5.80E+04	5.80E+06
Influent End									
Influent 1	0.03	1070	62.0	0.01	-	-	-	-	-
Influent 2	0.03	1100	70.0	-	-	-	-	-	-
Influent 3	-	-		-	-	-	-	-	-
Influent Avg	**0.03**	**1075.0**	**65.0**	**0.01**	**-**	**15.0**	**52**	**5.20E+04**	**5.20E+06**
Effluent A									
Effluent A1	1.10	1130	24.0	2608	5.0	5802	3	1.50E+03	1.50E+05
Effluent A2	1.70	1110	28.0	-	-	-	5	2.50E+03	2.50E+05
Effluent A3	-	-	-	-	-	-	1	5.00E+02	5.00E+04
Effluent A Avg	**1.40**	**1120**	**26.0**	**2608**	**5.0**	**5802**	**3**	**1.50E+03**	**1.50E+05**
Effluent B									
Effluent B1	1.00	1000	19.0	3531	10.0	5964	1	5.00E+02	5.00E+04
Effluent B2	0.60	1070	23.0	-	-	-	2	1.00E+03	1.00E+05
Effluent B3	-	-	-	-	-	-	1	5.00E+02	5.00E+04
Effluent B Avg	**0.80**	**1035**	**21.0**	**3531**	**10.0**	**5964**	**1**	**6.67E+02**	**6.67E+04**
Effluent C									
Effluent C1	0.70	1060	17.0	3451	10.0	5980	1	5.00E+02	5.00E+04
Effluent C2	1.10	1080	22.0	-	-	-	2	1.00E+03	1.00E+05
Effluent C3	-	-	-	-	-	-	1	5.00E+02	5.00E+04
Effluent C Avg	**0.90**	**1070**	**19.5**	**3450.8**	**10.0**	**5980.0**	**1**	**6.67E+02**	**6.67E+04**
Effluent Avg	**1.04**	**1075**	**22.2**	**3197**	**8.4**	**5915.3**	**2**	**9.44E+02**	**9.44E+04**

Table A10. Results Experiment # 10 - Aluminum Electrodes Reactor

EXPERIMENT # 10
Date: March 10, 2005

OPERATION PARAMETERS:

Contact Time, minutes	5		**Power Consumption**			AVG
Sample Volume, mL	850		Volts :	12	17	14.5
Current Density (mA/cm²)	5.5		Amps :	10.06	10.06	10.1
Cl⁻ Concentration (mg/L)	122.50		kWh/m³ :	11.8	16.8	14.3

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	1056	699	6.94	-16.9	19.9	5.83	0.19
Influent End	1051	692	7.09	-25.0	19.9	5.56	0.18
Influent Avg	**1054**	**696**	**7.02**	**-20.95**	**19.9**	**5.70**	**0.18**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	763	502	8.33	-95.9	29.9	5.64	0.10
Effluent B	762	502	8.48	-104.9	30.2	5.32	0.09
Effluent C	741	488	8.62	-112.1	30.0	6.21	0.08
Effluent Avg	**755**	**497**	**8.48**	**-104.3**	**30.0**	**5.72**	**0.09**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.04	122.0	63.0	0.01	-	12.0	35	3.50E+04	3.50E+06
Influent 2	0.05	124.0	65.0	-	-	-	36	3.60E+04	3.60E+06
Influent 3	-	-	-	-	-	-	42	4.20E+04	4.20E+06
Influent End									
Influent 1	0.04	122.0	55.0	0.01	-	-	-	-	-
Influent 2	0.04	122.0	60.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.04**	**122.5**	**60.8**	**0.01**	**-**	**12.0**	**38**	**3.8E+04**	**3.77E+06**
Effluent A									
Effluent A1	0.36	122.0	28.0	930.00	15.0	1849	14	7.00E+03	7.00E+05
Effluent A2	0.44	126.0	26.0	-	-	-	9	4.50E+03	4.50E+05
Effluent A3	-	-	-	-	-	-	18	9.00E+03	9.00E+05
Effluent A Avg	**0.40**	**124.0**	**27.0**	**930.0**	**15.0**	**1849**	**14**	**6.83E+03**	**6.83E+05**
Effluent B									
Effluent B1	0.42	125.0	29.0	828.91	20.0	2040	8	4.00E+03	4.00E+05
Effluent B2	0.36	122.0	19.0	-	-	-	11	5.50E+03	5.50E+05
Effluent B3	-	-	-	-	-	-	12	6.00E+03	6.00E+05
Effluent B Avg	**0.39**	**123.5**	**24.0**	**828.9**	**20.0**	**2040**	**10**	**5.17E+03**	**5.17E+05**
Effluent C									
Effluent C1	0.60	130.0	44.0	869.35	25.0	2032	6	3.00E+03	3.00E+05
Effluent C2	0.52	128.0	38.0	-	-	-	6	3.00E+03	3.00E+05
Effluent C3	-	-	-	-	-	-	11	5.50E+03	5.50E+05
Effluent C Avg	**0.56**	**129.0**	**41.0**	**869.3**	**25.0**	**2032.0**	**8**	**3.83E+03**	**3.83E+05**
Effluent Avg	**0.45**	**125.5**	**30.7**	**876.1**	**20.0**	**1973.7**	**11**	**5.28E+03**	**5.28E+05**

Table A11. Results Experiment # 11 - Aluminum Electrodes Reactor

EXPERIMENT # 11
Date: March 15, 2005

OPERATION PARAMETERS:

Contact Time, minutes	10		**Power Consumption**	
Sample Volume, mL	850		Volts :	3.8
Current Density (mA/cm^2)	3.5		Amps :	6.4
Cl$^-$ Concentration (mg/L)	580.00		kWh/m^3 :	4.77

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	2720	1797	7.19	-30.5	20.0	5.83	0.17
Influent End	2660	1767	7.39	-42.0	20.5	5.90	0.16
Influent Avg	**2690**	**1782**	**7.29**	**-36.25**	**20.3**	**5.87**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	2370	1561	8.77	-120.6	25.6	5.36	0.08
Effluent B	2380	1565	8.90	-128.0	25.9	5.41	0.07
Effluent C	2400	1577	8.92	-129.4	26.0	4.94	0.07
Effluent Avg	**2383**	**1568**	**8.86**	**-126.0**	**25.8**	**5.24**	**0.07**

LAB ANALYSES Coliform dilution = Feed 1000 Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.08	585.0	58.0	0.01	-	10.0	36	3.60E+04	3.60E+06
Influent 2	0.03	575.0	56.0	-	-	-	43	4.30E+04	4.30E+06
Influent 3	-	-		-	-	-	43	4.30E+04	4.30E+06
Influent End									
Influent 1	0.04	580.0	60.0	0.01	-	-	-	-	-
Influent 2	0.04	580.0	57.0	-	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-
Influent Avg	**0.05**	**580.0**	**57.8**	**0.01**	**-**	**1.00E+01**	**41**	**4.1E+04**	**4.07E+06**
Effluent A									
Effluent A1	0.26	580.0	15.0	881.1	>8	2400	14	7.00E+03	7.00E+05
Effluent A2	0.42	530.0	17.0	-	-	-	11	5.50E+03	5.50E+05
Effluent A3	-	-	-	-	-	-	22	1.10E+04	1.10E+06
Effluent A Avg	**0.34**	**555.0**	**16.0**	**881.1**	**-**	**2400**	**16**	**7.83E+03**	**7.83E+05**
Effluent B									
Effluent B1	0.40	535.0	12.0	801.0	>8	2581	12	6.00E+03	6.00E+05
Effluent B2	0.38	560.0	16.0	-	-	-	13	6.50E+03	6.50E+05
Effluent B3	-	-	-	-	-	-	0	0.00E+00	0.00E+00
Effluent B Avg	**0.39**	**547.5**	**14.0**	**801.0**	**-**	**2581**	**8**	**4.17E+03**	**4.17E+05**
Effluent C									
Effluent C1	0.36	495.0	13.0	740.9	>8	2613	17	8.50E+03	8.50E+05
Effluent C2	0.64	480.0	13.0	-	-	-	17	8.50E+03	8.50E+05
Effluent C3	-	-	-	-	-	-	0	0.00E+00	0.00E+00
Effluent C Avg	**0.50**	**487.5**	**13.0**	**740.9**	**-**	**2613.0**	**11**	**5.67E+03**	**5.67E+05**
Effluent Avg	**0.41**	**530.0**	**14.3**	**807.7**	**>8**	**2531.3**	**12**	**5.89E+03**	**5.89E+05**

Table A12. Results Experiment # 12 - Aluminum Electrodes Reactor

EXPERIMENT # 12
Date: March 22, 2005

OPERATION PARAMETERS:

Contact Time, minutes	15		Power Consumption	
Sample Volume, mL	850		Volts :	14
Current Density (mA/cm^2)	5.5		Amps :	10.06
Cl$^-$ Concentration (mg/L)	161.75		kWh/m^3 :	41.4

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent Start	1239	819	7.06	-24.1	21.5	4.91	0.18
Influent End	1237	817	7.11	-27.1	22.0	4.55	0.17
Influent Avg	**1238**	**818**	**7.09**	**-25.60**	**21.8**	**4.73**	**0.18**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	792	516	8.99	-135.2	43.0	2.82	0.05
Effluent B	823	538	8.96	-134.2	43.8	2.17	0.05
Effluent C	786	518	9.01	-136.4	43.8	2.47	0.04
Effluent Avg	**800**	**524**	**8.99**	**-135.3**	**43.5**	**2.49**	**0.05**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 200

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Aluminum (mg/l)	Aluminum (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Actual Coliforms (count per 100 mL)
Influent Start									
Influent 1	0.04	164.0	54.3	0.00	-	7.0	36	3.60E+04	3.60E+06
Influent 2	0.03	160.0	54.3	-	-	-	37	3.70E+04	3.70E+06
Influent 3	-	-		-	-	-	74	3.70E+04	3.70E+06
Influent End									
Influent 1	0.03	162.0	56.3	0.00	-	-	-	-	-
Influent 2	0.04	161.0	58.3	-	-	-	-	-	-
Influent 3	-	-		-	-	-	-	-	-
Influent Avg	**0.04**	**161.8**	**55.8**	**0.00**	**-**	**7.0**	**49**	**3.67E+04**	**3.67E+06**
Effluent A									
Effluent A1	0.92	187.0	14.0	1628.1	17.0	5648	6	1.20E+03	1.20E+05
Effluent A2	0.68	195.0	15.0	-	-	-	4	8.00E+02	8.00E+04
Effluent A3	-	-	-	-	-	-	7	1.40E+03	1.40E+05
Effluent A Avg	**0.80**	**191.0**	**14.5**	**1628.1**	**17.0**	**5648**	**6**	**1.13E+03**	**1.13E+05**
Effluent B									
Effluent B1	0.52	211.0	11.0	1547.7	17.0	5830	1	2.00E+02	2.00E+04
Effluent B2	0.28	214.0	13.0	-	-	-	1	2.00E+02	2.00E+04
Effluent B3	-	-	-	-	-	-	1	2.00E+02	2.00E+04
Effluent B Avg	**0.40**	**212.5**	**12.0**	**1547.7**	**17.0**	**5830**	**1**	**2.00E+02**	**2.00E+04**
Effluent C									
Effluent C1	0.72	198.0	11.0	1467.3	17.0	5691	1	2.00E+02	2.00E+04
Effluent C2	0.76	201.0	15.0	-	-	-	4	8.00E+02	8.00E+04
Effluent C3	-	-	-	-	-	-	2	4.00E+02	4.00E+04
Effluent C Avg	**0.74**	**199.5**	**13.0**	**1467.3**	**17.0**	**5691**	**2**	**4.67E+02**	**4.67E+04**
Effluent Avg	**0.65**	**201.0**	**13.2**	**1547.7**	**17.0**	**5723**	**3**	**6.00E+02**	**6.00E+04**

Table A13. Results Experiment # 1 – Stainless Steel Electrodes Reactor

EXPERIMENT # 1
Date: April 19, 2005

OPERATION PARAMETERS:

Contact Time (min)	15	**Power Consumption**		
Volume (ml)	800	Volts :	13.8	(avg.)
Current Density (mA/cm^2)	7.5	Amps :	13.06	(avg.)
Cl$^-$ Concentration (mg/L)	165	kWh/m^3 :	56.3	

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1103	728	6.97	-18.7	22.2	3.05	0.18
Influent *End*	1082	713	7.40	-43.2	20.5	3.22	0.16
Influent Avg	**1093**	**721**	**7.19**	**-30.95**	**21.4**	**3.14**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	725	478	9.09	-141.9	39.0	0.02	0.04
Effluent B	726	478	8.87	-130.6	42.0	0.02	0.05
Effluent C	770	506	8.93	-132.3	42.0	0.06	0.05
Effluent Avg	**740**	**487**	**8.96**	**-134.93**	**41.0**	**0.03**	**0.05**

LAB ANALYSES　　Coliform dilution =　　Feed 1000　　Effluent 200

	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	165	99.0	0.63	-	21	45	4.5E+04	4.5E+06
Influent 2	167	72.0	0.73	-	-	35	3.5E+04	3.5E+06
Influent 3	-	-	-	-	-	36	3.6E+04	3.6E+06
Influent End								
Influent 1	162	81.0	0.59	-	-	-	-	-
Influent 2	166	62.0	0.59	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-
Influent Avg	**165**	**78.5**	**0.64**	**-**	**21.00**	**39**	**3.87E+04**	**3.87E+06**
Effluent A								
Effluent A1	130	27	1500	1.70	3376	0	0	0
Effluent A2	133	23	1600	2.00	-	0	0	0
Effluent A3	-	-	-	-	-	0	0	0
Effluent A Avg	**132**	**25**	**1550**	**1.85**	**3376**	**0**	**0**	**0.0**
Effluent B								
Effluent B1	132	28.0	1000	0.40	2956	0	0	0
Effluent B2	145	20.0	900	1.15	-	0	0	0
Effluent B3	-	-	-	-	-	0	0	0
Effluent B Avg	**139**	**24**	**950**	**0.78**	**2956**	**0**	**0**	**0.0**
Effluent C								
Effluent C1	129	24.0	1040	3.80	3212	0	0	0
Effluent C2	139	13.0	1120	4.00	-	0	0	0
Effluent C3	-	-	-	-	-	2	400	40000
Effluent C Avg	**134**	**19**	**1080**	**3.90**	**3212**	**1**	**133**	**13333**
Effluent Avg	**135**	**22.5**	**1193**	**2.18**	**3181**	**0.2**	**44**	**4444**

Table A14. Results Experiment # 2 – Stainless Steel Electrodes Reactor

EXPERIMENT # 2
Date: April 21, 2005

OPERATION PARAMETERS:

Contact Time (min)	5		**Power Consumption**		
Volume (ml)	800		Volts :	8.0	(avg.)
Current Density (mA/cm^2)	3.5		Amps :	6.1	(avg.)
Cl$^-$ Concentration (mg/L)	161		kWh/m^3 :	5.1	

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1245	820	6.92	-15.7	21.5	2.59	0.19
Influent *End*	1224	805	7.14	-28.1	22.0	2.88	0.17
Influent Avg	**1235**	**813**	**7.03**	**-21.90**	**21.8**	**2.74**	**0.18**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1173	774	7.49	-49.5	24.0	3.74	0.15
Effluent B	1179	777	7.57	-53.0	25.0	4.81	0.15
Effluent C	1194	785	7.69	-59.6	26.0	4.91	0.14
Effluent Avg	**1182**	**779**	**7.58**	**-54.03**	**25.0**	**4.49**	**0.14**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	162	79.0	0.41	-	10	51	5.1E+04	5.1E+06
Influent 2	152	62.0	0.31	-	-	53	5.3E+04	5.3E+06
Influent 3	-	-	-	-	-	45	4.5E+04	4.5E+06
Influent End								
Influent 1	171	73.0	0.40	-	-	-	-	-
Influent 2	157	61.0	0.39	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-
Influent Avg	**161**	**68.8**	**0.38**	**-**	**10.00**	**50**	**4.97E+04**	**4.97E+06**
Effluent A								
Effluent A1	156	2.0	70.1	4.13	300	1	500	50000
Effluent A2	168	2.0	125.2	4.21	-	0	0	0
Effluent A3	-	-	-	-	-	0	0	0
Effluent A Avg	**162**	**2.0**	**97.6**	**4.17**	**300**	**0**	**167**	**16667**
Effluent B								
Effluent B1	160	5.0	105.1	2.04	280	0	0	0
Effluent B2	170	7.0	130.2	2.16	-	0	0	0
Effluent B3	-	-	-	-	-	0	0	0
Effluent B Avg	**165**	**6.0**	**117.6**	**2.10**	**280**	**0**	**0**	**0.0**
Effluent C								
Effluent C1	165	1.0	40.1	1.76	168	2	1000	100000
Effluent C2	178	1.0	65.1	1.76	-	1	500	50000
Effluent C3	-	-	-	-	-	1	500	50000
Effluent C Avg	**172**	**1.0**	**52.6**	**1.76**	**168**	**1**	**667**	**66667**
Effluent Avg	**166**	**3.0**	**89**	**2.68**	**249**	**0.6**	**278**	**27778**

Table A15. Results Experiment # 3 – Stainless Steel Electrodes Reactor

EXPERIMENT # 3
Date: April 25, 2005

OPERATION PARAMETERS:

			Power Consumption		
Contact Time (min)	5				
Volume (ml)	800		Volts :	14.6	(avg.)
Current Density (mA/cm^2)	7.5		Amps :	13.06	(avg.)
Cl$^-$ Concentration (mg/L)	127		kWh/m^3 :	19.9	

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1105	729	6.87	-16.1	21.4	2.32	0.19
Influent *End*	1103	728	6.88	-16.5	21.2	2.67	0.19
Influent Avg	**1104**	**729**	**6.88**	**-16.30**	**21.3**	**2.50**	**0.19**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1047	691	7.22	-36.0	29.5	3.81	0.16
Effluent B	1047	696	7.32	-42.5	31.4	3.11	0.15
Effluent C	1047	702	7.49	-51.6	32.0	3.20	0.14
Effluent Avg	**1047**	**696**	**7.34**	**-43.37**	**31.0**	**3.37**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 100

	Total Chlorine (mg/l)	Ozone (mg/l)	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	-	125	67.0	0.35	-	17	47	4.7E+04	4.7E+06
Influent 2	-	-	127	68.0	0.43	-	-	51	5.1E+04	5.1E+06
Influent 3	-	-	-	-	-	-	-	47	4.7E+04	4.7E+06
Influent End										
Influent 1	-	-	128	66.0	0.40	-	-	-	-	-
Influent 2	-	-	126	61.0	0.39	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**-**	**127**	**65.5**	**0.39**	**-**	**17.00**	**48**	**4.83E+04**	**4.83E+06**
Effluent A										
Effluent A1	1.12	0.11	136	7	51	0.50	88	0	0	0
Effluent A2	1.34	0.05	133	21	42	0.38	-	0	0	0
Effluent A3	-	-	-	-	-	-	-	0	0	0
Effluent A Avg	**1.23**	**0.08**	**135**	**14**	**46.52**	**0.44**	**88**	**0.0**	**0.00E+00**	**0.00E+00**
Effluent B										
Effluent B1	1.16	0.03	131	5	43	0.20	109	0	0	0
Effluent B2	1.14	0.03	126	18	53	0.38	-	0	0	0
Effluent B3	-	-	-	-	-	-	-	0	0	0
Effluent B Avg	**1.15**	**0.03**	**129**	**12**	**48.04**	**0.29**	**109**	**0.0**	**0.00E+00**	**0.00E+00**
Effluent C										
Effluent C1	1.10	0.04	165	3	46	0.28	131	0	0	0
Effluent C2	0.97	0.04	152	19	38	0.32	-	0	0	0
Effluent C3	-	-	-	-	-	-	-	0	0	0
Effluent C Avg	**1.04**	**0.04**	**159**	**11**	**41.97**	**0.30**	**131**	**0.0**	**0.00E+00**	**0.00E+00**
Effluent Avg	**1.14**	**0.05**	**141**	**12.2**	**46**	**0.34**	**109**	**0**	**<100**	**<10000**

Table A16. Results Experiment # 4 – Stainless Steel Electrodes Reactor

EXPERIMENT # 4
Date: May 3, 2005

OPERATION PARAMETERS:

			Power Consumption		
Contact Time (min)	10				
Volume (ml)	800		Volts :	12.2	(avg.)
Current Density (mA/cm²)	5.5		Amps :	9.58	(avg.)
Cl⁻ Concentration (mg/L)	126		kWh/m³ :	24.2	

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1038	683	6.87	-15.9	23.3	2.26	0.18
Influent *End*	1034	680	7.21	-35.6	21.9	3.03	0.17
Influent Avg	**1036**	**682**	**7.04**	**-25.75**	**22.6**	**2.65**	**0.18**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	973	640	7.77	-67.2	31.8	4.34	0.13
Effluent B	986	651	7.60	-58.5	31.7	3.26	0.13
Effluent C	972	640	7.68	-62.7	34.5	3.91	0.13
Effluent Avg	**977**	**644**	**7.68**	**-62.80**	**32.7**	**3.84**	**0.13**

LAB ANALYSES   Coliform dilution =   Feed: 1000   Effluent: 10

	Total Chlorine (mg/l)	Ozone (mg/l)	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	-	127	74.0	0.58	-	41	42	4.2E+04	4.2E+06
Influent 2	-	-	128	80.0	0.66	-	-	32	3.2E+04	3.2E+06
Influent 3	-	-	-	-	-	-	-	54	5.4E+04	5.4E+06
Influent End										
Influent 1	-	-	120	90.0	0.71	-	-	-	-	-
Influent 2	-	-	127	86.0	0.69	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**-**	**126**	**82.5**	**0.66**	**-**	**41.00**	**43**	**4.27E+04**	**4.27E+06**
Effluent A										
Effluent A1	1.20	0.18	128	22.0	61.1	1.06	217	0	0	0
Effluent A2	1.14	0.18	134	6.0	58.1	0.90	-	2	20	2000
Effluent A3	-	-	-	-	-	-	-	2	20	2000
Effluent A Avg	**1.17**	**-**	**131.0**	**14.0**	**59.6**	**0.98**	**217**	**1.3**	**1.33E+01**	**1.33E+03**
Effluent B										
Effluent B1	2.70	0.17	130	10.0	52.1	0.50	156	0	0	0
Effluent B2	2.29	0.10	138	6.0	45.1	0.52	-	0	0	0
Effluent B3	-	-	-	-	-	-	-	0	0	0
Effluent B Avg	**2.50**	**-**	**134.0**	**8.0**	**48.6**	**0.51**	**156**	**0.0**	**0.00E+00**	**0.00E+00**
Effluent C										
Effluent C1	0.73	0.16	119	3.0	89.1	0.50	302	6	60	6000
Effluent C2	0.89	0.16	142	22.0	79.1	0.38	-	4	40	4000
Effluent C3	-	-	-	-	-	-	-	3	30	3000
Effluent C Avg	**0.81**	**-**	**130.5**	**12.5**	**84.1**	**0.44**	**302**	**4.3**	**4.33E+01**	**4.33E+03**
Effluent Avg	**1.49**	**0.16**	**132**	**11.5**	**64.1**	**0.64**	**225**	**1.9**	**19**	**1889**

Table A17. Results Experiment # 5 – Stainless Steel Electrodes Reactor

EXPERIMENT # 5
Date: May 4, 2005

OPERATION PARAMETERS:

Contact Time (min)	15		**Power Consumption**		
Volume (ml)	800		Volts :	9.0	(avg.)
Current Density (mA/cm²)	3.5		Amps :	6.1	(avg.)
Cl⁻ Concentration (mg/L)	130		kWh/m³ :	17.2	

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1090	719	6.89	-16.4	21.8	2.25	0.19
Influent *End*	1048	691	7.10	-28.9	21.7	2.34	0.17
Influent Avg	**1069**	**705**	**7.00**	**-22.65**	**21.8**	**2.30**	**0.18**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1016	675	7.38	-45.5	29.0	3.04	0.15
Effluent B	974	643	7.46	-49.9	29.5	3.27	0.14
Effluent C	985	650	7.48	-51.1	30.0	3.92	0.14
Effluent Avg	**992**	**656**	**7.44**	**-48.83**	**29.5**	**3.41**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 10

	Total Chlorine (mg/l)	Ozone (mg/l)	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	-	129	70.0	0.41	-	15	57	5.7E+04	5.7E+06
Influent 2	-	-	130	67.0	0.53	-	-	58	5.8E+04	5.8E+06
Influent 3	-	-	-	-	-	-	-	58	5.8E+04	5.8E+06
Influent End										
Influent 1	-	-	128	68.0	0.51	-	-	-	-	-
Influent 2	-	-	132	60.0	0.53	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**-**	**130**	**66.3**	**0.50**	**-**	**15.00**	**58**	**5.77E+04**	**5.77E+06**
Effluent A										
Effluent A1	1.12	0.19	124	15.0	38.10	0.40	100	0	0	0
Effluent A2	1.10	0.10	140	10.0	43.11	0.50	-	0	0	0
Effluent A3	-	-	-	-	-	-	-	0	0	0
Effluent A Avg	**1.11**	**0.15**	**132.0**	**12.5**	**40.6**	**0.45**	**100**	**0**	**0.00E+00**	**0.00E+00**
Effluent B										
Effluent B1	0.69	0.16	141	20.0	55.14	0.00	158	0	0	0
Effluent B2	0.59	0.08	117	21.0	56.14	0.80	-	0	0	0
Effluent B3	-	-	-	-	-	-	-	0	0	0
Effluent B Avg	**0.64**	**0.12**	**129.0**	**20.5**	**55.6**	**0.40**	**158**	**0**	**0.00E+00**	**0.00E+00**
Effluent C										
Effluent C1	0.57	0.07	131	15.0	79.20	0.50	230	1	10	1000
Effluent C2	0.37	0.03	131	10.0	68.17	0.10	-	0	0	0
Effluent C3	-	-	-	-	-	-	-	0	0	0
Effluent C Avg	**0.47**	**0.05**	**131.0**	**12.5**	**73.7**	**0.30**	**230**	**0.3**	**3.33E+00**	**3.33E+02**
Effluent Avg	**0.74**	**0.11**	**131**	**15.2**	**56.6**	**0.38**	**163**	**0.1**	**1**	**111**

Table A18. Results Experiment # 6 – Stainless Steel Electrodes Reactor

EXPERIMENT # 6
Date: May 4, 2005

OPERATION PARAMETERS:

Contact Time (min)	10		**Power Consumption**	
Volume (ml)	800		Volts :	5.5	(avg.)
Current Density (mA/cm²)	1.5		Amps :	2.61	(avg.)
Cl⁻ Concentration (mg/L)	132		kWh/m³ :	3.0	

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1090	719	6.89	-16.4	21.8	2.25	0.19
Influent *End*	1048	691	7.10	-28.9	21.7	2.34	0.17
Influent Avg	**1069**	**705**	**7.00**	**-22.65**	**21.8**	**2.30**	**0.18**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1011	668	7.85	-71.5	23.9	4.86	0.13
Effluent B	1021	676	8.00	-79.7	23.8	4.39	0.12
Effluent C	1000	663	8.00	-80.3	23.8	4.60	0.12
Effluent Avg	**1011**	**669**	**7.95**	**-77.17**	**23.8**	**4.62**	**0.12**

LAB ANALYSES   Coliform dilution =   Feed [1000]   Effluent [10]

	Total Chlorine (mg/l)	Ozone (mg/l)	Chlorides (mg/l)	COD (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (diluted count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	-	132	70.0	0.50	-	17	48	4.8E+04	4.8E+06
Influent 2	-	-	125	67.0	0.52	-	-	42	4.2E+04	4.2E+06
Influent 3	-	-	-	-	-	-	-	55	5.5E+04	5.5E+06
Influent End										
Influent 1	-	-	134	67.0	0.52	-	-	-	-	-
Influent 2	-	-	136	58.0	0.51	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**-**	**132**	**65.5**	**0.51**	**-**	**17.00**	**48**	**4.83E+04**	**4.83E+06**
Effluent A										
Effluent A1	0.43	U.R.	106	24.0	26.07	0.72	78	1	10	1000
Effluent A2	0.55	U.R.	108	35.0	28.07	0.54	-	0	0	0
Effluent A3	-	-	-	-	-	-	-	0	0	0
Effluent A Avg	**0.49**	**-**	**107.0**	**29.5**	**27.1**	**0.63**	**78**	**0.3**	**3.33E+00**	**3.33E+02**
Effluent B						-				
Effluent B1	0.26	U.R.	116	32.0	35.09	0.54	120	9	90	9000
Effluent B2	0.28	U.R.	112	39.0	36.09	0.50	-	9	90	9000
Effluent B3	-	-	-	-	-	-	-	13	130	13000
Effluent B Avg	**0.27**	**-**	**114.0**	**35.5**	**35.6**	**0.52**	**120**	**10.3**	**1.03E+02**	**1.03E+04**
Effluent C										
Effluent C1	0.59	U.R.	117	18.0	25.06	0.50	122	28	280	28000
Effluent C2	0.41	U.R.	120	18.0	34.09	0.98	-	22	220	22000
Effluent C3	-	-	-	-	-	-	-	21	210	21000
Effluent C Avg	**0.50**	**-**	**118.5**	**18.0**	**29.6**	**0.74**	**122**	**23.7**	**2.37E+02**	**2.37E+04**
Effluent Avg	**0.42**	**-**	**113**	**27.7**	**30.7**	**0.63**	**107**	**11**	**114**	**11444**

Table A19. Results Experiment # 1 – Titanium Electrodes Reactor

EXPERIMENT # 1   (Addition of NaCl to increase conductivity)
Date: April 5, 2005

OPERATION PARAMETERS:

			Power Consumption			
Contact Time (min)	5			**A**	**B**	**C**
Volume (ml)	1000		Volts :	25.50	25.50	25.50
Current Density (mA/cm^2)	1.4		Amps :	2.70	2.08	2.56
Cl$^-$ Concentration (mg/L)	1105		kWh/m^3 :	5.7	4.4	5.4

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	4230	2810	7.26	-36.5	20.3	5.21	0.167
Influent *End*	-	-	-	-	-	-	-
Influent Avg	**4230**	**2810**	**7.26**	**-36.50**	**20.3**	**5.21**	**0.17**

	Conductivity (μS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	4230	2810	7.57	-55.0	21.1	4.62	0.148
Effluent B	4180	2760	7.55	-53.4	22.2	5.21	0.148
Effluent C	4220	2770	7.61	-57.9	22.7	5.33	0.143
Effluent Avg	**4210**	**2780**	**7.58**	**-55.43**	**22.0**	**5.05**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 1000

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	-	1090	65.0	-	17.9	53	5.3E+04	5.3E+06
Influent 2	-	1050	69.0	-	-	52	5.2E+04	5.2E+06
Influent 3	-	-	-	-	-	47	4.7E+04	4.7E+06
Influent End								
Influent 1	-	1140	85.0	-	-	-	-	
Influent 2	-	1140	77.0	-	-	-	-	
Influent 3	-	-	-	-	-	-	-	
Influent Avg	**-**	**1105**	**74.0**	**-**	**17.90**	**50.67**	**5.07E+04**	**5.07E+06**
Effluent A								
Effluent A1	0.07	870	47.0	U.R.	28	24	2.4E+04	2.4E+06
Effluent A2	0.13	910	36.0	U.R.	-	27	2.7E+04	2.7E+06
Effluent A3	-	-	-	-	-	24	2.4E+04	2.4E+06
Effluent A Avg	**0.10**	**890**	**41.5**	**-**	**28.0**	**25**	**25000**	**2500000**
Effluent B								
Effluent B1	0.18	1070	35.0	U.R.	16	33	3.3E+04	3.3E+06
Effluent B2	0.17	970	38.0	U.R.	-	28	2.8E+04	2.8E+06
Effluent B3	-	-	-	-	-	29	2.9E+04	2.9E+06
Effluent B Avg	**0.18**	**1020**	**36.5**	**-**	**16.0**	**30**	**30000**	**3000000**
Effluent C								
Effluent C1	0.26	1180	44.0	U.R.	16	26	2.6E+04	2.6E+06
Effluent C2	0.30	1060	41.0	U.R.	-	28	2.8E+04	2.8E+06
Effluent C3	-	-	-	-	-	33	3.3E+04	3.3E+06
Effluent C Avg	**0.28**	**1120**	**42.5**	**-**	**16.0**	**29**	**29000**	**2900000**

Table A20. Results Experiment # 2 – Titanium Electrodes Reactor

EXPERIMENT # 2
Date: May 9, 2005

OPERATION PARAMETERS:

			Power Consumption	A	B	C
Contact Time (min)	15		Volts :	25.80	25.33	26.25
Volume (ml)	600		Amps :	1.04	0.88	0.81
Current Density (mA/cm²)	0.87		kWh/m³ :	11.2	9.2	8.9
Cl⁻ Concentration (mg/L)	129					

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1150	760	6.90	-18.3	23.6	2.26	0.182
Influent *End*	1150	759	7.30	-42.0	22.1	3.03	0.160
Influent Avg	**1150**	**760**	**7.10**	**-30.15**	**22.9**	**2.65**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1167	768	7.25	-39.6	29.0	3.65	0.155
Effluent B	1155	756	8.03	-83.5	31.2	3.96	0.109
Effluent C	1142	750	8.62	-117.1	31.5	4.27	0.075
Effluent Avg	**1155**	**758**	**7.97**	**-80.07**	**30.6**	**3.96**	**0.11**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	-	121	94.0	-	4.0	50	5.0E+04	5.0E+06
Influent 2	-	137	77.0	-	-	41	4.1E+04	4.1E+06
Influent 3	-	-	-	-	-	49	4.9E+04	4.9E+06
Influent End								
Influent 1	-	129	83.0	-	-	-	-	
Influent 2	-	127	72.0	-	-	-	-	
Influent 3	-	-	-	-	-	-	-	
Influent Avg	**-**	**129**	**81.5**	**-**	**4.00**	**46.67**	**4.67E+04**	**4.67E+06**
Effluent A								
Effluent A1	0.05	150	61.4	U.R.	36.0	35	1.8E+04	1.8E+06
Effluent A2	0.06	135	63.4	U.R.	-	28	1.4E+04	1.4E+06
Effluent A3	-	-	-	-	-	40	2.0E+04	2.0E+06
Effluent A Avg	**0.06**	**142**	**62.4**	**-**	**36.0**	**34**	**17167**	**1716667**
Effluent B								
Effluent B1	0.07	135	45.3	U.R.	30.0	25	1.3E+04	1.3E+06
Effluent B2	0.08	127	40.3	U.R.	-	20	1.0E+04	1.0E+06
Effluent B3	-	-	-	-	-	17	8.5E+03	8.5E+05
Effluent B Avg	**0.08**	**131**	**42.8**	**-**	**30.0**	**21**	**10333**	**1033333**
Effluent C								
Effluent C1	0.19	128	41.3	U.R.	24.0	11	5.5E+03	5.5E+05
Effluent C2	0.24	130	56.4	U.R.	-	7	3.5E+03	3.5E+05
Effluent C3	-	-	-	-	-	9	4.5E+03	4.5E+05
Effluent C Avg	**0.22**	**129**	**48.8**	**-**	**24.0**	**9**	**4500**	**450000**

Table A21. Results Experiment # 3 – Titanium Electrodes Reactor

EXPERIMENT # 3
Date: May 11, 2005

OPERATION PARAMETERS:

			Power Consumption	**A**	**B**	
Contact Time (min)	15		Volts :	24.40	25.02	(avg.)
Volume (ml)	600		Amps :	1.47	1.15	(avg.)
Current Density (mA/cm^2)	A: 1.41 B: 1.10		kWh/m^3 :	14.9	12.0	
Cl$^-$ Concentration (mg/L)	1080					

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	4240	2780	7.16	-33.3	23.5	2.15	0.167
Influent *End*	4220	2790	7.39	-46.1	22.1	2.46	0.156
Influent Avg	**4230**	**2785**	**7.28**	**-39.7**	**22.8**	**2.31**	**0.162**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	4220	2780	8.19	-91.7	31.2	2.81	0.101
Effluent B	4160	2740	8.36	-97.7	32.0	3.82	0.094
Effluent Avg	**4190**	**2760**	**8.28**	**-94.70**	**31.6**	**3.32**	**0.098**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	-	1057	72.5	-	18.5	55	5.5E+04	5.5E+06
Influent 2	-	1077	69.5	-	-	57	5.7E+04	5.7E+06
Influent 3	-	-	-	-	-	54	5.4E+04	5.4E+06
Influent End								
Influent 1	-	1097	88.6	-	-	-	-	-
Influent 2	-	1087	76.5	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-
Influent Avg	**-**	**1080**	**76.8**	**-**	**18.50**	**55.33**	**5.53E+04**	**5.53E+06**
Effluent A								
Effluent A1	0.14	987	50.3	U.R.	45.5	1	5.0E+02	5.0E+04
Effluent A2	0.14	1047	54.4	U.R.	-	1	5.0E+02	5.0E+04
Effluent A3	-	-	-	-	-	2	1.0E+03	1.0E+05
Effluent A Avg	**0.14**	**1017**	**52.3**	**-**	**45.5**	**1**	**667**	**66667**
Effluent B								
Effluent B1	0.13	1007	40.3	U.R.	63.5	9	4.5E+03	4.5E+05
Effluent B2	0.18	987	43.3	U.R.	-	8	4.0E+03	4.0E+05
Effluent B3	-	-	-	-	-	9	4.5E+03	4.5E+05
Effluent B Avg	**0.16**	**997**	**41.8**	**-**	**63.5**	**9**	**4333**	**433333**

Table A22. Results Experiment # 4 – Titanium Electrodes Reactor

EXPERIMENT # 4
Date: May 11, 2005

OPERATION PARAMETERS:

Contact Time (min)	25		**Power Consumption**	**A**	**B**
Volume (ml)	600		Volts :	25.60	25.00	(avg.)
Current Density (mA/cm^2)	**A:** 1.06 **B:** 1.05		Amps :	1.11	1.10	(avg.)
Cl$^-$ Concentration (mg/L)	1080		kWh/m^3 :	19.6	19.2

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	4240	2780	7.16	-33.3	21.5	2.15	0.169
Influent *End*	4220	2790	7.39	-46.1	21.6	2.46	0.156
Influent Avg	**4230**	**2785**	**7.28**	**-39.7**	**21.6**	**2.31**	**0.163**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	4200	2760	8.38	-101.7	33.5	2.89	0.089
Effluent B	4210	2770	8.61	-116.4	35.0	2.94	0.073
Effluent Avg	**4205**	**2765**	**8.50**	**-109.05**	**34.3**	**2.92**	**0.081**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 500

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start								
Influent 1	-	1057	72.5	-	17.9	62	6.2E+04	6.2E+06
Influent 2	-	1077	69.5	-	-	60	6.0E+04	6.0E+06
Influent 3	-	-	-	-	-	74	7.4E+04	7.4E+06
Influent End								
Influent 1	-	1097	88.6	-	-	-	-	-
Influent 2	-	1087	76.5	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-
Influent Avg	**-**	**1080**	**76.8**	**-**	**17.90**	**65.33**	**6.53E+04**	**6.53E+06**
Effluent A								
Effluent A1	0.14	1107	30.2	U.R.	78.0	1	5.0E+02	5.0E+04
Effluent A2	0.14	1158	45.3	U.R.	-	2	1.0E+03	1.0E+05
Effluent A3	-	-	-	-	-	3	1.5E+03	1.5E+05
Effluent A Avg	**0.14**	**1133**	**37.8**	**-**	**78.0**	**2**	**1000**	**100000**
Effluent B								
Effluent B1	0.13	866	23.2	U.R.	108	0	0.0E+00	0.0E+00
Effluent B2	0.18	976	22.1	U.R.	-	0	0.0E+00	0.0E+00
Effluent B3	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent B Avg	**0.16**	**921**	**22.7**	**-**	**108.0**	**0**	**0**	**0**

Table A23. Results Experiment # 1 – Stainless Steel-Titanium Electrodes Reactor

EXPERIMENT # 1
Date: May 18, 2005

OPERATION PARAMETERS:

		Power Consumption	
Contact Time (min)	5		
Volume (ml)	800	Volts :	8.50
Current Density (mA/cm^2)	3.5	Amps :	6.18
Cl$^-$ Concentration (mg/L)	136	kWh/m^3 :	5.47

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1013	669	7.07	-27.1	24.2	1.43	0.173
Influent *End*	1004	661	7.20	-34.4	23.7	2.31	0.166
Influent Avg	**1009**	**665**	**7.14**	**-30.75**	**24.0**	**1.87**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	953	627	7.41	-47.0	27.5	3.24	0.150
Effluent B	950	626	7.32	-41.9	27.6	3.71	0.155
Effluent C	923	608	7.41	-47.5	26.5	3.42	0.150
Effluent Avg	**942**	**620**	**7.38**	**-45.47**	**27.2**	**3.46**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 100

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	130	71.0	-	0.33	-	19	59	5.9E+04	5.9E+06
Influent 2	-	137	61.0	-	0.28	-	-	58	5.8E+04	5.8E+06
Influent 3	-	-	-	-	-	-	-	63	6.3E+04	6.3E+06
Influent End										
Influent 1	-	138	69.0	-	0.21	-	-	-	-	-
Influent 2	-	139	66.0	-	0.24	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**136**	**66.8**	**-**	**0.27**	**#DIV/0!**	**19.00**	**60**	**6.00E+04**	**6.00E+06**
Effluent A										
Effluent A1	2.03	126	38.0	0.08	29.04	1.262	21	0	0.0E+00	0.0E+00
Effluent A2	1.60	114	45.0	0.03	29.04	1.242	-	0	0.0E+00	0.0E+00
Effluent A3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent A Avg	**1.82**	**120**	**41.5**	**0.06**	**29.0**	**1.3**	**21.0**	**0**	**0**	**0**
Effluent B										
Effluent B1	0.77	129	44.0	0.06	23.03	1.222	22	0	0.0E+00	0.0E+00
Effluent B2	0.67	129	39.0	0.04	30.04	1.161	-	0	0.0E+00	0.0E+00
Effluent B3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent B Avg	**0.72**	**129**	**41.5**	**0.05**	**26.5**	**1.2**	**22.0**	**0**	**0**	**0**
Effluent C										
Effluent C1	0.67	117	39.0	0.02	42.05	1.542	30	0	0.0E+00	0.0E+00
Effluent C2	0.68	121	43.0	0.02	46.06	1.542	-	0	0.0E+00	0.0E+00
Effluent C3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent C Avg	**0.68**	**119**	**41.0**	**0.02**	**44.1**	**1.5**	**30.0**	**0**	**0**	**0**
Effluent Avg	**1.07**	**123**	**41.3**	**0.04**	**33.21**	**1.33**	**24.33**	**0**	**< 100**	**<10000**

Table A24. Results Experiment # 2 – Stainless Steel-Titanium Electrodes Reactor

EXPERIMENT # 2
Date: May 18, 2005

OPERATION PARAMETERS:

			Power Consumption	
Contact Time (min)	5			
Volume (ml)	800		Volts :	5.10
Current Density (mA/cm²)	1.5		Amps :	2.65
Cl⁻ Concentration (mg/L)	136		kWh/m³ :	1.4

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1013	669	7.07	-27.1	24.2	1.43	0.173
Influent *End*	1004	661	7.20	-34.4	23.7	2.31	0.166
Influent Avg	**1009**	**665**	**7.14**	**-30.75**	**24.0**	**1.87**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	942	621	7.29	-40.1	25.1	5.90	0.159
Effluent B	945	624	7.33	-42.6	25.0	5.42	0.156
Effluent C	944	622	7.49	-51.1	25.2	5.78	0.148
Effluent Avg	**944**	**622**	**7.37**	**-44.60**	**25.1**	**5.70**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 100

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	130	70.0	-	0.33	-	19	59	5.9E+04	5.9E+06
Influent 2	-	137	68.0	-	0.28	-	-	58	5.8E+04	5.8E+06
Influent 3	-	-	-	-	-	-	-	63	6.3E+04	6.3E+06
Influent End										
Influent 1	-	138	66.0	-	0.21	-	-	-	-	-
Influent 2	-	139	70.0	-	0.24	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**136**	**68.5**	**-**	**0.27**	**#DIV/0!**	**19.00**	**60**	**6.00E+04**	**6.00E+06**
Effluent A										
Effluent A1	0.57	124	57.0	0.00	11.01	2.583	16	0	0.0E+00	0.0E+00
Effluent A2	0.43	126	54.0	0.06	12.02	2.583	-	0	0.0E+00	0.0E+00
Effluent A3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent A Avg	**0.50**	**125**	**55.5**	**0.03**	**11.5**	**2.6**	**16.0**	**0**	**0**	**0**
Effluent B										
Effluent B1	0.61	123	43.0	0.06	7.01	2.703	18	0	0.0E+00	0.0E+00
Effluent B2	0.52	131	47.0	0.11	7.01	2.663	-	0	0.0E+00	0.0E+00
Effluent B3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent B Avg	**0.57**	**127**	**45.0**	**0.09**	**7.0**	**2.7**	**18.0**	**0**	**0**	**0**
Effluent C										
Effluent C1	0.82	128	43.0	0.00	6.01	2.383	16	0	0.0E+00	0.0E+00
Effluent C2	0.58	127	60.0	0.02	11.01	2.363	-	0	0.0E+00	0.0E+00
Effluent C3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent C Avg	**0.70**	**128**	**51.5**	**0.01**	**8.5**	**2.4**	**16.0**	**0**	**0**	**0**
Effluent Avg	**0.59**	**127**	**50.7**	**0.04**	**9.01**	**2.55**	**16.67**	**0**	**< 100**	**<10000**

Table A25. Results Experiment # 3 – Stainless Steel-Titanium Electrodes Reactor

EXPERIMENT # 3
Date: May 23, 2005

OPERATION PARAMETERS:

Contact Time (min)	2.5
Volume (ml)	800
Current Density (mA/cm²)	3.5
Cl⁻ Concentration (mg/L)	118

Power Consumption

Volts :	5.10
Amps :	6.18
kWh/m³ :	1.6

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1125	735	6.81	-21.0	25.5	2.01	0.178
Influent *End*	1109	734	7.16	-42.1	24.4	2.42	0.158
Influent Avg	**1117**	**735**	**6.99**	**-31.55**	**25.0**	**2.22**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1055	695	7.16	-42.1	26.0	4.61	0.156
Effluent B	1051	693	7.26	-47.3	26.7	4.63	0.150
Effluent C	1041	693	7.24	-44.9	27.0	4.85	0.152
Effluent Avg	**1049**	**694**	**7.22**	**-44.77**	**26.6**	**4.70**	**0.15**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 10

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	100	68.0	-	0.43	-	7	47	4.7E+04	4.7E+06
Influent 2	-	123	67.0	-	0.42	-	-	49	4.9E+04	4.9E+06
Influent 3	-	-	-	-	-	-	-	48	4.8E+04	4.8E+06
Influent End										
Influent 1	-	117	68.0	-	0.38	-	-	-	-	-
Influent 2	-	130	59.0	-	0.39	-	-	-	-	-
Influent 3	-	-	-	-	-	-	-	-	-	-
Influent Avg	**-**	**118**	**65.5**	**-**	**0.41**	**#DIV/0!**	**7.00**	**48**	**4.80E+04**	**4.80E+06**
Effluent A										
Effluent A1	0.76	120	49.0	U.R	4.91	4.15	13	0	0.0E+00	0.0E+00
Effluent A2	0.87	130	52.0	U.R.	4.41	4.15	-	0	0.0E+00	0.0E+00
Effluent A3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent A Avg	**0.82**	**125**	**50.5**	**-**	**4.7**	**4.2**	**13.0**	**0**	**0**	**0**
Effluent B										
Effluent B1	0.63	133	49.0	0.00	4.61	3.88	11	0	0.0E+00	0.0E+00
Effluent B2	0.61	131	38.0	U.R.	5.51	3.84	-	0	0.0E+00	0.0E+00
Effluent B3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent B Avg	**0.62**	**132**	**43.5**	**0.00**	**5.1**	**3.9**	**11.0**	**0**	**0**	**0**
Effluent C										
Effluent C1	0.68	131	33.0	U.R.	4.81	3.72	13	0	0.0E+00	0.0E+00
Effluent C2	0.66	132	41.0	U.R.	4.81	3.8	-	0	0.0E+00	0.0E+00
Effluent C3	-	-	-	-	-	-	-	0	0.0E+00	0.0E+00
Effluent C Avg	**0.67**	**132**	**37.0**	**-**	**4.8**	**3.8**	**13.0**	**0**	**0**	**0**
Effluent Avg	**0.70**	**130**	**43.7**	**0.00**	**4.84**	**3.92**	**12.33**	**0**	**< 10**	**<1000**

Table A26. Results Experiment # 4 – Stainless Steel-Titanium Electrodes Reactor

EXPERIMENT # 4
Date: May 23, 2005

OPERATION PARAMETERS:

		Power Consumption	
Contact Time (min)	2.5		
Volume (ml)	800	Volts :	5.15
Current Density (mA/cm²)	1.5	Amps :	2.65
Cl⁻ Concentration (mg/L)	118	kWh/m³ :	0.7

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Influent *Start*	1125	735	6.81	-21.0	25.5	2.01	0.178
Influent *End*	1109	734	7.16	-42.1	24.4	2.42	0.158
Influent Avg	**1117**	**735**	**6.99**	**-31.55**	**25.0**	**2.22**	**0.17**

	Conductivity (µS)	TDS (mg/l)	pH	ORP (mV)	Temp (oC)	D.O. (mg/L)	V vs. NHE
Effluent A	1113	701	7.40	-54.2	25.2	5.18	0.145
Effluent B	1119	701	7.41	-57.0	25.0	5.16	0.142
Effluent C	1096	699	7.71	-71.0	24.9	5.52	0.128
Effluent Avg	**1109**	**700**	**7.51**	**-60.73**	**25.0**	**5.29**	**0.14**

LAB ANALYSES   Coliform dilution =   Feed 1000   Effluent 10

	Total Chlorine (mg/l)	Chlorides (mg/l)	COD (mg/l)	Ozone (mg/l)	Total Iron (mg/l)	Total Iron (mg/l) Super Natant	TSS (mg/l)	Coliforms (count per mL)	Coliforms (count per mL)	Coliforms (count per 100mL)
Influent Start										
Influent 1	-	100	68.0	-	0.43	-	7	47	4.7E+04	4.7E+06
Influent 2	-	123	66.0	-	0.42	-	-	49	4.9E+04	4.9E+06
Influent 3	-	-	-	-	-	-	-	48	4.8E+04	4.8E+06
Influent End										
Influent 1	-	117	62.0	-	0.38	-	-	-	-	
Influent 2	-	130	70.0	-	0.39	-	-	-	-	
Influent 3	-	-	-	-	-	-	-	-	-	
Influent Avg	**-**	**118**	**66.5**	**-**	**0.41**	**#DIV/0!**	**7.00**	**48**	**4.80E+04**	**4.80E+06**
Effluent A										
Effluent A1	0.33	140	50.0	0.00	2.20	1.86	8	156	1.6E+03	1.6E+05
Effluent A2	0.28	161	50.0	0.02	2.20	1.86	-	142	1.4E+03	1.4E+05
Effluent A3	-	-	-	-	-	-	-	147	1.5E+03	1.5E+05
Effluent A Avg	**0.30**	**151**	**50.0**	**0.01**	**2.20**	**1.86**	**8.0**	**148**	**1483**	**148333**
Effluent B										
Effluent B1	0.40	155	46.0	U.R.	2.50	1.70	8	156	1.6E+03	1.6E+05
Effluent B2	0.376	159	50.0	0.00	2.70	1.76	-	159	1.6E+03	1.6E+05
Effluent B3	-	-	-	-	-	-	-	166	1.7E+03	1.7E+05
Effluent B Avg	**0.39**	**157**	**48.0**	**0.00**	**2.60**	**1.73**	**8.0**	**160**	**1603**	**160333**
Effluent C										
Effluent C1	0.32	159	49.0	U.R.	1.90	1.64	5	170	1.7E+03	1.7E+05
Effluent C2	0.34	159	43.0	U.R.	1.90	1.60	-	167	1.7E+03	1.7E+05
Effluent C3	-	-	-	-	-	-	-	165	1.7E+03	1.7E+05
Effluent C Avg	**0.33**	**159**	**46.0**	**-**	**1.90**	**1.62**	**5.0**	**167**	**1673**	**167333**
Effluent Avg	**0.34**	**156**	**48.0**	**0.01**	**2.24**	**1.74**	**7.00**	**159**	**1587**	**158667**

VITA

Maria Elena Pulido Guzmán was born in Caracas, Venezuela on July 5, 1977. She graduated from Colegio Los Campitos (High School) in 1994, and went on to receive a Bachelor of Science in Chemical Engineering from Universidad Simón Bolívar (USB), Caracas, Venezuela in October 1999.

Between February 2000 and December of 2001, Maria E. Pulido worked as a Graduated Research Assistant at the University of New Orleans (UNO), New Orleans, Louisiana, pursuing a Masters of Science in Engineering. During 2002 she worked in Valencia, Venezuela for IDOM Engineering, Architecture and Consulting Firm.

In spring 2003, the author started pursing her PhD again at the University of New Orleans (UNO), New Orleans, Louisiana, and also worked as a Graduated Research Assistant, achieving her final academic goal in August 2005. The author graduated with an overall GPA of 4.0. Her research emphasized on electrochemical technologies for wastewater treatment and wastewater disinfection. She is a registered engineering intern in the State of Louisiana.