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A Study of the Treatment of Nitrate-Contaminated Water by Electrodeionization

By

**Norman Meyer
B.Sc.(Eng.)**

**A Thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of Master of Engineering***

**Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario
Canada**

May 10, 2001

***The Master of Engineering program is a joint program with
the University of Ottawa administered by the Ottawa-Carleton
Institute for Civil Engineering**

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**A STUDY OF THE TREATMENT OF NITRATE-CONTAMINATED
WATER BY ELECTRODEIONIZATION**

submitted by

Norman Meyer, B.Sc.(Eng.)

In partial fulfillment of

The requirements for the degree of

Master of Engineering

Dr. Paul Van Geel, P.Eng.
Thesis Co-Supervisor

Dr. Wayne Parker, P.Eng.
Thesis Co-Supervisor
Chair, Department of Civil and Environmental Engineering

Carleton University
Ottawa, Canada
May 11, 2001

Abstract

Nitrate pollution of surface and groundwaters has become a major problem in some agricultural areas. The removal of nitrate from potable waters has received increased attention in recent years as the health effects of nitrate ingestion have come to the forefront. This thesis examines the use of a bench-scale electrodeionization (EDI) unit (155 cm² cross-sectional membrane area), a hybrid electrodialysis and ion exchange system, for the removal of nitrates from potable water sources. The performance parameters of interest were nitrate fluxes (meq/cm²/sec), flux relative to competing anions and energy requirement per equivalence removed (J/meq). From the experimental results it was determined that EDI is nitrate selective at lower operating voltages (current densities under 2.0 mA/cm²). Also, the fluxes and energy requirement result in treatment costs (0.40 \$/m³), that are close to competing technologies such as ion exchange (0.28 – 0.32 \$/m³).

Acknowledgements

The author wishes to thank his supervisors, Dr. W J. Parker and Dr. P. J. Van Geel, for their help, guidance and accessibility during this research. The Civil & Environmental Engineering Department at Carleton is privileged to have such high-quality and knowledgeable faculty, hopefully for many years to come.

The author would like to thank Mr. Mahabala Adiga for bringing the possibility of this project to the attention of Professors Parker and Van Geel. The author would also like to thank ESTAC for providing the funding for this research.

The author would like to thank his immediate family. Without their love and support this thesis would not have been possible. I count myself lucky to have such a wonderful family. Mom, Dad, Robert, Sue and André; I am in your debt. Thank you.

The author would like to thank his friend Anne-Marie for all the advise over coffee and the good cheer she brings with her wherever she goes.

Lastly, the author would like to thank the Trant family. Gerry & Sarah, for always telling it like it is (and your love) I can not thank you enough. Caroline, it is thanks to you I am here writing the acknowledgements. Maybe that says it all.

Table of Contents

Abstract.....	iii
Acknowledgements.....	iv
List of Tables.....	vii
List of Figures.....	viii
Nomenclature.....	xii
1.0 Introduction.....	1
2.0 Electrodeionization.....	6
3.0 Methodology and Materials.....	31
4.0 Ion Exchange Experiments.....	43
5.0 Once-through Single Species Experiments.....	50
6.0 Recycle Experiments.....	69
7.0 Once-through Multi-Species Experiments.....	83
8.0 Complex Water Experiments.....	109
9.0 Alternative Operating Modes.....	128
10.0 Competing Technologies and Cost Comparison.....	142
11.0 Conclusions and Recommendations.....	152
References.....	155

Appendix A: Ion Exchange Experiments.....	160
Appendix B: Once-through Single Species Experiments.....	162
Appendix C: Recycle Experiments.....	212
Appendix D: Once-through Multi-Species Experiments.....	241
Appendix E: Once-through Complex Water Experiments.....	293
Appendix F: Cycling Experiments.....	321
Appendix G: Cost Analysis.....	338

List of Tables

<u>Title</u>	page
Table 1.1 Limits for Nitrate in Drinking Water.....	2
Table 1.2 Population Exposed to Nitrate in Community Water System wells by Distribution Percentile.....	3
Table 1.3 Estimates of Population Exposed to Nitrate by Concentration for Community Water System Wells.....	4
Table 2.1 Electrodeionization results of Montpellier drinking water.....	26
Table 3.1 Chemicals used for the species tested.....	37
Table 4.1. Resin properties.....	44
Table 6.1 Energy consumption at different voltages and spacing for recycle and once through modes of operation.....	82
Table 8.1 Analysis of complex process streams prior to dosing.....	110
Table 8.2 Comparison of the effect of voltage on nitrate and chloride flux.....	122
Table 9.1 Comparison of nitrate and chloride fluxes in regular and power cycling mode.....	133
Table 9.2 Removal rates in Flow and Power Alternating Mode.....	139
Table 10.1 Ion-exchange costs for nitrate contaminated groundwater.....	145
Table 10.2 Cost of treatment for complex waters (\$/m ³).....	148

List of Figures

<u>Title</u>	<u>page</u>
Figure 2.1 Schematic of electrodeionization internal structure.....	7
Figure 2.2 Representation of a gel-type strong acid cation exchange.....	10
Figure 2.3 Ion penetration vs. equivalent fraction.....	22
Figure 2.4 Ionic fluxes with non-selective membrane	28
Figure 2.5 Ionic fluxes with nitrate selective membrane.....	29
Figure 3.1 Schematic of EDI System.....	32
Figure 3.2 Flow chart of experimental plan.....	37
Figure 4.1 Comparison of sorption curves for both resins.....	47
Figure 5.1 Average nitrate concentrations vs time at different voltages.....	52
Figure 5.2 Effect of applied voltage on flux at different flow rates.....	53
Figure 5.3 Impact of applied voltage on energy consumption.....	54
Figure 5.4 Example of hindered performance at high process flow rate.....	57
Figure 5.5 Impact of resin on flux and energy consumption.....	60
Figure 5.6 Impact of membrane spacing on nitrate flux.....	63
Figure 5.7 Impact of nitrate concentration on flux and energy consumption.....	64
Figure 5.8 Relative fluxes at different concentrations versus voltage.....	65
Figure 5.9 Relative nitrate energy consumption at various voltages versus process water concentration.....	66
Figure 5.10 Effect of the number of membrane pairs on nitrate flux.....	67

Figure 6.1 Nitrate concentration and current at 3.3 V per membrane pair.....	71
Figure 6.2 Nitrate fluxes and energy consumption versus time.....	73
Figure 6.3 Comparison of fluxes calculated with Equations 6.1 & 6.2.....	74
Figure 6.4 Nitrate concentration versus time at different voltages.....	75
Figure 6.5 Nitrate flux at different voltages versus concentration.....	76
Figure 6.6 Energy consumption versus concentration at different voltages.....	77
Figure 6.7 Nitrate flux versus process concentration.....	78
Figure 6.8 Comparison of nitrate fluxes at different concentrations.....	80
Figure 6.9 Comparison of nitrate fluxes at different voltages	82
Figure 7.1 Nitrate & Chloride concentration and the current	86
Figure 7.2 Flux of nitrate vs chloride (2.0 V/pair).....	87
Figure 7.3. Impact of voltage on nitrate & chloride flux.....	88
Figure 7.4 Comparison of total flux between single and multi-species experiments.....	90
Figure 7.5 Effect of voltage on energy consumption.....	91
Figure 7.6 Effect of Resin Type on Multi-Species Fluxes.....	92
Figure 7.7 The effect of resin on total flux and energy consumption.....	94
Figure 7.8 Effect of flow rate on multi-species removal rates	95
Figure 7.9 Effect of flow rate on energy consumption	95
Figure 7.10 Effect of concentration on flux.....	96
Figure 7.11 Comparison of energy consumption for single and multi-species experiments	97

Figure 7.12 Total anion flux versus voltage at varying spacing.....	99
Figure 7.13 Fluxes of various species.....	100
Figure 7.14 Fluxes of chloride and sulphate at different voltages.....	102
Figure 7.15 Nitrate and chloride fluxes for extended duration run.....	104
Figure 7.16 Comparison of fluxes for short and extended duration experiments.....	105
Figure 7.17 Comparison of energy requirement for short and extended duration experiments.....	107
Figure 8.1 Effluent concentrations of nitrate, chloride and sodium and current (Ottawa-Carleton tap water).....	111
Figure 8.2 Fluxes and energy consumption for Ottawa-Carleton water (2.0 V/pair).....	112
Figure 8.3 Fluxes of major charged species for Ottawa-Carleton water (2.0 V/pair).....	113
Figure 8.4 Comparison of nitrate and chloride fluxes for synthetic and complex process streams.....	114
Figure 8.5 Nitrate and chloride fluxes for both complex feed streams.....	115
Figure 8.6 Fluxes of major charged species for Ottawa-Carleton water.....	116
Figure 8.7 Fluxes of major charged species for Manotick water.....	117
Figure 8.8 Energy consumption for various process streams.....	118
Figure 8.9 Comparison of nitrate and chloride fluxes for complex and synthetic feed streams.....	119
Figure 8.10 Impact of resin on complex fluxes of nitrate and chloride.....	120
Figure 8.11 The effect of complex stream on energy consumption.....	121

Figure 8.12 The effect of voltage on energy consumption for real and synthetic feed streams.....	123
Figure 8.13 Effect of flow on chloride removal relative to nitrate removal...	124
Figure 8.14 Fluxes of nitrate and chloride for Ottawa-Carleton water.....	125
Figure 9.1 Fluxes of nitrate and chloride vs time in 5 minute cycling mode.....	131
Figure 9.2 Fluxes of nitrate and chloride vs time for short cycling period experiments.....	132
Figure 9.3 Relative removal of nitrate and chloride for regular and continuous flow/power alternating operation.....	134
Figure 9.4 Comparison of energy efficiency for regular and 1 minute cycling experiments	135
Figure 9.5 Comparison of nitrate and chloride fluxes for regular and flow alternating -power alternating cycling experiments.....	138
Figure 9.6 Effect of voltage increase on nitrate and chloride fluxes I in power and flow alternating mode.....	140
Figure 9.7 Comparison of energy consumption at different voltages between regular and power & flow alternating modes.....	141
Figure 10.1 Costs of EDI unit operation on complex feed at 3.3 volts per membrane pair.....	150

Nomenclature

U	volts
NO_3^-	nitrate
Cl^-	chloride
SO_4^{2-}	sulphate
HCO_3^-	bicarbonate
Na^+	sodium
Mg^{2+}	magnesium
Ca^{2+}	calcium
ISA	ionic strength adjuster
meq/L	milliequivalents per litre
TDS	total dissolved solids

1.0 INTRODUCTION

Nitrate pollution of surface and groundwaters has become a major problem in some agricultural areas. The removal of nitrate from potable waters has received increased attention in recent years as the health effects of nitrate have come to the forefront. Although the problems related to nitrate consumption are frequently referred to as nitrate poisoning, the toxicity is primarily due to nitrite (Dimotis and McGarrey, 1995). Nitrate consumed either in food or drinking water is reduced to nitrite in the gut by bacteria in infants under 6 months of age. This in turn impairs oxygen transport by reacting with hemoglobin to produce methemoglobin. This so called "blue baby" disease was originally observed primarily in rural areas where the main causes seem to have been farm runoff and nitrogen fertilizer usage (Bouchard et al., 1992).

The potential sources of water contamination by nitrates include the effluent from wastewater treatment plants and septic systems, landfills, agricultural fertilizers and others (Canter, 1997). The World Health Organization recommendation on the maximum admissible concentration in drinking water is 10 mg NO_3^- -N/L, which corresponds to 44 mg NO_3^- /L. Health and Welfare Canada (Guidelines 1993) has established the same maximum acceptable concentration (MAC). Refer to Table 1.1 for a full list of nitrate limits in drinking water.

Table 1.1 Limits for Nitrate in Drinking Water

Organization	Year	Limit Specification	mg/L of NO ₃ ⁻ -N
WHO European Standards	1970	Recommended	11.3
		Acceptable	11.3-22.6
		Not Recommended	>22.6
WHO International Standards	1971	General Population	
		Acceptable	11.3
		Borderline	11.3-22.6
		Unacceptable	>22.6
		Infants < 6 months	
U.S. EPA	1977	Unacceptable	11.3
		Maximum contaminant level	10.2
Health and Welfare Canada	1978	Maximum acceptable concentration	10.2
EEC (Directive on quality of surface water intended for abstraction of drinking water)	1977	Imperative limit	11.3
		Guide level	5.6
EEC (Directive on quality of water for human consumption)	1980	Maximum admissible concentration	11.3
		Guide level	5.6
WHO guidelines for drinking water quality	1984	Guideline value	10.0

(Source: World Health Organization, *Health Hazards from Nitrates in Drinking Water*, 1985)

The U.S. EPA recently completed a 5 year National survey of Pesticides and Nitrates in drinking water wells. A sample of 7083 community water system (CWS) wells was selected randomly from 51,000 CWSs. Tables 1.2 and 1.3 present estimates of the number of people exposed to nitrate in CWS wells. The following comments are of importance.

1. Approximately 3 million people drink water from CWS wells that contain nitrate at a concentration of at least 10 mg/L, the MCL for nitrate. Of the people exposed to nitrate above the level, approximately 43,500 are expected to be infants at possible risk of developing methemoglobinemia, particularly if the water is also contaminated with bacteria.
2. Approximately 85 million people drink water from CWS wells that contain nitrate.
3. The median nitrate concentration to which people in the United States are exposed to is approximately 0.63 mg/L.

Table 1.2 Population Exposed to Nitrate in Community Water System wells by Distribution Percentile

Percentile	People Exposed	Concentration (mg/L)	<u>95% Confidence Interval</u>	
			Lower Bound (mg/L)	Upper Bound (mg/L)
Median	68,000,000	0.63	0.45	0.95
95	6,800,000	6.52	5.34	7.70
99	1,360,000	14.2	10.6	17.7

(Source: U.S. EPA, "National Survey of Pesticides in Drinking Water Wells", 1992)

Table 1.3 Estimates of Population Exposed to Nitrate by Concentration for Community Water System Wells

Concentration (mg/L)	People Exposed	<u>95% Confidence Interval</u>	
		Lower Bound	Upper Bound
All concentrations >0	85,300,000	78,100,000	98,900,000
≥10	2,980,000	1,600,000	4,260,000

(Source: U.S. EPA, "National Survey of Pesticides in Drinking Water Wells", 1992)

Currently the treatment of nitrate contaminated water is accomplished by either biological, reverse osmosis (RO), electrodialysis or ion exchange technologies. Biological processes are only suitable for large scale applications due to the higher maintenance associated with this type of treatment. Several types of small commercial RO units and ion exchange cartridge systems exist for denitrification however the strict pretreatment requirement for RO and frequent replacement of ion exchange cartridges or regeneration of the ion exchange columns makes them costly.

This thesis focuses on the use of an emerging technology known as electrodeionization (EDI) which combines electrodialysis (ED) with ion exchange. The use of EDI has been relatively restricted to the production of high purity water for the semi-conductor or pharmaceutical industries (Ganzi et al., 1997). Few applications in attaining drinking water specifications have been examined.

The goals of this investigation, through the use of a bench-scale EDI unit, were to evaluate the impact of process design and operating parameters

on the removal of nitrate from selected water streams. Responses that were of particular interest included the flux of nitrate from the water stream, the energy consumption and the selectivity of nitrate removal relative to other ions. A range of different experiments were performed in order to identify possible conditions of greater selectivity or less costly operation.

2.0 ELECTRODEIONIZATION

Electrodeionization (EDI) is a process that removes ionizable species from liquids using ion-selective membranes, electrically active media and an electrical potential to enhance ion transport, as seen in Figure 2.1. The electrically active media in EDI devices may function to alternately collect and discharge ionizable species, or to facilitate the transport of ions continuously by ionic or electronic substitution mechanisms. In addition the presence of the resin reduces the electrical resistance for relatively clean water streams that have low ionic strength (Dejean et al., 1997).

Figure 2.1 depicts four membrane pairs or packed cells. Ten membranes in total are contained in this configuration because the first packed cell requires four membranes. Any subsequent packed cells require the addition of only two membranes (a membrane pair).

EDI stems from a branch of science known as separation science and more specifically membrane science. Electrodeionization is distinguished from electrodialysis (ED) solely by the presence of the media within the cell compartments. In this sense it is a hybrid of an ED system. While EDI is the more common description given to the specific process, the term is not universally used. Other nomenclature includes packed-bed or filled cell ED.

In order to comprehend the processes involved in the operation and development of EDI it is necessary to first understand the processes involved in ion exchange and electrodialysis.

Figure 2.1 Schematic of electrodeionization internal structure

2.1 Ion Exchange Resins

Ion exchange resins are insoluble polymers which have active ionogenic groups covalently bonded to the polymer. The fixed groups are either permanently ionized so that they always possess a formal charge, or are capable of ionization or acceptance of protons to form the charged site. The resin interacts with the mobile ions from an external solution. Ions of opposite charge to that on the resin, and which are exchanged by the resin, are known as counter ions. Ions of the same charge as that of the exchange sites are known as co-ions. The polymeric network of the resin is known as the matrix.

Ion exchange differs from sorption processes in that sorption involves a net or bulk movement of solute onto a solid surface, ion exchange involves an exchange of ions reaching an equilibrium state with no net change in charge occurring. This is known as conserving electroneutrality.

Ion exchange resins capable of exchanging cations are referred to as cation exchangers, and resins capable of exchanging anions are referred to as anion exchangers. Certain resins are capable of exchanging both cations and anions and are known as amphoteric ion exchangers.

An ion exchange resin can be considered as a concentrated solution of anions and cations in its own phase, in which one of the ionic species is bound to an insoluble polymeric matrix, and the other is mobile and capable of exchanging with ions of its type in the external solution (Bolto et al., 1986). The composition of the two main types of ion exchangers can be summarized as follows:

Type	Fixed charges	Counter-ions	Co-ions
Cation exchanger	(-)	Cations (+)	Anions (-)
Anion exchanger	(+)	Anions (-)	Cations(+)

The total ion exchange capacity is the concentration of fixed charges in the resin, and is defined by the number of equivalents of fixed charges per liter of wet resin. It describes the maximum amount of ions that have been exchanged when all the fixed charges are balanced by counter-ions.

The majority of organic resins have a matrix of an irregular, three-dimensional network of macromolecular hydrocarbon chains. In most cases this consists of a copolymer of styrene and divinylbenzene (DVB), with the latter providing the cross-linking (Hell et al., 1995).

The properties of the resin are determined, above all else, by the ion-exchange groups present on the matrix. In general, these may be divided into three groups: cation exchangers (strong acid or weak acid groups); anion exchangers (strong base or weak base groups); specific ion exchangers (selective chelating groups). However, the chemical activity of the exchange sites can be modified by the nature of the matrix (Bolto et al., 1986).

2.2 Physical Structure

2.2.1 Gel Resins

The first organic exchangers that were developed were gel resins. Gel resins have an essentially homogeneous distribution of water throughout the resin matrix, as depicted in Figure 2.2. The resin swells under some exchange conditions and the imbibed water causes an increase in the distance between the polymeric chains.

Figure 2.2. Representation of a gel-type strong acid cation exchanger (Bolto et al. 1987)

The tendency to swell depends on the degree of cross-linking, which for polystyrene resins can vary between 2 and 20% DVB. High degrees of cross-linking make the resin less susceptible to swelling, but more brittle in nature. It is not possible to achieve an even distribution of cross-links throughout the resin matrix. The cross-linking is less uniform when the resin bead is larger, and this inhomogeneity causes some problems in practical use of the resin. For example, some regions within a resin bead have a different swelling ability than other regions resulting in the build up of internal pressure and fracturing of the bead (Bolto et al., 1987). A region of denser cross-linking can also hinder the release of large organic molecules from the bead during regeneration of the exhausted resin.

In general, when ions diffuse through a resin bead their progress is retarded by the matrix polymer. This limitation is less when there are fewer cross-links and the beads are more swollen. However, resins having a low degree of cross-linking are not physically strong and are more sensitive to an oxidizing environment (Wachinski and Etzel, 1997). More highly cross-linked resins are more stable in every respect however the tighter network in the matrix provides a greater resistance to diffusion and hence results in lower rates of ion exchange.

2.2.2 Macroporous Resins

As a way around the cross-linking dilemma, resins having a macroporous structure were developed. By appropriate synthesis methods based on having a solvent present during the polymerization so that the growing polymer chains are precipitated in the form of microspheres, macropores are formed between the precipitated microspheres (Hell et al., 1995). The resulting resin bead is now heterogeneous and consists of two phases: homogeneous regions containing the matrix and water and water-filled voids between these regions.

Ions entering the resin can now do so via the large pores and the amount of matrix they must diffuse through is much less than a gel-type resin. A more highly cross-linked matrix is employed making the bead mechanically stronger and less susceptible to penetration by large organic molecules that cause fouling problems (Sengupta, 1995).

As the resin contains a second discrete phase in the form of the voids, the amount of matrix and hence the number of exchange sites is lower on a volume basis. Also, the quantity of chemicals required for regeneration is increased.

2.3 Capacity

On a quantitative basis, the capability of a resin to exchange ions is defined as its exchange capacity. Total exchange capacity is defined as the number of ionic sites per unit weight or volume of resin. Because it is impractical to use all available sites during exchange, the net number of sites used in a specific volume of resin in a given cycle is defined as the operating capacity. From a design point of view resin capacity is probably the most important property of an ion exchange resin (Wachinski, 1997). The exchange capacity of a resin comes from the substituted functional groups in the resin matrix.

It is important to distinguish between the total capacity of a resin and its operating capacity. Total capacity is a measure of the total number of counter ions that can be exchanged. For strong-acid cation exchange resins, one sulfonate group, on average, can be attached to each benzene ring in the matrix. Hence the dry weight capacity of the resin, expressed in milliequivalents per gram of dry resin (meq/g) can be determined. The dry weight capacity is simply a measure of the extent of functional group substitution in the exchanger and is therefore a constant for each specific resin. Typically for sulfonated styrene-DVB resins, the dry weight capacity is 5.0 +/- 0.5 meq/g (Anderson, 1979). For strong-base anion exchangers more than one functional group can be attached at each benzene ring. Hence the dry weight capacity is more variable than with strong-acid resins and can range from 2 to 5 meq/g.

Operating capacity is the exchange capacity of the resin operated in a columnar mode under defined operating conditions and a predetermined breakthrough level. Breakthrough occurs when the predetermined concentration of a target ion or ions occurs in the effluent of an ion exchange system.

While mention of resin use in an ion exchange column may seem to have little direct relevance to its use in an EDI unit, this is not the case. It is necessary to be aware of exchange capacity in order to determine the point of resin saturation. This is especially true with a “fresh” resin but also at any other point in time where the feed stream changes its concentration of ionic species considerably because a new equilibrium will be established with counter ions either being sorbed or desorbed from the resin beads depending on whether or not the feed stream increased or decreased in concentration. This is important knowledge when attempting to determine what portion of the ion removal is due to the electric potential and what portion is due to exchange with the fresh resin.

2.4 Electrodialysis

It was in 1940 that Meyer and Strauss proposed what is basically the modern ED unit with a series of alternating cation and anion exchange membranes with a feed stream and concentrate stream circulating through the unit. These two streams were unable to mix with the proper sequencing of the membranes (Kesore et al., 1997). Development ultimately led to an increase in

the number of compartments contained within the ED stack to the point where hundreds of compartments are now arranged in series.

The realization of the principle of alternating cation permeable and anion permeable membranes in multi-compartment electrodialysis became possible after the manufacture of selective membranes from ion exchangers. Soon after this the basic principle of the electrochemistry of ion exchange membranes and the basic directions of electrodialysis with ion exchange membranes were developed and refined. They are; purification, desalination of weak electrolytes with low dissociation constants, and of non-electrolytes; concentration of solutions; synthesis of acids and bases from their salts; reactions of double chemical conversion; methods for the separation of ions according to their mobilities, magnitude and sign of charge and to their differences in abilities to form complexes (Wilson, 1960).

2.5 Theory of EDI

Semi-permeable ion-exchange membranes selectively restrict the free flow of ions. Anions can diffuse through an anion membrane towards the anode and vice versa for the cations. The result is that the compartments bounded by the anion membrane facing the anode and the cation membrane facing the cathode become depleted of their ionic constituents. The flow through these compartments is thus known as the product or dilute stream. Conversely, the compartments bounded by the anion membranes facing the cathode and the

cation membranes facing the anode become more ionically concentrated. This stream is known as the concentrate stream. (See Figure 2.1).

Continuous electrodeionization devices remove ionizable constituents from water using ion-exchange membranes, ion exchange resins, and a DC electrical potential.

Water itself is an ionizable compound. At 25 degrees C, pure water is in equilibrium with 10^{-7} molar hydrogen and hydroxide ions. This equates to about 0.1 parts per billion (ppb) and 1.7 ppb respectively. These are concentrations that are higher than the specified limits for many of the water contaminants of concern for use in reagent preparation, preparation of pharmaceuticals, and rinsing of microelectronic components (Ganzi, 1997).

Ion exchange membranes are essentially ion exchange resins in sheet form. The two primary types are comprised of anion or cation exchange resins. Ion exchange membranes are permeable to counter-ions, impermeable to co-ions, and relatively impermeable to water. The property of water impermeability allows ion-exchange membranes to be used as a boundary of a liquid flow conduit.

Ion exchange resins are most commonly available as cross-linked polymeric beads. They are synthesized with a porosity that allows for the absorption of water. For water purification, the active functional groups of organic anion resins are most commonly amine based, and the active functional groups of cation resins are most commonly sulfonate based. However, a wide variety of functional chemistries are available (Ganzi, 1997).

The functional groups create regions of fixed charge that are associated with mobile counter ions of essentially equal charge in the water absorbed by the resin. For this reason a highly conductive condition exists within a resin bead. In low conductivity solutions resin beads are orders of magnitude more conductive than the solution in which they are immersed. This explains why filling the compartments of an ED unit and transforming it into an EDI unit, through the inclusion of resin, allows for greater removal rates and higher fluxes when all other operating parameters and variables are equal.

In a simplified representation, the actual transport of a given anion from the desalination compartment may be considered as the sum of the migrations of the anion from the bulk of the feed into the anion exchange resin; then from it to the anion exchange membrane surface in the direction of the anode; and finally through the membrane to the concentrate compartment (Egozy et al., 1988). Heteropolar contacts of ion conducting spacers play an important role in the transfer of ions in the desalinating compartment (Kesore et al., 1997). Such contacts of the individual ion exchange resin granules with the cation exchange membrane generate hydroxyl ions due to irreversible water dissociation occurring at these points. The hydroxyl anions regenerate the anion exchange granules, thus making way for the migration of nitrate and other anions. The hydroxyl and hydrogen ions liberated after the ion exchange recombine to form water molecules. As such, the heteropolar contacts act like a regenerator for the ion exchange material inside the desalination compartment at low current densities (Giuffrida et al. 1987).

Electrical conductivities of ions in ion exchange materials are smaller than those in solution because of the higher viscosity of the amorphous solid phases (Kesore et al., 1997). Nevertheless, the instantaneous regeneration process of the anion exchange resin in the desalination compartment brings about an effective transport medium for the directed migration of anions to the anion exchange membrane surface. The counter-ions are forced to move out of the resin. Because of the different affinities possessed by the ion exchange resin to the different anions, a differentiation in their transport is experienced (Ganzi, 1997).

2.5.1 Electrolysis of Water

The splitting of water into hydrogen and hydroxide ions under an applied voltage (electromotive force) has been observed since the 18th century. Under the conditions encountered in a traditional electrolytic cell, where hydrogen and hydroxide ions are allowed to contact the electrodes, hydrogen and oxygen gas are produced at the cathode and anode by the following half-reactions:

The splitting of water is facilitated by increased temperature and the presence of other ions (Ganzi, 1997).

In the case of EDI hydrogen gas is produced at the cathode but no appreciable production of oxygen occurs at the anode (Giuffrida et al., 1987). This is due to the sequencing of the membranes and the presence of NaCl in the anode/cathode wash compartments ($\text{Cl}_2(\text{g})$ is produced at the anode rather than $\text{O}_2(\text{g})$). Also, the hydroxide serves as a catalyst to alternatively regenerate the resin when displacing a counter-ion and recombining with hydrogen when in solution. At some applied voltage, specific to a particular EDI assembly, (as hypothesized by Ganzi, (1997)), the rate of water splitting exceeds the capacity of the resin to use the liberated hydroxide ions and a portion of the current is carried by the free hydroxide and hydrogen ions. This results in higher energy consumption per equivalence removal of the desired species.

2.6 ED & Nitrate Selectivity

Electrodialysis, in its traditional version, is a general method for the overall demineralization of the feed. Nitrate removal is a side effect of the primary desalination process. As such ED becomes more feasible and practical as a desalination technique if the water to be treated has several contaminants of high salinity. But, demineralized water is not suitable for drinking. Therefore, attention must be paid to the fact that the other ions present in ground and surface water are not removed during the production of drinking water, as they are needed for the normal physiological functioning of the human body. Also,

sulphate and chloride ions compete permanently against nitrate ions in the elimination process, reducing the efficiency of the method (Hell et al., 1995) As a result, there is a need for selective removal of nitrates from drinking water, without altering the main parameters for potability.

Studies on electrodialysis as a method for the elimination of nitrate from drinking water have been carried out by several researchers such as Miguel and Oldani (1988) and Kesore et al. (1994). In order to render ED into a selective nitrate removal process, Eyal and Kedem (1988) attempted to enhance selectivity in the elimination of nitrates during electrodialysis by the introduction of polyfunctional (tertiary and quaternary ammonium groups) in an anion exchange membrane. An enhanced nitrate eliminating process has been reported for their membranes.

In an analogous work by Indushekar et al. (1991), a nitrate specific anion exchange membrane was prepared from chloromethylated polysulphone by partial amination with a secondary amine followed by a tertiary amine for the completion. While effective in terms of nitrate selectivity the primary limitation of both the above-mentioned methods was that they only considered binary nitrate/chloride solutions.

Oldani et al. (1992) investigated the same problem with an aim to optimize ED for nitrate selectivity. They carried out a relatively large comparative study on eight different commercially available anion exchange membranes and two experimental ones developed by Kedem at the Weizman Institute of Science in Rehovot, Israel for the electrodialytic elimination of nitrates from synthetic

drinking water at low current densities. The best performances were found for the ACS anion exchange membrane of Tokuyama Soda. However, for low sulfate removal the membrane showed greater selectivity for monovalent anions. This implies a high chloride transport which is undesirable. Miguel and Oldani (1988) reported on a successful electrodialysis process for the removal of nitrates from drinking water, commercially known as NITREM. Other attempts in the same field are described by Lutin et al. (1982) and Hell et al. (1995) but the membranes reported are selective for monovalent anions over multivalent ions.

This increased selectivity for monovalent ions can be seen in Figure 2.3. The horizontal axis represents the monovalent fraction of ions in the raw water stream as a percentage of total ions. The vertical axis represents the percentage of the total ions passing through the membrane that are monovalent.

Figure 2. 3 Ion penetration vs. equivalent fraction. (Hell et al., 1998)

Figure 2.3 illustrates that the fraction of monovalent ions present in the concentrate stream for the monovalent selective resin is greater than the fraction present in the feed stream, indicating that the resin is selective to monovalent ions. The opposite can be said for the standard membrane, in that it is selective to divalent or trivalent ions.

The result of this increased selectivity to monovalent anions is that nitrate removal is increased simply due to its being a monovalent anion. Also, in the case of Hell et al., (1998) excellent nitrate selectivity was found relative to other monovalent anions for some commercially available membranes. These results were obtained by testing several different membranes and determining effluent concentrations.

2.8 Fouling

Fouling of either the internal resin structure or membrane pores is of concern due to its effect on performance (flux and energy consumption).

Principle areas of concern are due to organics, particulates, and precipitate either being present in the process stream or formed in the EDI chambers themselves.

2.8.1 Organic

Organic fouling decreases EDI performance in two ways. Firstly, the large organic molecules become strongly if not irreversibly sorbed to the resin as its functional sites attach themselves to a corresponding number of sites of opposite functionality on the resin (Bolto et al., 1987). Second, the large organic molecules pose a problem to the membranes as they will either attach to sites on the membranes and /or "lodge" themselves within the membrane matrix thus reducing the area of the membrane available for exchange of the desired ionic species (Davis, 1979). Therefore if organic species are indiscriminately allowed to enter an EDI unit poorer performance will result

2.8.2 Particulates

Particulate matter, whether organic or inorganic, can cause fouling of and thus decreased performance of an EDI unit (Ganzi, 1997). It is generally recommended by most researchers that some sort of pretreatment be employed prior to treatment in an electrodeionization unit. While there is rarely specific mention of concentrations or size of solids that pose the greatest threat to

performance, Hemon et al. (1994) report good results in the use of an reverse osmosis/EDI system in the production of high purity water at a nuclear power plant in Port Gibson, Missouri.

2.8.3 Precipitates

Precipitates can also cause severe problems in the operation of an EDI unit. Precipitates can block void spaces both within the resin bed and at the liquid membrane interface, adversely affecting performance (Kesore et al., 1997). Typical species of interest are metal hydroxides and calcium sulphate.

In EDI operation, as with ED, the more usual occurrence of precipitation occurs in the concentrate stream. This rather obvious occurrence stems from the ever increasing concentration of all ionic species with the continued operation of the unit. It is therefore necessary to determine the rate of concentrate stream dilution (replacement of a portion of the stream with “clean” concentrate, identical to the concentrate present prior to operation) that is required in order to maintain the concentration of problematic species below their solubility limits. This can be accomplished with either the feed stream or the clean product stream depending on the feed stream composition and the compounds causing the precipitation problem (Egozy and Dick, 1988). This also, eventually, necessitates the disposal of the highly concentrated waste that was the concentrate stream.

2.9 Case Studies

A thorough literature review found some research had been performed on EDI for the purposes of achieving selectivity for a certain species or increasing overall flux and/or reduction of energy consumption. This research primarily involved altering the packing or resin within the units chambers and/or altering the flow regime. The following is a brief summation of their results.

2.9.1 Resin-filled Chamber

Salem et al. (1994) operated a pilot EDI unit in order to determine both nitrate removal and overall ionic flux. A synthetic nitrate stream with a concentration of 3×10^{-3} M (186 ppm) was used. They utilized a general purpose membrane (ADS Morgane) as the anion exchange membrane. The process was also applied to Montpellier drinking water, with sodium nitrate added, so as to simulate a nitrate polluted drinking water containing other ions generally present in natural waters. The nitrate polluted water was treated by EDI in batch mode with a current density of 1.5 mA/cm^2 . The nitrate elimination ratio that was eventually achieved with continued circulation of the feed stream was about 99%. Similar results were obtained for other ions as detailed in Table 2.1.

Table 2.1 Electrodeionization results of Montpellier drinking water.

Time (min)	U (volts)	NO ₃ ⁻ (ppm)	Cl ⁻ (ppm)	SO ₄ ²⁻ (ppm)	HCO ₃ ⁻ (ppm)	Na ⁺ (ppm)	Mg ²⁺ (ppm)	Ca ²⁺ (ppm)
0	9.0	82.9	62.0	32.5	366	45	10.3	106.4
30	14.5	19.6	8.38	1.01	116	16	2.1	14.2
60	24.5	2.57	2.08	0.285	48	3.7	-	1.8
90	24.5	1.41	1.16	0.241	25	1.8	-	1.6
120	24.5	1.03	0.826	0.239	14	0.8	-	1.6
150	24.5	1.02	0.820	0.230	7.3	0.9	-	1.6

Other data confirmed that nitrate removal was greater when the unit was operated as an EDI unit relative to when it was operated as an ED unit.

Depending on the operating conditions the improvement was about 30-40% at the same applied potential.

Salem et al. conclude that electrodeionization has a faster extraction rate than electrodialysis and that EDI is a proven technology for the production of high purity water. They also suggest that the process efficiency for nitrate removal can be improved with the use of an anion exchange membrane with high nitrate selectivity. The authors do not, however, supply any data with such a membrane in use to support their supposition.

2.9.2 Reacted Spacer

Kesore et al. (1997) report the use of ion conducting inter-membrane spacers. The spacers were made up of fine strips of cation exchange membrane and twisted into a net like material. This “net” was then cut to fit the desalting compartment of the ED unit. Slots in the net were then filled with the nitrate selective anion exchange resin Wofatait SN35L (Bitterfield AG, Germany), a macroporous resin with triethylammonium as a functional group. It had a total exchange capacity of not less than 1.0 meq/cm^3 (soaked), humidity of 40-50% and a granular size of 0.2-0.3 mm. experiments.

Electrodialysis of identical feed solutions was carried out under the same conditions with an inert spacer made from perforated PVC to evaluate the contribution of the ion conducting spacer. The reason given for not operating the unit as a simple ED, in order to judge the effectiveness of the inter-membrane spacer, was that it is known that any type of “filling” promotes turbulence and therefore improves mixing of the influent (Vassilyeva, 1991). This in turn results in increased removal of the ionic species.

The feed solution was a synthetic drinking water containing the potassium salts of nitrate, sulphate, chloride and bicarbonate anions. The results indicated that preferential nitrate removal was found when using the nitrate selective spacer, specifically at lower current densities. At 0.25 mA/cm^2 nitrate accounts for approximately two thirds of the total flux of all the species. At current densities above 2.0 mA/cm^2 the fluxes of the three species show little if any difference (See Fig 2.4 and 2.5). Interestingly, all the monovalent species

experienced higher fluxes for the nitrate-selective spacer over the inert spacer. However, the conditions under which nitrate experienced its highest fluxes relative to the other species was at lower current densities. Thus, the authors concluded that if one wishes to operate in a more nitrate selective zone the unit should be operated at low current densities and therefore at low power.

Figure 2.4. Ionic fluxes with non-selective membrane (Kesore et al., 1997).

Figure 2.5. Ionic fluxes with nitrate selective membrane (Kesore et al., 1997)

2.10 Conclusions

The bulk of EDI research remains in ultrapure water production. Typically these investigations revolve around how to further reduce power requirements or increase flux at low ionic strength feed streams.

Electrodeionization as a means of accomplishing selective removal of a given species has been performed but sparingly. The same statement may be made concerning treating water to potable standards with EDI. As a result no research was found concerning EDI optimization for these purposes. Similarly

no cost analysis or comparison between ion exchange or biological denitrification were found in the literature.

3. METHODOLOGY & MATERIALS

3.1 Apparatus

A bench scale electrodeionization unit with an active cross-sectional area of 155 cm² (17.2 cm x 9.0 cm), constructed by Mr. Mahabala Adiga, formed the basis of the experimental investigations. Low flow pumps (Barnant Company, Barrington, Illinois) were used to circulate the various streams. The power source was a Hewlett-Packard Model 6261A power supply capable of supplying 500 mA of direct current at up to 30 volts. Figure 3.1 presents a simple schematic of the system. The anode was composed of a platinum coated material and the cathode was made of stainless steel. The apparatus was operated in both once-through and continuous recycle regimes by diverting the product stream leaving the unit to the feed reservoir in the latter case.

Three commercially available ion-exchange resins (2 nitrate selective, 1 general anionic) were used within the unit. The anion and cation exchange membranes (MA-3475 and MC-3470, respectively) were manufactured by Sybron Chemicals Inc., Birmingham, New Jersey. The initial concentrate and electrode rinse streams consisted of 1200 mg/L NaCl solutions. Feed streams for all experiments, except for the complex waters, consisted of distilled water spiked with various chemicals in order to introduce the desired ionic species to the system.

Figure 3.1 Schematic of EDI system

3.2 Analysis

Concentrations of the relevant anions and cations were measured using Orion ion selective electrodes where possible (See Table 3.1). These species were NO_3^- , Cl^- , Na^+ and Ca^{2+} . Ion chromatography and inductively coupled plasma were employed to analyze SO_4^{2-} and Al^{3+} , respectively. These samples were analyzed by a commercial laboratory. Prepared samples of known concentration were measured with the ion selective electrodes to ensure the validity of the results. A probe was used to measure pH, and two multimeters were used to measure current and voltage.

Standards for each of the species of interest were prepared by adding a measured mass of chemical to a measured volume of water. In this manner 1000, 100 and 10 ppm standards were prepared for nitrate, chloride, calcium and sodium (the species for which electrodes were available). These standards were kept sealed in 1 litre plastic containers.

At the beginning of each day of experimentation the electrodes were calibrated against the standards. In each case 50 mL of standard was measured and 1 mL of ionic strength adjuster (ISA), as recommended by the manufacturer, was added to the sample. The sample was then mixed with a magnetic stir bar for 5 -10 seconds prior to introduction of the electrode. The mV reading for the given species being tested was then recorded once the value stabilized, generally after 2-3 minutes. By calibrating with the three separate standards, which each varied by an order of magnitude in concentration, a calibration curve was obtained. Electrode theory is governed

by the Nernst Equation which results in an approximate 58 mV change in the reading for each order of magnitude change in concentration (for a monovalent species) at room temperature.

3.3 Process Stream

The synthetic water employed in the experiments was prepared by dosing a volume of distilled water with a measured mass of chemical. Typical concentrations of various ions were 1-4 meq/L. The concentrations of the feed stream were verified using the ion-selective electrodes prior to starting an experiment. Small adjustments were made by either adding chemical or distilled water to the synthetic water until the desired probe readings were achieved. Table 3.1 lists the chemicals which were employed to create the synthetic waters and the electrodes used to measure their concentrations.

Table 3.1 Chemicals used for the species tested.

Species	Chemical	Probe
Nitrate	Sodium nitrate	Orion 9682BN
Chloride	Sodium chloride	Orion 9617BN
Calcium	Calcium sulphate	Orion 9720BN
Sodium	Sodium nitrate	Orion 8611BN
Aluminum	Aluminum chloride	NA
Sulphate	Calcium sulphate	NA

There were two complex or real waters used in the complex water experiments. They were a Manotick (Ottawa Area) groundwater and Ottawa-Carleton tap water. They were also dosed with the same chemicals as the synthetic water in order to achieve desired initial concentrations of nitrate, chloride or sulphate.

Depending on the type of experiment, samples were collected at different time intervals from either the product stream and/or one or more of the feed, concentrate or rinse tanks. The concentrations of the different species in these samples were always determined in the same way:

- 1) Ionic strength adjuster (ISA) was added to obtain a 50:1 volumetric ratio of sample water to ISA
- 2) Stirring magnet was introduced to sample
- 3) Rinsing of electrode with distilled water and introduction into the sample
- 4) Meter reading was recorded after 3 minutes
(Appropriate time for stable reading)

The operating parameters that were varied in both single and multi-species EDI experiments were:

- 1) Feed flow rate (250-500 mL/min)
- 2) Voltage per membrane pair (2.0-5.0 V)
- 3) Inter-membrane spacing (1.0-2.0 mm)

- 4) Resin type (Three commercially available resins as well as resin absent)
- 5) Number of cell pairs (2-5)
- 6) Product stream concentrations

Prior to the commencement of any experiment the resin was completely saturated with the feed solution to minimize uptake due to ion-exchange reactions during the experiment . This procedure simplified the analysis with respect to isolating removal that was due to ion-exchange and that which was due to actual removal from the feed stream chamber.

3.4 Experimental Plan

An experimental plan that consisted of a number of different types of experiments was completed to address the previously stated objectives. A summary of all the experiments that were completed is presented in Figure 3.2.

Simple exchange experiments on the ion exchange resins were performed to ascertain the initial exchange capacity of the fresh resin. By determining the equilibrium state between the liquid phase and resin phase (at a given concentration), information that was required to determine the saturation of the resin prior to the commencement of full EDI experimentation was obtained. The intent was to eliminate this source of potential experimental error.

Figure 3.2 Flow chart of experimental plan

These experiments were performed in column ion-exchange breakthrough experiments with both nitrate selective resins and the general anion exchange resin. These experiments were the only ones not specifically undergoing electrodeionization.

The first round of EDI experimentation involved a synthetic water stream spiked only with sodium nitrate (known as single species experiments) to compare process operating conditions with a simple matrix. These experiments provided a baseline for comparison with the results of the multi-species experimentation. Before these experiments were performed the mode of operation of the reactor was evaluated (i.e. once-through vs recycle operation).

Once-through operation consisted of preparing a quantity of feed solution that flowed through the EDI unit only once. This type of operation is the usual method with which EDI is normally performed in its ultrapure water applications. The unit size or number of units is designed to handle the flow and level of treatment desired by the operators for the given application.

These experiments were performed to determine the response of the unit with time to a single unchanging feed stream. This allowed the flux under the given operating conditions to be established by obtaining data points at a number of experimental times. A range of process operating conditions were evaluated under this mode of operation. A disadvantage of the once-through experiments is that each experiment provides information on only one possible operating condition.

The recycle or batch mode experiments consisted of recycling the treated feed back to the feed stream tank (Fig 3.1). In this mode of operation the concentration in the feed tank continues to decline with time. This allowed operation to an eventual end point of no further detectable removal of any species. These experiments provided the following information:

- i) measurement of fluxes and energy consumption for a range of nitrate concentrations in one experiment.
- ii) an indication of the process conditions when the nitrate contaminated stream reached the threshold of drinking water standards.

A comparison of the once-through experimental data with coinciding data points from the recycle experiments was conducted to verify that the results from the recycle experiments could be extrapolated to once-through operation. Hence, the operating conditions required for achieving a targeted effluent quality could be determined from the recycle experiments rather than conducting numerous once-through experiments.

The recycle experiments were performed on feed streams made up of a synthetic feed stream of distilled water that was dosed only with sodium nitrate. All subsequent experimentation to was performed in once-through mode of operation.

After these experiments were completed a number of longer duration experiments were performed to investigate long-term operation of the process. These experiments were identical to the single species once-through experiments except that a much larger volume of feed was prepared prior to experimentation. These experiments were typically 8 to 12 hours in duration.

Experiments were conducted with a synthetic water that contained additional species of anions and cations to determine the effect of competing anions on nitrate flux, energy consumption and also to determine if preferential removal of nitrate was possible. Therefore, multi-species experiments with feed streams containing chloride and sulphate, along with nitrate, calcium and aluminum, were performed. These ions represent a range of ionic charges for both anions and cations. These experiments were identical to the regular duration single species experiments operated in once-through mode except for the make up of the feed stream.

The potential to enhance preferential removal of nitrate over that of other ionic species was evaluated in a series of experiments that were conducted under non-typical operating conditions. The experiments involved sequential repeating of two conditions. In one condition the power to the anode and cathode was not activated and feed flow was activated. In the subsequent condition, the conditions were reversed. The hypothesis was that nitrate selective ion exchange would occur in the first mode of operation. In the second mode, ion migration from the clean water chamber to the concentrate stream would occur.

After the EDI unit's performance was determined for simple feed streams, experiments were performed on complex or real ground and surface waters. These experiments were conducted to compare the fluxes of nitrate under the two different types of feed (synthetic and complex).

3.5 Presentation of Results

Given that six operating parameters may be varied per EDI experiment and the large number experiments presented in graphical format, a convention for presentation was established to remove ambiguity. The convention was to establish base conditions for operating parameters that were constant unless otherwise mentioned in figure title. They were the following:

1) Feed flow rate:	250 mL/min
2) Voltage per membrane pair :	3.3 V
3) Inter-membrane spacing:	1.0 mm
4) Packing:	Resin #1
5) Number of cell pairs:	3
6) Feed Concentration:
(per anion species)	2 meq/L

These were established as the base values because of their frequency established in the experimental plan.

Also pertaining to the graphical presentation are the error bars. They represent, in all figures in which they are present, two standard deviations (σ) from the mean (assuming a normal distribution).

4.0 ION EXCHANGE EXPERIMENTS

Two commercially available nitrate selective resins and a general anion exchange resin from different manufacturers were used as the ion exchange resins contained within the EDI unit in this study. The EDI process incorporates an anion exchange resin in the feed flow chambers. Hence it can be expected that when there is a change in the nitrate concentration in the feed stream (i.e. during startup) there will be a concomitant change in the mass of contaminant that associates with the solid phase. The experiments described in this section were performed to assess the ion exchange capacity of the differing resins at the concentration range employed in the subsequent EDI experiments. The results provide insight into the time required for concentrations to reach a new steady state when concentrations are changed.

4.1 Method:

The method used to perform these exchange capacity experiments was to pass a solution of known sodium nitrate concentration through a small column containing 100 grams of resin. Outlet concentrations were monitored over time until nitrate was not being exchanged with the resin. Duplicate experiments were performed with all three resins. For reference purposes Resin #1 and Resin #2 denote the two nitrate selective resins while the non-selective anion exchange resin is referred to as General Resin. Information regarding the physical and chemical properties of the nitrate selective and general resins is contained in Table 4.1.

The concentration and flow rate were chosen to reflect the concentration (100 mg/L) and flow rate (250 mL/min) commonly encountered in the EDI experimentation.

It can be seen from Table 4.1 that there were differences between the two nitrate selective resins. Specifically their water retention and total volume capacities differed by about 10% and 20 %, respectively. Another difference, of chemical significance, was the active group for the nitrate selective resin. Resin #1 had a triethyl amine active group and Resin # 2 had a trialkyl amine active group.

Table 4.1. Resin properties.

	General Resin	Resin # 1	Resin # 2
Manufacturer	Sybron Chemicals Inc. Birmingham, New Jersey	ResinTech Inc. Cherry Hill, New Jersey	Sybron Chemicals Inc. Birmingham, New Jersey
Resin Name	ASB-1	SR-100-HP	SR-7
Copolymer Matrix	Styrene-Divinylbenzene	Styrene-Divinylbenzene	Styrene-Divinylbenzene
Active Group	Quaternary ammonium	Triethyl amine	Trialkyl amine
Weight Capacity	2.2 meq/g	1.8 meq/g	1.8 meq/g
Volume Capacity	1.4 meq/ml	1.1 meq/ml	0.9 meq/ml
Co-ion	Chloride/Hydroxide	Chloride	Chloride
Effective size	0.30-0.35 mm	0.45 - 0.50 mm	0.45 - 0.50 mm
Water Retention	50-55%	48 - 52 %	50 - 65 %

Alkyl amines are formed by the substitution of one hydrogen on ammonia with an alkyl group. In the case of a trialkyl amine what is meant is that all three of the hydrogen atoms surrounding the nitrogen atom have been replaced by alkyl groups. For triethyl amine, the chemical formula is:

Where the ambiguity arose was that the term alkyl denotes any fragment of an alkane and as a result may be any one of methyl, ethyl, propyl, butyl, etc. It is unclear if the active group of Resin # 2 was made up of only one or a combination of alkyl groups. It was therefore not possible to make inferences about nitrate selectivity and/or performance with regards to active group since the manufacturer's data concerning Resin # 2 did not specify the chemical structure of its resins in any more detail.

Research into the properties of experimental resins for nitrate selectivity (in ion exchange columns) by Guter (1992) gave the following significant trends:

1) As the number of carbons in the alkyl groups increased:

- Nitrate selectivity increased.
- Moisture content decreased from 51 to 33 %.
- The total anion capacity decreased from 1.41 to 1.00 equivalents per litre.

2) As the number of ethoxy groups increased from 0 to 3:

- Nitrate selectivity decreased.
- Moisture content decreased from 51 to 31 %.
- The anion capacity decreased from 1.41 to 1.23 equivalents per litre.

It is interesting to note that water content of the resins was unrelated to nitrate-sulphate selectivity. The most selective and least selective resins had about equal water contents.

Also of note is that there was a tradeoff between selectivity and capacity. The greater selectivity acquired with the larger alkyl group resulted in a decrease of capacity by a factor of approximately 2.

4.2 Results:

The results of the ion exchange experiments, comparing the two nitrate selective resins and the general anion resin, appear in Figure 4.1. It can be seen from Figure 4.1 that Resin # 2 achieved quicker breakthrough than Resin # 1, if breakthrough is set around the MAC of 45 mg/L as NO_3^- . It is also evident that Resin # 1 followed a much closer to ideal breakthrough curve. Resin # 1 was able to treat approximately 220 bed volumes (BVs) before breakthrough while Resin # 2 only treated approximately 170 BVs before breakthrough occurred. The General Resin experiment also produced an ideal breakthrough curve. Since it had a larger overall exchange capacity than the

selective resins, (2.4 vs 1.8 meq/mL) it required a larger number of bed volumes (270 BVs) for breakthrough to result.

Figure 4.1. Comparison of sorption curves for ion exchange resins

A possible reason Resin # 1 more closely conformed to ideality was due to the smaller average diameter of Resin # 1 relative to Resin # 2. According to Wachinski and Etzel(1997) particle size has a major influence on ion exchange applications. The kinetics of exchange are such that, for a diffusion limited process, the rate of exchange is proportional to the inverse of the square of the particle diameter .

The manufacturers' data describe both nitrate selective resins as having the same average diameter from sieve testing but visual inspection would seem to indicate that Resin # 2 had the larger bead on average. In the case of the General Resin the difference in average diameter was almost exactly half of the selective resins.

Capacity is defined the mass of ions exchanged divided by a given mass of resin. The mass of resin was known by weighing prior to use. The mass of nitrate exchanged was determined by calculating the area in the sorption graph between the out coming (or product) concentration and the initial concentration until such time as the outflow concentration matched the inflow, using Equation 4.1:

$$M_{NO_3} = \sum_{i=1}^n Q(C_{in}^i - C_{out}^i) \Delta t^i \quad (4.1)$$

where : M_{NO_3} = Mass of nitrate exchanged (mg)

Q = Flow rate (L/s)

C_{in}^i , = average concentration in during interval i (mg/L)

C_{out}^i = average concentration out during interval i (mg/L)

Δt^i = duration of interval i (s)

The resin capacities were determined to be very near the manufacturers' published values of 2.2 meq/L for the General Resin and 1.8 meq/L for the nitrate selective resins. The capacity of the General Resin was calculated to be

2.14 meq/L (+/- 5%). The capacities of Resin #1 and Resin #2 were calculated to be 1.72 meq/L (+/- 5%) and 1.66 meq/L (+/- 5%) respectively.

From the data obtained in these experiments it was determined that approximately 3 hours of saturation of either resin, for any feed stream within the predetermined concentration ranges, for the EDI unit at a flow of 250 ml/min would be necessary. This allowed for the proper volume of feed solution to be prepared and made early saturation checks unnecessary. They were therefore eliminated from the experimental procedure.

It is understood that a feed stream containing multi-species will change the actual saturation time and that some percentage of chloride and/or sulphate will take up exchange sites. However the only criteria needed at the beginning of any EDI experiment is that the resin be at equilibrium with the feed stream prior to commencement of the experiment. Thus, no multi-species ion exchange experiments were conducted. It was found that saturation time in the concentration ranges being investigated was always in the 2 to 4 hour range.

5.0 Once-Through Single Species Experiments

A number of experiments were performed in once through mode of operation. The EDI unit performance was evaluated with respect to nitrate flux and energy consumption under a range of operating conditions and process configurations. Flux was calculated as the product of the change in concentration between the product and feed streams and the flow divided by the cross-sectional area of the membrane in each pair.

5.1 Energy Consumption

To assess the energy consumption of the process operating at different voltages, the energy consumed per equivalent of nitrate removed was determined. The energy consumption or J/eq was calculated solely on the basis of the energy supplied by the power unit; by Equation 5.1:

$$PowerConsumption\left(\frac{J}{eq}\right) = \frac{Power}{(area * flux)} = \frac{V * I}{(area * flux)} \quad (5.1)$$

Pumping requirements were not taken into account because the desire was to determine the effect of changing operating parameters strictly on the processes occurring within the unit. Secondly an actual full-scale model will be using much different pumps with different power requirements relative to the power needed for ionic transport within the unit.

5.2 Results and Discussion

5.2.1 Impact of Voltage and Flow

Figure 5.1 presents the average outlet concentration of two replicate experiments for three separate voltages; (2.0, 3.3 and 5.0 volts per membrane pair.) The process conditions were 1 mm spacing, Resin # 1, 250 mL/min process flow rate and 3 membrane pairs. The initial concentration of nitrate for these experiments was 124 mg/L (2 meq/L). From Figure 5.1 it can be seen that after an initial increase in the outlet concentration with time, steady-state concentrations were established. At steady-state the average effluent concentrations were 106, 98 and 92 mg/L of nitrate for the 2.0, 3.3 and 5.0 volts per membrane pair conditions respectively. The currents experienced for these same voltages were 85, 112 and 141 mA respectively.

It can be seen from Figure 5.1 that the smallest outlet concentrations occurred with the highest voltage (5.0 V per membrane pair). The increased nitrate fluxes result from the increased current density that is created at the higher voltages. The result was a greater driving force that increased the rate at which nitrate ions were forced through the anion selective membrane (and sodium ions through the cation membrane) as well as through solution. It is also apparent from Figure 5.1 that the reproducibility of the data is good.

Figure 5.1 Average effluent nitrate concentrations vs time at different voltages ($C_o = 124$ mg/L).

Figure 5.2 presents the calculated fluxes of nitrate for the experiments where the applied voltage and feed stream flow rate were varied. The applied voltage significantly impacted fluxes. When the voltage was increased from 2.0 to 3.3 volts per membrane pair the flux increased by 48%. Increasing to 5.0 volts per membrane pair resulted in a 73% increase in flux over operation with 2.0 volts per membrane pair.

One should note however, that an increase of applied voltage from 2.0 to 5.0 volts is a 150% increase. Therefore a 73% increase in flux is not necessarily an efficient use of energy. The energy consumption as a function of operating voltage and feed stream flow is presented in Figure 5.3. From these results it

Figure 5.2 Effect of applied voltage on flux at different flow rates

is apparent that energy consumption was higher at the higher voltage. There was approximately a 65% increase in the energy requirement when operating at 3 volts as compared to 2 volts, and a 150% increase in the energy requirement when operating at 5 volts as compared to 2 volts, regardless of flow rate. Hence it is apparent that the optimal design (when only nitrate is considered) will reflect a compromise between increased capital costs that are required to construct a system that operates at lower fluxes and the increased energy consumption for operating at higher voltages.

Figure 5.3. Impact of applied voltage on energy consumption.

It should be noted that from the theory of concentration polarization as presented by Barragan (1998) that at smaller current densities the relationship between voltage and current density should be linear. This means that, if the range of voltages being investigated for these experiments was in this ideal range, an increase in voltage from 2.0 to 3.3 volts would result in a 65% increase in current. This in turn means that the power requirement has increased by a magnitude of $(1.65)^2$ or 2.72. Similarly an increase from 2.0 to 5.0 volts would result in a $(2.5)^2$ or 6.25 times increase in magnitude.

What this means is that even under the most ideal conditions, assuming that flux increases linearly with voltage, the increase in the total amount of power

used is limited by Equation 5.1. Since Power = current * voltage, and flux, voltage and the cross-sectional area are unchanging, Equation 5.1 reduces to;

$$\text{Energy Consumption} \propto IV/I \propto V \quad (5.2)$$

Therefore any increase in voltage results in, at best, a proportional increase in the amount of energy required per equivalence of nitrate removed. When the unit no longer performs in this range, i.e. flux begins to not increase proportionally with increased current, then the energy requirement begins to approach the worst operating range of;

$$\text{Energy Consumption} \propto \text{Power} \quad (5.3)$$

It can be seen from Figure 5.3 that the energy requirement per equivalence at either feed stream flow rate follows the ideal behavior of Equation 5.2 at all voltages tested. The increases from 2.0 to 3.3 to 5.0 volts are 1.65 and 2.50 respectively.

The departure from linearity that can be seen at higher current densities results from the splitting of water into ions at the higher applied voltages. Those additional ions consume a portion of the current thereby increasing the energy consumption without increasing nitrate flux.

From Figure 5.2 it is apparent that feed stream flow rate had little impact upon the nitrate fluxes observed. (Low flow in this case was 250 mL/min and

high flow was 500 mL/min). This implies that boundary layer effects, which may be impacted by the liquid velocity, did not change significantly over the range of velocities tested. Hell et al. (1998) found that flux is independent of flow, for electrodialysis, until the velocity decreases to some minimum velocity attained for which concentration polarization affects the overall flux detrimentally.

One of the presumed reasons for greater operating fluxes of EDI relative to ED is the decrease or elimination in boundary layer thickness. Therefore it is reassuring to see insignificant variations in flux for experiments in which only flow rate was varied. Attempts at determining any boundary layer effects at lower flows were not performed because any flow lower than approximately 200 mL/min was difficult to properly control.

For some experiments where the flow was increased to 750 mL/min, significant decreases in flux were observed (Figure 5.4). It was observed upon opening of the unit that at such high flow rates the resin was typically shunted to the edges or walls of the chamber thus creating preferential flow paths (short circuiting) within the unit. When this occurred the unit was functioning more as an ED unit. In order to minimize the occurrence of resin “shunting”, even at lower flows, the mass of resin present in a 1 mm spacing of membranes was increased from 16 grams to 20 grams. This was more difficult to accomplish during assembly because it increased the likelihood of resin beads becoming lodged between spacers, resulting in leakage.

Also, for a scaled model there will be an optimum amount of resin that should be present in the product stream compartments because more resin

results in higher head losses for the same flow. This in turn, decreases the total number of compartments one may have operating in series as the usual constraint on operating pressure of EDI units is typically no greater than 60 psi (Patzay, 1998). At pressures greater than this the ion exchange membranes no longer form an effective barrier to water molecules; i.e. water is forced through them. For the purposes of the bench scale experimentation, the added resin did not have a large effect on operating pressure and therefore did not result in any noticeable leakage through the membranes themselves.

5.4. Example of hindered performance at high process flow rate (3.3 V/pair).

There was approximately a 25% - 35% increase in energy consumption, as presented in Figure 5.4, for high feed stream flow conditions as compared to low flow conditions over the range of voltages (the greatest increase in consumption occurred at 5 V per membrane pair). It is less apparent why energy consumption increased with increased flow. While overall removal as a percentage of incoming flow decreased with flow rate, it was previously demonstrated that fluxes remained constant under the same experimental conditions. Thus the reason for increased energy consumption was due to an increase in the power requirement. The increase in the power requirement, for an unchanging applied voltage, can only be explained by an increase in the current traveling from the anode to the cathode, which in turn is dependent on a decrease in the overall resistance.

A decrease in resistance can be explained by increased mixing within the flow chamber due to the greater velocities causing turbulence. The resulting increase in current should then, by definition, result in increased flux. This was not however the case. Therefore some species other than nitrate was carrying charge. The one available option in a sodium nitrate spiked water is therefore the water. Water must presumably have been splitting, in the feed stream, and carrying charge through the anion and cation exchange membranes. No noticeable pH change occurred in either the product or concentrate stream. For the feed and concentrate stream this means that there was no noticeable imbalance in the rate at which hydrogen and hydroxide left the process stream and entered the concentrate stream. Since no effect on pH had occurred in the

concentrate stream, which is all one continuous series of adjoining compartments, the hydroxide and hydrogen ions entering the concentrate compartment must be doing so in a 1:1 ratio.

5.2.2 Impact of Resin

Three commercially available nitrate selective resins were used in these experiments to determine their impact on performance. Experiments comparing the three resins were performed at the same spacing, operating voltage, feed concentrations, flow rates and initial mass of resin present in the feed stream chamber. In addition, tests without resin present were conducted to evaluate operation in electrodialysis mode.

The results of the experiments that were performed to evaluate the impact of resin type are presented in Figure 5.5. From Figure 5.5 it can be observed that Resin #1 yielded fluxes 10-15 % greater than Resin #2, 30-40% greater than the general resin and 45-65% greater than ED operation which experienced fluxes of 2.4×10^{-6} meq/(cm²*sec). Resin #1 consumed 10 -15 % less energy than Resin #2, 20-30 % less energy than the General Resin and 40-50 % less energy than ED.

It is unclear why Resin # 1 performed better than Resin #2 since both are nitrate selective resins. It is interesting to consider the improved EDI performance along with the behaviour observed in the ion exchange experiments. In the exchange experiments both resins performed similarly in overall capacity however Resin #1 followed a more ideal breakthrough or

saturation curve. Therefore Resin #1, because of its faster rate of exchange compared to Resin #2, would intuitively be considered the resin most likely to perform the best, or at least perform similarly, when inserted in the EDI unit.

Figure 5.5. Impact of resin on flux and energy consumption

Two mechanisms may explain the superior performance of Resin # 1:

- 1) The mixing or physical contact points between the surfaces of Resin #1 occur more frequently and have a better distribution within the chamber resulting in enhanced transport of the ionic species present.

2) The differing surface properties of the two resins, while resulting in the same exchange capacity in an exchange column, result in Resin #1 achieving better results.

One possible reason for the poorer performance of Resin #2 was the aforementioned channeling. Resin #2 may have experienced more shunting or settling of the resin due to poorer initial packing. However no more or less displacement of the resin was apparent upon inspection during dismantling. In addition the performance of Resin #2 relative to Resin #1 was consistent in all experiments including duplicates. If channeling was to occur randomly a greater variance in duplicate experiments would be expected. However this was not observed.

It is interesting to note that both nitrate selective resins performed better than the general anion exchange resin under EDI operation. It should be remembered from the column experiments that the General Resin had as idealic a breakthrough curve as Resin # 1 and a greater overall exchange capacity than either of the nitrate selective resins. Therefore, it is reasonable to conclude that under an applied voltage the internal structure and chemistry of the nitrate selective resins offers less resistance to nitrate transport than does the general anion exchange resin.

The observation that electrodialysis experienced both lower fluxes and higher energy consumption under the same run conditions confirms that the ion exchange resin created a region of lower resistance to current (ion transport)

compared to the bulk liquid phase. The enhanced flux and decrease in energy consumption of EDI relative to ED is well established. It was, however, still necessary to obtain a baseline from which comparisons with multi-species and complex process streams can be made.

5.2.3 Impact of Membrane Spacing

Another important design feature is the spacing between the ion-exchange membranes in the feed water chamber. Too small a space could result in too short a residence time and/or significant head losses and too large a space may cause increased resistance and result in poorer performance.

Figure 5.6 presents the impact of increased inter-membrane spacing on flux. The process conditions were, Resin # 1, 250 mL/min process flow rate and 3 membrane pairs. It is apparent that a doubling of the inter-membrane spacing from 1 mm to 2 mm resulted in a 20 -30 % decrease in flux regardless of the applied voltage. Operation at the higher spacing resulted in a 5 -10 % decrease in current and 10 - 15 % increase in energy consumption.

The nature of the energy consumption equation (Equation 5.3) is such that the current and flux appear in the numerator and denominator respectively. Hence an identical percentage decrease in both does not affect energy consumption, (however it will affect the surface area of membrane needed to treat a given flow rate of process because this is flux dependent). Since the flux decreased by a greater percentage than current as spacing increased, it is

apparent that current is not the only variable affecting flux; path length for ions to travel is also an important consideration.

Figure 5.6. Impact of membrane spacing on nitrate flux.

5.2.4 Nitrate Concentration

The impact of nitrate concentration in the feed stream on process performance was evaluated over a range of concentrations from 100-500 mg/L as nitrate. The data contained in Figure 5.7 presents nitrate fluxes and energy consumption for an applied voltage of 2.0 volts, 1 mm inter-membrane spacing and process flow rate of 250 ml/min. The nitrate fluxes for feed stream

concentrations from 2 meq/L (124 mg/L) to 6 meq/L (372 mg/L) ranged from 2.5×10^{-6} to 5.6×10^{-6} meq/cm²/s respectively.

Energy consumption, for the same feed stream concentrations ranged from 145 J/meq to 130 J/meq respectively. These relatively stable values can be explained by the current increasing at approximately the same rate as the flux regardless of the feed stream concentration. Figure 5.9 demonstrates this trend for three different voltages.

Figure 5.7. Impact of nitrate concentration on flux and energy consumption (2.0 V/pair).

Relative fluxes were used to normalize values for the purpose of comparing different operating conditions by dividing all fluxes by those observed at 2 meq/L. Figure 5.8 presents the relative fluxes for initial nitrate concentrations of 2 meq/L, 4 meq/L and 6 meq/L for three different voltages. From Figure 5.8 it is apparent that there was little interaction between nitrate concentration and operating voltage in their impact on nitrate flux.

Figure 5.8. Relative fluxes at different concentrations versus voltage.

While nitrate fluxes increased with nitrate concentration, further analysis was required to determine whether overall energy consumption also improved correspondingly. Figure 5.9 presents the relative energy consumption at three different concentrations over the range of voltages tested. It can be seen that

there is no observable trend in energy consumption versus voltage at these high feed stream concentration levels. (Performance at lower feed stream concentrations can be found in Chapter 6: Recycle Experiments.) This information is of importance in determining the optimum size and operating parameters of a scaled up model in the case where the nitrate contamination is relatively constant and known.

Figure 5.9. Relative nitrate energy consumption at various voltages versus process water concentration.

5.2.5 Number of membrane pairs

Figure 5.10 shows the effect of the number of membrane pairs on flux with flow kept constant. It can be seen from this figure that fluxes remained relatively

constant for a given voltage per membrane pair. There was approximately a 5 to 10 % decrease in flux when the number of pairs was increased from 3 to 5.

The reason for the decrease in flux is due to a proportional decrease in current. This may be due to a number of reasons; such as the fact that with a larger number of membranes, for a given flow, the effluent concentration is lower (due to the greater surface area available for transport). This results in a lower average ionic strength within the unit and therefore a lower observed current at a given voltage. Also, increased opportunities for short circuiting in any given compartment, or a diminished ability to resist the passage of feed water through the membrane will occur with an increasing number of membrane pairs.

Figure 5.10 Effect of the number of membrane pairs on nitrate flux.

It is known that above a certain number of pairs the pressure required to pump the feed stream through an EDI unit is such that increased water passage through the membranes starts to occur (Patzay, 1995). This problem did not arise or at least was not detectable with 5 membrane pairs.

Since the decrease in flux and current were nearly identical, the energy consumption with a greater number of pairs, at a given applied voltage, remained identical. Therefore any size up requirements that result in the addition of membrane pairs will only be negatively impacted by a decrease in flux and not power requirement.

6.0 Recycle Experiments

Experiments were conducted in a recycle mode to evaluate process performance under a range of ionic concentrations in one experiment. A key process parameter to quantify in these experiments was the flux of nitrate out of the process water stream.

The same sampling and electrode usage methods were used in determining concentrations as in the once-through experiments. The only difference was that the product stream was fed back into the feed stream reservoir rather than being discharged.

6.1 Nitrate Flux

Two different methods may be used to determine the flux being experienced for a given experiment and both are equally valid. In one approach, the concentration of the feed tank and the product stream were taken at every sample time. The flux was then determined by Equation 6.1:

$$\text{Flux} = (C_f - C_p) * \text{Flow Rate} / \text{Area} \quad (6.1)$$

Where:

- C_f = The concentration in the feed tank (mg/L)
- C_p = The concentration in the product stream (mg/L)
- Area = The cross-sectional membrane area (cm²)
- Flow Rate = The flow rate of the feed stream (L/s)

In the second method only the concentration difference in the feed tank, at the beginning and end of a time interval, were used to determine an overall flux for a certain time step; as demonstrated in Equation 6.2:

$$\text{Flux} = (C_1 - C_2) \times \text{Volume} / (\text{Area} \times (T_2 - T_1)) \quad (6.2)$$

Where:

- C_1 = The initial concentration (mg/L)
- C_2 = The final concentration (mg/L)
- Volume = The volume of the feed tank (L)
- Area = The cross-sectional membrane area (cm²)
- T_1 = The initial time (s)
- T_2 = The final time (s)

The second method only requires half the number of samples for analysis because the final concentration of the first time step is the initial concentration for the subsequent time step. Another benefit of Equation 6.2 is that the volume of the feed tank and the length of the time interval can be more accurately measured than can the flow rate of the feed stream over a small time interval. The disadvantage of this method relative to the first is that it gives an average flux over a range of feed concentrations rather than an instantaneous flux at a given concentration, ie. $(T_2 - T_1)$ must be relatively small for this approach to be effective.

6.2 Results & Discussion:

Two experiments for each voltage setting were performed in order to gain confidence in the raw data. Figure 6.1 presents the concentrations and currents measured for two experiments with 3 membrane pairs, Resin # 1, 1 mm spacing, process stream flow of 250 mg/L and 3.3 volts per membrane pair.

From Figure 6.1 it can be seen that there was excellent replication between experiments. This result gave confidence that the results were reproducible and consistent. In subsequent plots only average values of replicate experiments are presented.

Figure 6.1 Nitrate concentration and current at 3.3 V per membrane pair.

It can be seen from Figure 6.1 that with time the EDI unit achieved nitrate concentration levels in the product stream that were below the MAC. Thus an important performance objective of unit operation had been established. Under these run conditions, it took approximately 5 hours to treat the 20 L feed stream to the MAC level.

Equally apparent from the figure is that the rate at which the concentration decreased with time slowed. The current seemed initially to decline linearly with concentration until a process stream concentration of approximately 90 mg/L, at which point the rate at which current decreased slowed relative to the decrease in concentration. The results indicate that as the concentration of nitrate declined fewer ions were available to carry charge and as a result current decreased at a rate roughly equivalent to the rate at which nitrate concentration decreased. However below about 90 mg/L, the current did not decrease at the same rate as the process stream concentration. Thus, either water was splitting and carrying charge across the chamber or the portion of current that resulted from transport within the resin structure was greater relative to that which resulted from bulk fluid transport.

Figure 6.2 presents the fluxes (using equation 6.2) and energy consumption calculated from the data contained in Figure 6.1. From Figure 6.2 it can be seen that flux generally declined with time while the energy consumption increased somewhat. The lack of apparent smoothness of the flux data relative to the concentration data from the previous figure is a result of the inherent sensitivity of flux to small variations in concentrations. Since the flux was

dependent on the difference in initial and final concentrations of the product stream, and these differences were small (typically under 10 mg/L), the effect on flux calculation was significant. In other words if two concentration values are determined to be 60.0 mg/L and 56.0 mg/L rather than 59.0 mg/L and 57.0 mg/L, the flux of the second set of readings is half of the first because the difference in the two sets of readings is 2 mg/L rather than 4 mg/L. (The electrode measurement error was $\pm 1\%$)

Figure 6.2 Nitrate fluxes and energy consumption versus time (3.3 v/par).

Energy consumption is a function of both nitrate flux and current. The general increase in energy consumption with time can be explained by the

diverging trends in nitrate concentration and current that were observed in Figure 6.1. While the nitrate concentrations declined steadily with time the decrease in current was not as significant. Hence there was a greater amount of energy consumed per equivalent of nitrate that was removed.

Figure 6.3 compares the fluxes calculated using Equation 6.1 and Equation 6.2 with the data contained in Figure 6.1. It is visually apparent that the results from Equation 6.1 are more variable than the results from Equation 6.2. This is due to the time averaged concentration values used in Equation 6.2 versus the instantaneous concentration values used in Equation 6.1. As a result Equation 6.2 was the only method used in subsequent flux determinations in the recycle mode of operation.

Figure 6.3 Comparison of fluxes calculated with Equations 6.1 & 6.2.

The recycle experiments provided an opportunity to compare the impact of operating conditions on nitrate flux and energy use over a range of concentrations and voltages. Figure 6.4 presents the concentrations versus time at three different voltages. One of the data lines was previously presented in Figure 6.1 for 3.3 volts per membrane pair. The other two sets of data points were the average concentrations for two experiments at 2.0 and 5.0 volts per membrane pair.

It can be seen that as the voltage per membrane pair increased the time needed to reach a certain concentration decreased. For 12 L of feed, the time needed to reach a concentration of 45 mg/L (NO_3^-) was approximately 210 minutes at 5.0 volts per membrane pair and 280 minutes at 3.3 volts per

Figure 6.4 Nitrate concentration versus time at different voltages.

membrane pair. After 390 minutes of operation, at 2.0 volts per membrane pair, the process stream was just nearing the MAC.

Figure 6.5 presents the fluxes calculated from the data contained in Figure 6.4 versus nitrate concentration. The decrease in nitrate flux seemed generally linear for a given voltage with decreasing nitrate concentration levels. Again, the apparent variability in the results is due to the chemical analysis. There is no need in knowing the behaviour of flux at concentration levels lower than the MAC for the purposes of treating drinking water.

Figure 6.5 Nitrate flux at different voltages versus concentration.

Figure 6.6 presents the energy consumption versus product stream concentration for the same three voltages. For all voltages there was a decrease

in energy consumption as the product stream concentration increased. It is apparent that the rate of increase in energy consumption was greater at lower concentrations in comparison to higher concentrations. This means that the EDI unit required more energy per equivalence removed at the lower process stream concentrations. The relative energy requirement at a given concentration for the different voltages appeared to remain constant (i.e. 5.0 volts consistently requires about twice the energy of 2.0 volts). Therefore there did not appear to be any interaction between concentration and voltage on the relative energy consumption.

Figure 6.6 Energy consumption versus concentration at different voltages.

Figure 6.7 presents the observed flux versus feed stream nitrate concentration for the same operating conditions as those employed to generate the data in Figures 6.1 and 6.2 but over a larger range of concentration. From Figure 6.7 it can be seen that at concentrations above 124 mg/L (as NO_3^-) the relationship between flux and concentration was non-linear. As the feed concentration decreased below 124 mg/L so did the flux in a roughly linear manner.

Figure 6.7 Nitrate flux versus feed concentration (3.3 V/pair).

The non-linear results at higher concentrations suggest that there is a limited capacity to transport ions and above certain concentrations, fluxes do not increase linearly. This phenomena was not considered to be of great importance

since nitrate concentrations are rarely found at these levels in drinking waters. Secondly, it is the unit's performance at close to MAC levels that is of more importance as it is these smaller fluxes which will control sizing requirements.

The flux that was observed at a concentration of 2 meq /L or 124 mg/L and 3.3 volts per membrane pair was approximately 4.0×10^{-6} meq/(cm²*sec) which was within 5% of the flux found in the once through experiments, under the same conditions (3.87×10^{-6} meq/(cm²*sec)). This value can be found in Figure 5.2 on page 53.

Generally the fluxes found with recycling ranged within +/- 10% of the fluxes determined in the once-through experiments. As noted earlier, there was more uncertainty in the fluxes obtained from the recycle experiments as there was only 1 data point at a given concentration per experiment. Similar trends were determined for the once-through experiments.

Figure 6.8 compares the fluxes of the two modes of operation at three different concentrations (for 3.3 Volts per membrane pair). Again, values were generally within +/- 10 % of each other. The results suggest that the recycle experiments can serve as initial flux and energy requirement indicators for the EDI process prior to more rigorous experimentation. In other words, having established that the fluxes measured in the recycle experiments were generally within 10% of those determined for once-through experiments, it is feasible to run a set of recycle experiments in order to determine the fluxes that a certain feed stream will experience at different concentrations without running a full set of once-through experiments. In this manner, broad determinations of size up

requirements and performance under differing feed streams and run conditions can be more quickly determined.

Figure 6.8 Comparison of nitrate fluxes at different concentrations (3.3 V/pair).

At a point where greater confidence is required in a certain area then more stringent once-through experiments can be run. Figure 6.9 compares the fluxes of recycle and once-through experiments at different voltages but otherwise same run conditions (250 mg/L feed stream flow, 1 mm spacing and Resin #1) and feed stream concentrations.

Similar comparisons of the effect of voltage on flux under the same run conditions except for increased inter-membrane spacing of 2 mm can be seen in

Figure 6.10. It can be seen that the flux determined from the recycle experiments was again within 10% of the once-through experiments.

Figure 6.9 Comparison of nitrate fluxes at different voltages (1 mm spacing)

Results similar to those obtained for flux also held true for energy consumption as the currents observed under the same run conditions were very similar to those observed in once through experiments (see Table 6.1). Given that energy consumption is the calculation of energy needed per equivalence removed using the flux and power requirements, identical (or at least similar) fluxes and currents mean similar energy requirements for both modes of operation.

Figure 6.10 Comparison of nitrate fluxes at different voltages (2 mm spacing).

Table 6.1 Energy consumption at different voltages and spacing for recycle and once through modes of operation.

Volts per pair	Energy consumption (1 mm spacing)		Energy consumption (2 mm spacing)	
	Recycle	Once	Recycle	Once
2.0	162 J/meq	144 J/meq	165 J/meq	153 J/meq
3.3	220 J/meq	212 J/meq	274 J/meq	247 J/meq
5.0	375 J/meq	324 J/meq	442 J/meq	398 J/meq

7.0 Once-Through Multi-Species Experiments

The primary goals of the multi-species testing were to:

- 1) Evaluate the impact of the presence of other ions on nitrate flux and energy consumption
- 2) Determine if preferential removal was possible
- 3) Determine the impact of process variables on goals 1 & 2

In order to satisfy these goals a set of experiments were performed under the same operating conditions as in section 5.0 but with the addition of one or more competing species.

In order to assess energy consumption in the case of multi-species experiments it was necessary to determine the manner in which comparisons were to be made. For such cases it was defined as:

$$EnergyConsumption \left(\frac{J}{eq} \right) = \frac{Power}{(area * nitrateflux)} \quad (7.1)$$

Strictly speaking the energy required per equivalence of nitrate removed is some percentage of the overall energy use since some energy goes towards the removal of other species. But, since removal of the other species is not the objective of EDI operation, the power consumption may simply be considered hindered by competing species and the full “cost” of the energy requirement is borne by the nitrate flux alone.

In some cases, where the desire was to make comparisons in energy consumption between feed streams of the same ionic strength (but different composition), the total anionic flux was substituted for nitrate flux in Equation 7.1 yielding the following:

$$PowerConsumption\left(\frac{J}{eq}\right) = \frac{Power}{(area * anionflux)} \quad (7.2)$$

In order to assess if any preferential removal of nitrate occurred it was necessary to establish the method with which this would be determined. It was deemed that the most appropriate method was determining the nitrate flux as a percentage of overall flux, as shown in Equation 7.3:

$$Nitrate\ Selectivity = \frac{Nitrate\ Flux}{Total\ Anion\ Flux} * 100 \quad (7.3)$$

Therefore, in the case of a two species synthetic feed, a value greater than 50% indicates a degree of nitrate selectivity for the process. In cases where more than two anion species are present it is necessary to determine and compare the percentage of overall flux each species accounts for in order to determine if nitrate selectivity has occurred.

7.1 Operation with Nitrate and Chloride

The majority of multi-species experimentation was performed with a feed stream containing a mixture of nitrate and chloride because of the ease with which chloride could be measured. Since ion specific electrodes do not exist for sulphate, a lesser number of experiments were performed with it as a competing species. Appendix D lists all the types and number of experiments conducted for this research.

7.1.1 Impact of Voltage (Multi-species)

Figure 7.1 presents the effluent concentrations that were observed when an equi-molar mixture of nitrate and chloride, with each present at 2 meq/L, was evaluated. The experiment was performed at 250 mL/min of process flow, 2.0 volts per membrane pair, Resin #1 and 3 membrane pairs. It can be seen from Figure 7.1 that nitrate was preferentially removed from the process stream over chloride. The current remained relatively constant with time.

Figure 7.1 Nitrate & Chloride concentration and the current (2.0 V/pair, $C_0 = 2.0$ meq/L).

Figure 7.2 presents the fluxes of nitrate and chloride that were calculated from the data presented in Figure 7.1. It can be seen from Figure 7.2 that under these operating conditions the flux of nitrate was approximately 60% greater than that of chloride, this results in a nitrate selectivity of 62% using Equation 7.3. This pattern of preferential nitrate removal was observed in all the runs involving solely NaNO_3 and NaCl with nitrate selective resins. The phenomena is most apparent at lower applied voltages (current densities), these results are presented Figure 7.3.

Figure 7.2. Flux of nitrate vs chloride at 2.0 V per pair and low flow conditions

The impact of voltage on nitrate selectivity was evaluated by conducting a series of experiments with equimolar concentrations of nitrate and chloride in the process water stream. It can be seen in Figure 7.3 that, while overall flux increased with increasing voltage (in the same relative proportions as for single species increases in voltage), selectivity decreased with increasing voltage. The increase in the nitrate flux from 2.0 to 5.0 volts was from 2.74×10^{-6} to 4.18×10^{-6} meq/cm²/s respectively or approximately 50%. However, over the same voltage change chloride flux increased over 100%. The resulting effect on nitrate selectivity was a decrease in nitrate flux from 61% to 53% of overall anion removal.

Figure 7.3. Impact of voltage on nitrate & chloride flux.

Dejean et al. (1997) found that above a given current density preferential removal of nitrate in an EDI unit becomes negligible. Specifically they found that, for their unit, above 1.5 mA/cm² preferential removal was lost. The current density for these run conditions at 2.0 and 5.0 volts was 0.88 and 1.60 mA/cm² respectively. Hence, the results of the current study appear to confirm those of Dejean et al. (1997).

It would seem that for low current densities enhanced nitrate transport is due to the affinity it has for the nitrate selective resin. For high current densities either bulk liquid phase flux dominates (thus losing any advantage gained using a selective resin) or higher current densities simply “force” all anions through.

The first scenario seems more likely. Since actual travel through the resin matrix, without an applied voltage, is known to be nitrate selective (for the purposes of exchange) it would seem reasonable to suggest that this phenomena results in the preferential transport of nitrate under low voltages.

Figure 7.4 compares the combined fluxes obtained at different voltages for two separate process streams; one made up entirely of nitrate and the other half chloride and half nitrate, with a total anionic concentration of 4 meq/L each. It can be seen that at a given anionic strength, and under the same run conditions, the process streams containing only nitrate had a slightly higher flux than the mixed streams. (Despite falling within the values of the error bars, all multi species equivalent ionic strength streams incurred lower overall flux than nitrate only streams). This stands to reason as nitrate was preferentially removed over all other anionic species tested. It seemed to encounter less resistance or to travel on a superior pathway than the other species. In other words at lower voltages solid phase or resin transport has a greater influence on selectivity than at higher voltages where bulk phase transport reduces selectivity. As a result any process stream containing other anionic species is achieving some ratio less than one of the maximum possible flux under the given operating conditions (when packed with a nitrate selective resin).

Figure 7.4. Comparison of total flux between single and multi-species experiments.

Figure 7.5 shows the total anion flux and energy requirement (based on Equation 7.1) for different voltages. The run conditions were 250 mL/min flow with Resin #1. Energy consumption increased because the increase in power (ie. the product of the applied voltage and the current) was more than the increase in nitrate flux as the operating voltage was increased. This increase in power must be greater than the increase in flux for energy consumption to increase because the relationship between flux and energy required is inverse.

Figure 7.5 Effect of voltage on energy consumption.

7.1.2 Impact of Resin Type

Initial multi-species experimentation was performed with four packing scenarios in order to establish if preferential nitrate removal was possible. The resulting fluxes of nitrate and chloride presented in Figure 7.6 are for a 250 mL/min process flow, 1 mm spacing, 2 meq/L initial concentration (for nitrate and chloride) and 3.3 V per membrane pair.

It is apparent from Figure 7.6 that operation with the nitrate selective resins resulted in preferential nitrate removal. As with the single species testing it is apparent that the General Resin yielded fluxes approximately 25% larger than without resin. Operation with the General Resin and without resin (ED

mode) experiments had no perceivable preference for nitrate over chloride. This suggests that it was the affinity of nitrate for the internal resin structure of the selective resins that was aiding in preferential removal relative to other anions.

Figure 7.6. Effect of Resin Type on Multi-Species Fluxes (3.3 V/pair).

The decrease in the observed nitrate and chloride flux between Resin #1 and Resin #2 was similar in magnitude to the decrease observed for the single species experiments (approximate 10-15 % reduction). Resin #2 did not enhance or diminish selectivity relative to Resin #1. If, as hypothesized earlier, a preferential pathway due to the functional chemistry of the resin bead was the reason for selective nitrate removal then all nitrate selective resins should be

somewhat nitrate selective in EDI operation. That they should be selective in the same relative proportions is unknown.

The energy consumption of the unit with the different packings is presented in Figure 7.7. As with the single species experimentation the order of least energy consumption was the two nitrate selective resins followed by the general resin and then ED. The difference in energy consumption (using Equation 7.2 because it takes total flux into account) between the general resin and nitrate selective resins for the multi-species experiment was less than the single species experiments (18 percent difference for the single species as compared to a 12 percent difference for multi-species). This may be explained by the fact that neither resin had a specific affinity for chloride and as a result neither resin was better at enhancing transport through the process chamber. This would suggest that, with each addition of a non-nitrate anion, the difference in energy consumption between the nitrate selective and general anionic resins, (when consumption is defined as energy per total anionic removal), will diminish.

Since preferential nitrate removal had been established for only the nitrate selective resins a larger number of experiments were performed to investigate the behavior of the unit with these resins.

Figure 7.7 The effect of resin on total flux and energy consumption (3.3 V/pair, $C_0 = 2.0$ meq/L).

7.1.3 Flow Rate

Figure 7.8 presents the fluxes for nitrate and chloride for a 2 meq/L initial process concentration for each species and Resin #1 and 1 mm spacing. Fluxes are presented as a function of applied voltage and flow rate. It can be seen from Figure 7.8 that flux was independent of flow, as was determined in the single species experiments. It was also evident that flow rate had no effect on nitrate removal selectivity.

The power requirement for the same experiments are presented in Figure 7.9. As with the single species experimentation, energy consumption was detrimentally affected by high flow conditions. The energy required per equivalence removed increased by approximately 10-20 %, depending on voltage, for 500 mL/min process flows compared to 250 mL/min.

Figure 7.8 Effect of flow rate on multi-species removal rates

Figure 7.9 Effect of flow rate on energy consumption

7.1.4 Concentration of Feed Stream

The effect of changes in feed stream concentration was investigated in experiments with differing feed stream concentrations consisting of a 1:1 ratio of chloride and nitrate. Three total anionic concentrations of 2, 4 and 6 meq/L were investigated. The experiments were conducted at a 250 mL/min process flow rate, 3.3 V per membrane pair and Resin #1.

Figure 7.10 shows that as the total concentration of anions in the process stream increased the combined flux of nitrate and chloride approached the value of nitrate alone at the same concentration. This was due to the greater increase in chloride flux with increasing concentration. As a result, at 6 meq/L virtually no selective removal of nitrate was observed. At such high concentrations the

Figure 7.10 Effect of concentration on flux (3.3 V/pair).

conductivity of the process stream was much higher and it would seem transport through the bulk water phase was not greatly impeded, thus reducing the effect that internal resin transport had on the overall flux.

The results presented in Figure 7.11 clearly show that, for the species tested, the energy consumption (J/meq of all anions) remained relatively constant at the same total anion concentration. The energy consumption for the 1:1 process stream was within 5% of the energy consumption of nitrate only process streams (at equivalent anion concentration). Hence the results suggest that little preferential transport was occurring at these concentrations.

Figure 7.11. Comparison of energy consumption for single and multi-species experiments (3.3 V/pair)

If nitrate was travelling a path of lower resistance, as compared to other anions, then the lowest energy requirement for anionic removal of feed streams of the same concentration should be for nitrate alone (as is the case for $C_o = 2.0$ meq/L. Any other feed stream should require some greater amount of energy for removal of an equivalent amount of anions.

7.1.5 Spacing

The impact of membrane spacing on the removal of nitrate in the presence of chloride was investigated in four experiments that had 2 mm spacing, which corresponded to the previous experiments that were conducted with a spacing of 1 mm. These experiments were conducted at voltages of 2.0, 3.3 (duplicate) and 5.0 volts per membrane pair. The run conditions were 250 mL/min process flow rate, Resin # 1 and initial concentrations of nitrate and chloride at 2 meq/L each. Also, a doubling of the spacing meant a doubling of the mass of resin in each feed stream chamber (from 20 mg to 40 mg).

The resulting total nitrate and chloride fluxes at spacings of 2 mm and 1 mm are presented in Figure 7.12. Of note is that both the nitrate and chloride flux decreased by 20-25%, which was similar to the reduction in nitrate flux that was observed in the single species experimentation when spacing was increased from 1 mm to 2 mm. The removal of nitrate relative to chloride was unchanged by the spacing increase. The energy efficiency was similarly affected by increased spacing with a 20-30% decrease in efficiency.

This may be due to one of two possibilities. Due to larger inter-membrane spacing, without an internal support structure for the resin, channeling effects allow for greater opportunities for resin movement and hence poorer performance. Also, average path length is increased with increased spacing thus introducing both greater resistance to transport and increased travel time for ion removal.

Figure 7.12 Total anion flux versus voltage at varying spacing

7.1.4 Other Competing Species

Figure 7.13 presents the fluxes of nitrate when present alone and in mixtures with other species (NaCl & CaSO₄) at a process flow rate of 250 mL/min, Resin #1 and a 4 meq/L total anionic concentration. From Figure 7.13 it is

apparent that nitrate fluxes decreased in the presence of chloride and sulphate. In addition, the degree of the decrease was to some extent dependent upon the charge of the competing species, with lower nitrate fluxes associated with the divalent competing species, sulphate, than the monovalent competing species, chloride.

Figure 7.13 Fluxes of various species (3.3 V /pair, $C_{0Total} = 4$ meq/L)

The chloride and sulphate fluxes were 73% and 86% of the nitrate flux respectively. This corresponds to a nitrate selectivity of 58% and 54%. This behavior continued to be observed for sulphate removal relative to chloride removal when parameters such as voltage and concentration were changed. That is that nitrate selectivity was less when sulphate was present relative to when chloride was the sole competing anion.

It is general knowledge that (Sengputa et al., 1988) for a general anion exchange resin the removal sequence or hierarchy (in exchange operation) is;

sulphate→ nitrate→ chloride

and is due in some measure to the divalent nature of sulphate. Therefore it is not surprising that for a nitrate selective resin in EDI operation there is still a greater affinity for sulphate than chloride.

Figure 7.14 shows the relative fluxes of chloride and sulphate, in competition with nitrate, at different voltages but otherwise the same run conditions (Resin #1, 250 mL/min process flow rate, 2 meq/L initial concentration). The flux of sulphate was approximately 15 and 10% greater at 2.0 and 3.3 volts per membrane pair respectively. At 5.0 V there was no observable difference.

The energy consumption was unaffected by the change from chloride to sulphate in the process stream. The overall flux and power usage for a nitrate - sulphate feed was very similar to a nitrate-chloride feed.

Figure 7.14 Fluxes of chloride and sulphate at different voltages ($C_o = 2 \text{ meq/L}$).

7.2 Extended Duration:

It was noted early for the once-through experiments that some of the experiments experienced decreasing fluxes in the first 10 to 20 minutes. (These experiments generally ran 45-60 minutes). As a consequence it was deemed necessary to perform a few longer duration experiments to ascertain if the fluxes did indeed remain constant after this initial drop or if there continued to be decreasing performance with time. Included in this experimentation was an attempt to determine why the rapid initial decline was not consistently observed.

7.2.1 Method:

The method used was identical to that performed for any of the no-recycle runs with the exception that 120 - 200 L of feed solution, diluted from a concentrated stock solution, was prepared prior to the commencement of the experiment to ensure a sufficient quantity for an extended duration. Initially it was decided to evaluate performance of the EDI unit over a period of 8 to 10 hours and then determine if further investigations were necessary. Given the extended length of the experiment, samples were only collected every half hour, after the first hour, in order to reduce the total number of sample readings.

7.2.2 Results and Discussion:

The results of two extended (12 hour) runs at 3.3 volts, 3 membrane pairs, 1 mm spacing and 2 meq/L initial concentration are contained in Figure 7.15. It can be seen from the figure that the fluxes remained relatively constant with time. It can also be seen in Figure 7.15 that one of the two runs presented experienced a greater variation than the other. This may be attributable to some source of human error, possibly in the initial cleaning of the probes before the commencement of the experiment. Other extended duplications did not experience this same variation.

Though Run 2 experienced greater variance than Run 1 neither run showed a decrease in flux with time. These experiments were more than 10 times longer than most normal length experiments. That no decrease in flux with time was observed after the first 10-20 minutes of experimentation seems to indicate that some initial equilibration accounted for the observed phenomena.

However, other experiments that were prepared similarly did not show this initial drop in flux. It is therefore unclear if this is a typical phenomena or improper preparation of the unit.

Figure 7.15 Nitrate and chloride fluxes for extended duration run (3.3 V/pair, $C_0 = 2$ meq/L).

Figure 7.16 shows the fluxes achieved for extended and short duration runs under the same run conditions. The short duration run was completed in 45 minutes and the extended duration run in 12 hours. In this figure the data has been presented over its sampling periods in order to facilitate the viewing of the fluxes over the duration of the experiment. In other words an individual time step

between sampling periods for the extended duration data was 60 minutes; while for a short duration run it was 5 minutes.

Figure 7.16. Comparison of fluxes for short and extended duration experiments (3.3 V/pair, $C_0 = 2 \text{ meq/L}$).

The reason for the initial decrease in fluxes in the “short” experiments is difficult to explain. It may be that the resin was not completely saturated at the beginning of any individual run and therefore the greater initial flux stemmed from the presence of an exchange component that was not intended to be present. Despite the fact that resin saturation was regularly performed before all experiments it may be that in the few minutes between ensuring saturation and the beginning of an actual EDI experiment some sorption sites became available

again. This may have been due to initially unavailable exchange sites becoming available under the presence of a potential or simply a new equilibrium establishing itself before the beginning of an experiment. No literature concerning this phenomenon was found.

Also, it may be that during the first hour of operation a maximum flux occurred before a steady state was established due to the larger number of resin contact points being available after initial packing of the unit. Since the EDI unit was sensitive to resin packing any shift in resin within the unit would result in hindered performance that, at its most severe, would cause performance similar to ED operation.

It was noted that in some, but not all, of the cases where an initial flux drop was experienced, upon dismantling of the unit, that channeling of the resin was observed. It therefore seems reasonable to assume that at least part of this phenomena could be explained by channeling within the resin packed compartments. The contribution of each process was difficult to ascertain.

Figure 7.17 presents the energy requirement calculated for nitrate removal of both extended and regular duration experiments at different voltages. It can be seen from Figure 7.17 that there was no observable difference in the energy requirement for experiments under the same operating conditions.

Figure 7.17. Comparison of energy requirement for short and extended duration experiments (3.3 V/pair, $C_o = 2$ meq/L).

A small continuing decrease in flux with increased time may be attributable to an increase in the concentrate concentration with time; as its ionic strength increases the osmotic pressure difference between the feed compartment and the concentrate compartment will increase. This is one reason why concentrate streams are bled at a certain rate; along with the more important concern of remaining below the solubility of the species present in order to avoid precipitation and eventually fouling or clogging of pathways and/or tubing.

Although, given that the concentration of the concentrate stream was 1200 mg/L of NaCl, several hours of operation should not greatly affect the overall

ionic strength of this stream. In fact at a typical flux of 4.0×10^{-6} meq/(cm²*sec) the mass of nitrate entering the concentrate stream was about 180 mg per hour of operation. Over a 10 hour run this results in 1800 mg of nitrate being added to 15 L of concentrate solution, or approximately 120 mg/L. In equivalencies this resulted in a less than 10% increase in ionic strength of the concentrate stream.

8.0 Complex Water:

The purposes of the complex water experimentation were;

- 1) To compare performance relative to the synthetic feed stream experiments.
- 2) To obtain data with which to compare the cost per volume of treated water with competing technologies.

8.1 Method:

The experimentation for the complex process stream was performed on two potable waters; Ottawa-Carleton treated tap water and a groundwater from Manotick, Ontario. Experiments were performed by dosing these waters with known concentrations of nitrate, chloride, and sulphate; representing a contaminated surface or ground water. These experiments were all performed in once through mode of operation.

Table 8.1 shows the results of a full analysis of the two feed streams prior to dosing with sodium nitrate and sodium chloride. It should be noted from the analysis that the conductivity of the two feed streams differed substantially with approximately 1 meq/L for the Ottawa-Carleton water and 5 meq/L for the Manotick water. Thus, even after dosing to achieve the desired initial concentrations of nitrate and chloride, the overall ionic strength of the two streams remained different. The result was that the Manotick water, because the initial concentration of chloride was above 2 meq/L, was only included for the 4 meq/L and 6 meq/L experiments.

In the case of the Ottawa-Carleton water experiments the volume treated was in excess of 600 L for the longest experiment and 40 L for several others. The Manotick water experimentation was performed on a smaller volume of 30 L, with multiple other runs on smaller volumes. (Appendix A gives the full experimental breakdown). The 600 L experiment was performed over 4 consecutive days to determine if decreased performance, due to membrane fouling, would take place.

Table 8.1 Analysis of complex process streams prior to dosing

Parameter	Units	Ottawa-Carleton	Manotick
Calcium	mg/L	20.0	59.8
Magnesium	mg/L	2.31	28.2
Potassium	mg/L	0.9	7.5
Sodium	mg/L	15	110
Iron	mg/L	<0.02	0.15
Manganese	mg/L	<0.01	0.01
Bicarbonate	mg/L	44	243
Carbonate	mg/L	<1	<1
Chloride	mg/L	4.8	115
Nitrate-NO ₃ ⁻	mg/L	1.0	0.6
Sulphate	mg/L	27.0	65
TDS	mg/L	400	914
pH		7.59	7.83

Sampling, preparation and measurement of samples were performed in an identical fashion to single and multi-species experimentation of synthetic feed streams.

8.2 Results and Discussion:

Figure 8.1 presents the raw data that were collected when a two species equi-molar mixture (nitrate and chloride) of 2 meq/L was evaluated for Ottawa-Carleton water. The experiment was performed at 250 mL/min of process flow, 2.0 volts per membrane pair, Resin #1 and 3 membrane pairs. The concentrations of the major species and current readings are presented in Figure 8.1.

Figure 8.1 Effluent concentrations of nitrate, chloride and sodium and current . (Ottawa-Carleton tap water, 2.0 V/pair, $C_o = 2$ meq/L).

Figure 8.2 presents the resulting fluxes and energy consumption for the experiment. It can be seen from Figure 8.2 that nitrate selective removal occurred with the complex feeds. This was despite the presence of other competing species, TDS, etc. Of note in making comparisons between Ottawa-Carleton and synthetic results was that, despite the same initial concentration of nitrate and chloride, the overall ionic strength was 5 meq/L rather than 4 meq/L. This was due to the additional presence of bicarbonate and sulphate in the complex stream.

Figure 8.2 Fluxes and energy consumption for Ottawa-Carleton water (2.0 V/pair, $C_o = 2$ meq/L).

Figure 8.3 shows the fluxes for all the major anions and cations contained in the feed stream. It can be seen from Figure 8.3 that the anion flux was dominated by nitrate and chloride, and sodium represented the majority of the cation flux. This was due to their high concentrations relative to the other species.

Figure 8.3 Fluxes of major charged species for Ottawa-Carleton water (2.0 V/pair).

Figure 8.4 compares the fluxes of nitrate and chloride for the complex water and the synthetic water experiments for the same run conditions. It can be seen from Figure 8.4 that decreases in flux of approximately 10 percent for nitrate and 8 percent for chloride were observed. Hence, there was a slight decrease in nitrate selectivity relative to chloride.

The complex stream demonstrated higher currents than the synthetic stream and therefore the energy requirement was greater. The energy per equivalence of nitrate removed for the synthetic stream was 220 J/meq, while the consumption for the complex water was 283 J/meq representing a 25% increase.

Figure 8.4 Comparison of nitrate and chloride fluxes for synthetic and complex process streams

8.2.1 Effect of Concentration:

The average fluxes experienced during two runs each for the Ottawa-Carleton feed stream and Manotick feed stream under 3.3 volts per membrane, 3 membrane pairs, Resin #1, 1 mm spacing, 250 mL/min flow, and 4.0 meq/L initial concentration are presented in Figure 8.5. The total anion (and cation)

concentration for the Ottawa-Carleton and Manotick streams were 9 meq/L and 13 meq/L respectively.

It is apparent from Figure 8.5 that nitrate and chloride experienced consistently lower fluxes for the Manotick feed stream relative to the Ottawa-Carleton feed stream. This was likely due to a greater overall amount of competing anions in the Manotick water. Specifically bicarbonate was present at 4 meq/L. Multi-species synthetic testing demonstrated that, while flux goes up with increasing process flow concentration, the incremental increases become smaller. Therefore as concentration levels rise, adding a competing anion impacts nitrate fluxes more than at lower concentration levels.

Figure 8.5 Nitrate and chloride fluxes for both complex feed streams (3.3 V/pair).

It is also apparent that selectivity decreased for the Manotick water relative to the Ottawa-Carleton water (from 53% to 51% when only nitrate and chloride are compared). The decreased selectivity for the Manotick water likely resulted from the higher overall anionic concentration of the Manotick water. In the synthetic multi-species experimentation it was determined that selectivity decreased as ionic strength went up. This is a result of the current density increasing with increased ionic strength.

Figures 8.6 and 8.7 show the fluxes of all the major species contained in the process streams for the 4 meq/L experiments with Ottawa-Carleton and Manotick waters respectively. It can be seen how, due to the higher initial concentration of bicarbonate in the Manotick water relative to the Ottawa-Carleton water (and its resulting flux), that the nitrate flux as a percentage of the total anion flux has gone down in both relative and absolute terms.

Figure 8.6 Fluxes of major charged species for Ottawa-Carleton water .

Figure 8.7 Fluxes of major charged species for Manotick water.

Figure 8.8 demonstrates that the energy consumption (per equivalence of nitrate removed) was higher for the Manotick water than the Ottawa-Carleton water. The greater ionic strength resulted in more species carrying charge, thus decreasing resistance and increasing current. When combined with the lower nitrate fluxes for the Manotick water, the overall effect becomes pronounced. The increases in energy consumption for the Ottawa-Carleton and Manotick waters relative to the synthetic water were 15% and 75% respectively.

Figure 8.8 Energy consumption for various process streams (3.3 V/pair, $C_o = 4$ meq/L).

Figure 8.9 compares the fluxes between the two complex feeds and a similar synthetic stream. It is apparent from Figure 8.9 that the fluxes for the real waters were lower than the synthetic feed stream. Specifically the Ottawa-Carleton water experienced 10-15% lower nitrate fluxes than did the synthetic stream. The Manotick water had an even lower performance of 20-25% below the synthetic fluxes.

Figure 8.9 Comparison of nitrate and chloride fluxes for complex and synthetic feed steams.

It is also apparent from Figure 8.9 that the nitrate flux decreased by a greater percentage as compared to the synthetic water flux than did the chloride flux. As a result, the selectivity of nitrate over chloride was lower for real waters relative to the synthetic water, with the poorest selectivity obtained for the Manotick water. For the synthetic stream the chloride flux was approximately 80% that of nitrate, while for the Ottawa-Carleton and Manotick waters the values were 90% and 95% respectively.

8.2.2 Effect of Resin Type:

Figure 8.10 illustrates the flux of nitrate and chloride for the Ottawa-Carleton feed stream for both nitrate selective resins. The run conditions were 2 meq/L initial concentration and 2.0 volts per membrane pair. It can be seen from Figure 8.10 that there was approximately a 10% decrease in nitrate flux and a 5-10% decrease in chloride flux for Resin #2 relative to Resin #1. The relative differences in flux between the two resins were similar to those found in the synthetic experimentation. Hence, the increased nitrate flux for Resin #1 relative to Resin #2 appears to be independent of the water matrix that is being treated.

Figure 8.10 Impact of resin on complex fluxes of nitrate and chloride (2.0 V/pair)

Figure 8.11 illustrates the ratio of energy consumption for the Ottawa-Carleton feed stream relative to the synthetic feed stream for different voltages and for both nitrate selective resins. It can be seen from the figure that there was a 15-35% increase in energy consumption for the complex water regardless of the applied voltage or resin type. Therefore the factors impacting energy consumption were independent of these process parameters.

Figure 8.11 The effect of complex stream on energy consumption

8.2.3 Impact of Voltage

The fluxes of nitrate and chloride for the complex and synthetic feeds at different voltages and at 2 meq/L initial concentration are presented in Table 8.2.

The other experimental conditions for this data were 1 mm spacing, 250 mL/min process flow and Resin #1.

From the results presented in the table, the same trends with respect to voltage were observed for both water streams. That is that, though flux increased with increasing voltage, selectivity decreased. Very little selectivity was observed at 5.0 volts per membrane pair with either process feed.

Table 8.2 Comparison of the effect of voltage on nitrate and chloride flux

Voltage /pair	Nitrate Flux (meq/cm ² /s)		Chloride Flux (meq/cm ² /s)		Nitrate Selectivity (%)	
	Synthetic	Ottawa- Carleton	Synthetic	Ottawa- Carleton	Synthetic	Ottawa- Carleton
2.0	2.72E-06	2.46E-06	1.77E-06	1.63E-06	61	59
3.3	3.73E-06	3.42E-06	2.81E-06	2.66E-06	57	55
5.0	4.18E-06	4.02E-06	3.98E-06	3.97E-06	51	50

Figure 8.12 presents the energy consumption of the two complex streams at different voltages. Although the fluxes for nitrate and chloride decreased for the complex feed stream relative to the synthetic, the current measured for the complex experiments experienced a slight increase. This was due to the presence of other charged species available to carry charge. The result, when energy consumption was determined as the power consumed by the unit per equivalence removal of nitrate, was an increase in the energy requirement (decrease in energy efficiency) of approximately 25-35%.

Presumably the presence of dissolved solids and other species will reduce the transport of nitrate and chloride towards the anode. However, since nitrate experiences preferential removal under some conditions the effect of the constituents will have a greater impact on nitrate than chloride.

Figure 8.12 the effect of voltage on energy consumption for real and synthetic feed streams ($C_o = 2 \text{ meq/L}$).

The total flux results from the transport in the bulk fluid and the resin. Therefore, because overall flux had decreased, at least one of these two components must have also. Since nitrate selectivity appears to result from enhanced "resin" transport and selectivity decreased it would seem that some component present in the complex water negatively impacted the resin transport.

8.2.4 Flow Comparison:

Figure 8.13 presents the percent removal of chloride relative to nitrate (chloride flux/nitrate flux) under three different voltages and low and high flow (250 mL/min & 500 mL/min) for the Ottawa-Carleton water. As with the multi-species synthetic experiments there was no apparent effect on selectivity with increased feed stream flow rate.

Figure 8.13 Effect of flow on chloride removal relative to nitrate removal ($C_o = 2$ meq/L).

8.3 Extended Duration

An extended duration run was performed with Ottawa-Carleton water in order to determine if any change in performance would occur over a 48-hour period (600 L).

Figure 8.14 shows the results of the extended duration experiment with the Ottawa-Carleton feed stream. The run conditions for this experiment were 3.3 V per membrane pair, 250 mL/min process flow, 3 membrane pairs, Resin #1 and 1 mm spacing. The initial nitrate and chloride concentrations were 2 meq/L. It is apparent from Figure 8.14 that there was not a readily noticeable decrease in flux or selectivity with time. Over the 48-hour period the fluxes remained constant in absolute value (within experimental error). The average fluxes of nitrate and chloride for this single experiment were 3.45×10^{-6} meq/(cm² x sec) and 2.69×10^{-6} meq/(cm² x sec) respectively. These values were approximately 90% and 95% of the synthetic multi-species fluxes, under similar run conditions.

Figure 8.14 Fluxes of Nitrate and Chloride for Ottawa-Carleton water ($C_o = 2$ meq/L).

Even though no decrease in flux was apparent it is recommended that testing be performed at even longer durations (ie. months) to confirm these early results. This is required to estimate the rate of decrease of performance and therefore maintenance schedule of a full-scale unit.

The life span of ion exchange membranes that operate in ultrapure water production is 10-15 years (Sandeaux et al., 1995). It is logical to assume that the serviceable life of the membranes will be shorter for ground and surface water treatment. This is because in ultrapure water production the feed stream to the unit has already undergone numerous pretreatments, (prefiltration, RO, etc.) removing almost all the suspended solids and organic constituents. It is a fact that the feed stream for ultrapure water production is already relatively clean and therefore minimizes any detrimental effect it may have on membrane life.

8.4 Summary:

The general overall effect of a complex feed stream on the performance of the EDI unit was to cause a general decrease in performance (flux and selectivity) and an increase in energy requirement as compared to simple matrices. The unit's performance was most deleteriously affected by the Manotick water which had higher concentrations of hardness, dissolved solids, calcium carbonate and other more minor constituents than the Ottawa-Carleton water.

The decrease in the flux of the different species tested may be the result of greater impedance caused by the presence of the dissolved solids within the

streams and the increased competition of extra ions for current. This is born out somewhat by the lower fluxes experienced for the Manotick water versus the Ottawa-Carleton water. The increase in the energy requirement results from the smaller percentage of current performing only nitrate removal. With more charged species present the current was greater and when combined with lower fluxes the power requirement per equivalence of nitrate removed must increase.

9.0 Alternative Operating Modes:

A number of experiments were performed to determine if the selectivity of nitrate removal could be increased. These experiments attempted to make use of the preferential exchange capacity that Resin #1 and Resin #2 had for nitrate. In this regard EDI performance in two separate operating regimes, an exchange mode (power off) and a regular mode (power on) was evaluated.

It was anticipated that during the power-off phase a fraction of the ion-exchange resin would have available exchange sites. Since the resins were nitrate selective, any available sites would preferentially exchange nitrate. If the resins were to exchange more nitrate relative to other anionic species than in the regular mode of operation then this would increase the overall selectivity of the process.

Two separate types of operation were investigated; One with the product flow always on and the power cycle alternating between on and off (Flow Continuous - Power Alternating) and another with the flow on only when no voltage was applied and flow off when voltage was applied (Flow and Power Alternating). These two separate types of cycling experiments were chosen to fully investigate any possible operating conditions in which nitrate selectivity could potentially be enhanced.

Method - Cycling Experiments

The cycling experiments were conducted in the same manner as the non-cycling experiments in that resin saturation was ensured before the start of any experiment. Similar parameters were varied and fluxes and energy requirements were determined. A programmable timer (ChronTrol Corp., San Diego) that was able to start and stop the power going to a circuit at intervals as small as one second was employed.

Method: Flow Continuous - Power Alternating

These experiments differed from the regular mode experiments in that the power to the EDI's power supply was periodically stopped. For the sake of simplicity the power was alternated at regular intervals in order for results to be more easily interpreted and samples to be collected at the proper intervals. Several different cycling durations were performed to evaluate this type of flow regime. They were: On 5 min - Off 5 min, On 1 min - Off 1 min, On 30 sec - Off 30 sec, On 5 sec - Off 5 sec, and On 1 sec - Off 1 sec.

Voltage and flow were varied for the On 1 min - Off 1 min and the On 5 sec - Off 5 sec experiments to determine if applied voltage or flow rate had any effect in this operating regime relative to the changes observed for voltage and flow variation in non-cycling experiments. For the 5 minute and 1 minute cycling experiments it was possible to collect product from both the power on and power off cycles. However, for smaller cycling durations it was not possible to determine the portion of the flow exiting the EDI product flow hose that had

experienced removal due to the applied potential and what portion has experienced simple exchange. Hence the sampling performed on the less than 1 minute cycles was conducted by collecting all the product over a period of 5 or 10 minutes and taking a grab sample from this volume. The samples reflected the net effect of both aspects of the cycling experiment.

Results: Flow Continuous - Power Alternating

The results of the cycling experiments followed the trend presented in Figure 9.1 for alternating 5 minute cycles of applying a potential across the unit and without any applied electromotive force. The run conditions for this experiment were 3.3 volts per membrane pair for 3 membrane pairs, Resin # 1, 1mm spacing and 250 ml/min process flow rate.

The fluxes for the two species (nitrate and chloride), when the power supply was on, were somewhat lower than the range previously determined for non-cycling experiments under the given run conditions. Average fluxes of 3.73×10^{-6} and 2.81×10^{-6} meq/cm²/sec for nitrate and chloride respectively were observed for regular operation; and 3.44×10^{-6} and 2.61×10^{-6} meq/cm²/sec were obtained for this experiment. The average flux for the cycling experiment was determined by averaging the observed fluxes for power on cycles. Thus, the nitrate flux for the cycling experiment was 10% lower than for regular operation and the chloride flux was lower by approximately 5%. As a result any increased selectivity during the power off cycle would have to be very significant to make up for the poorer selectivity encountered during the power on cycle.

Figure 9.1 Fluxes of nitrate and chloride vs time in 5 minute cycling mode (3.3 V/pair, $C_o = 2\text{meq/L}$).

The power off cycle did seem to demonstrate small removals which would indicate some exchange with the resin. The removals could be interpreted as fluxes since they are calculated on a product stream concentration versus feed stream basis.

The results of the shorter cycling period experiments also did not offer any indication of increased selectivity or ability to benefit from a preferential power off cycle. Figure 9.2 presents the fluxes calculated from the raw data for the 30 s, 5 s and 1 s cycling durations. For all of these experiments the ratio of chloride to nitrate removal was in the 70-80% range which was the same as was observed for non-cycling experiments.

Figure 9.2 Fluxes of nitrate and chloride vs time for short cycling period experiments (3.3 V/pair, $C_o = 2\text{meq/L}$).

Table 9.1 compares the average fluxes of nitrate and chloride and relative removal for a regular non-cycling mode of operation and three power alternating modes of operation (under the same run conditions as Figure 9.1). The cycling values are averaged over both cycles. The data obtained in all of these runs are contained in Appendix F. The regular mode of operation values and the cycling values represent an average of two experiments.

Table 9.1 Comparison of nitrate and chloride fluxes in regular and power cycling mode (3.3 V/pair, $C_o = 2\text{meq/L}$).

Mode of Operation	Nitrate Flux (meq/cm ² /sec)	Chloride Flux (meq/cm ² /sec)	Chloride Flux / Nitrate Flux
Regular	3.73 E-06	2.81E-06	75 %
5min/5min	1.96 E-06	1.48 E-06	76 %
1min/1min	1.77 E-06	1.28 E-06	72 %
5sec/5sec	1.72 E-06	1.37 E-06	80 %

The power off phase did favour nitrate removal somewhat but less so than the selectivity experienced during regular operation. (It should be noted that with such small differences between the product and feed stream concentrations greater relative error in determining fluxes was experienced). The chloride flux to nitrate flux ratio was up to 10% poorer under all cycling experiments. As a result no advantage of operating under these conditions was realized under these or any other run conditions.

Also, even if increased selectivity were to be determined it would be necessary to weigh this versus the decreased overall anionic flux. In other words, even if this was a more nitrate selective mode of operation the fluxes were so low there was hardly any "bulk" removal occurring.

Figure 9.3 presents the relative removal of nitrate and chloride for regular operation and two cycling modes of operation at 5 V per membrane pair. In each case the nitrate flux was set at 100% and the chloride flux was related to it. It can be seen that no increase in selectivity was experienced at this voltage, as

was the case at 3.3 V per membrane pair. In fact a slight decrease in selectivity was observed.

It is important to remember that the overall flux in this cycling mode was approximately 50% of regular operation (i.e. the power source was on half the time and this was when almost all of the charged species removal occurred.) Therefore, only half the amount of water could be treated in cycling mode, or a unit of twice the capacity would be necessitated.

Figure 9.3 Relative removal of nitrate and chloride for regular and continuous flow/power alternating operation (5.0 V/pair, $C_o = 2\text{meq/L}$).

Similarly, flow had no discernable affect on performance in this mode of operation. This concurs with single species and multi-species experiments where no effect on flux or selectivity was observed except for some higher flow rates when channelling or short-circuiting could result.

Energy consumption for all of these cycling experiments was similar to those for regular operation at the same run conditions (See Figure 9.4). In this context energy consumption was the amount of energy required to remove an equivalence of nitrate rather than the energy required to remove an equivalence of anionic species.

Figure 9.4 Comparison of energy efficiency for regular and 1 minute cycling experiments ($C_o = 2\text{meq/L}$).

The similar energy consumption resulted from the fact that very little removal occurred during the power off cycle. As a result the EDI unit was only operating half the time in its usual manner. During these times the current density for the given run conditions was the same as in regular operation. Therefore, the energy consumption was the same, but at half the flux and no greater selectivity than regular operation. Due to these observations no further investigations on this type of cycling experimentation were performed.

Method - Flow and Power Alternating:

A similar approach was taken with these cycling experiments with the exception that the feed stream pump was off when the DC power supply was on and the power supply was off when the feed stream pump was on.

The method used to determine removal rates in all the cycling runs included collection and analysis of grab samples obtained from 20 L of product that was produced through the duration of the experiment. This was done in order to be certain that the sample was an average of the product. Analysis was performed on four different fractions of the 20 L sample to evaluate whether there was a time dependent response under any of the run conditions. For example the removal rates and selectivity from a sample of the first 5 L of product of a given run were compared to a sample from the last 5 L of product from a given run.

Numerous run conditions were investigated in this cycling mode. They were P10 -F10, P5-F5, P2-F2, P10-F5 and P5-F10. The letters describing the

cycling experiments represent power and flow, the number represents the number of seconds each was on. Therefore P10-F10 means the power source was on for 10 seconds followed by the flow being on for 10 seconds (then the cycle repeats itself). Also, voltage and flow were varied for a P5-F5 run condition in order to determine if applied voltage or flow rate had any effect in this operating regime.

Results: (Flow and Power Alternating)

The fluxes observed for some of the flow and power alternating runs are presented in Figure 9.5. It can be seen that as the time between power and flow cycles became larger the overall fluxes of both nitrate and chloride diminished, from a high of $3.07 \times 10^{-6} \text{ meq}/(\text{cm}^2 \times \text{sec})$ at P2-F2 to a low of $2.58 \times 10^{-6} \text{ meq}/(\text{cm}^2 \times \text{sec})$ at P10-F10 (for nitrate).

This was not unexpected since for extended intervals the number of available sites for exchange during the exchange phase would become insignificant resulting in no removal and therefore no flux. Therefore early on in the experiments it was determined that any possible benefits in this cycling mode would have to be in the range of seconds rather than minutes.

Figure 9.5 Comparison of nitrate and chloride fluxes for regular and flow alternating -power alternating cycling experiments (3.3 V/pair, $C_o = 2$ meq/L).

The overall selectivity results of the flow and power alternating runs are presented in Table 9.2. For the summarized results of 3.3 V per membrane pair, 3 membrane pairs, Resin #1 and a flow of 250 mL/ min nitrate selectivity varied from 50 % (no preference for nitrate removal) to 59 %. None of these results are a marked improvement on the 58 % selectivity experienced in regular operation under the same conditions. No readily identifiable trends were observed for these runs that would warrant further testing.

Table 9.2 Removal rates in Flow and Power Alternating Mode (3.3 V/pair, $C_o = 2$ meq/L).

Summary						
Power/Flow (sec)	Nitrate Removal (%)		Chloride Removal (%)		Nitrate Selectivity (%)	
	1st Run	2nd Run	1st Run	2nd Run	1st Run	2nd Run
10,10	8.4	7.5	6.6	5.3	56	59
5,5	7.3	9.3	5.9	6.8	55	58
2,2	9.1	8.7	9.1	6.8	50	56
5,10	6.7	8.3	6.1	8.0	52	51
10,5	6.5	7.5	5.2	5.3	56	59

The effect on flux and selectivity of varying the voltage from 3.3 to 5.0 volts per membrane pair on a P10-F10 cycling experiment are presented in Figure 9.6. It can be observed that added potential caused an even greater decrease in selectivity in this mode of operation as compared to regular operation.

The effect on flux and selectivity of varying the voltage from 3.3 to 5.0 volts per membrane pair on a P10-F10 cycling experiment are presented in Figure 9.6. It can be observed that added potential caused an even greater decrease in selectivity in this mode of operation as compared to regular operation.

Figure 9.6 Effect of voltage increase on nitrate and chloride fluxes in power and flow alternating mode ($C_o = 2$ meq/L).

The energy consumption of operating in this type of cycling mode is presented in Figure 9.7. It is apparent that as the duration of the time steps increased the energy requirement per equivalence for the removal of nitrate also increased (ie. energy efficiency decreased). It can also be observed that the most energy efficient operation of the EDI unit, at 3.3 V/pair, was in regular mode. Therefore the cycles at 3.3 V/pair required more energy and therefore power and cost to accomplish the same amount of removal that was experienced in regular operation. At 5.0 V/pair little difference between modes was observed.

Figure 9.7 Comparison of energy consumption at different voltages between regular and power & flow alternating modes of operation ($C_o = 2 \text{ meq/L}$).

If any possible cost savings were to be achieved in a scaled up model operating under cycling conditions the first criteria is greater selectivity. Then it may be possible to determine a sizing and flow that would benefit from the greater selectivity despite the lower overall treatment (i.e. when the flow is off no product is being produced therefore less overall process water is being treated than in regular mode). Since this first necessary criteria was not achieved operating and size up costs in the cycling mode were not determined.

10.0 Competing Technologies and Cost Comparison

The removal of nitrate from water sources can be accomplished in several different ways. In principle there are biological and chemo-physical technologies, which can be divided into degradation processes (biological or catalytic nitrate reduction) and separation processes. The separation processes include ion exchange, reverse osmosis, electrodialysis and electrodeionization. Each of these processes has its own advantages and disadvantages. In contrast to biological processes, physical separation processes can easily be started and stopped over longer periods, which makes them suitable for seasonal operation.

10.1.1 Biological Denitrification

The advantage of biological denitrification is the direct degradation of nitrate to molecular nitrogen. The only by-product of biological processes is a small amount of biomass. Nevertheless, due to the biological activity, these processes are only applicable for full time operation and respond poorly to quick changes in influent nitrate concentration. Another drawback is that typically ethanol (or a similar carbon source) and phosphorous are also required for the process to function properly (Kesore et al. 1997).

10.1.2 Ion Exchange

In the field of ion exchange, simple nitrate selective ion exchange resins operated in a columnar mode are the typical method of nitrate removal. The column is operated by introducing the influent to the top of the column and monitoring the effluent to determine breakthrough. The problem that arises is that these nitrate selective resins are strongly basic anion exchangers and as a result require a large quantity of harsh regenerant chemicals (i.e., NaOH); relative to weakly basic, non-specific resins (Matejka et al., 1999). This results in the disposal of large quantities of spent regenerant solutions, containing high concentrations of regenerant chemicals and also nitrates displaced from the anion exchanger.

10.1.3 Reverse Osmosis

As compared to ion-exchange, reverse osmosis has a very low chemical demand. Reverse osmosis is a pressure driven system with a partially selective membrane. The disadvantage is that demineralization is high and unselective. Also there are high capital costs for equipment that can withstand the high operating pressures and high energy costs to generate the pressure.

10.2 Cost Comparison

It was deemed more appropriate to perform the cost comparison between EDI and ion exchange alone and not biological denitrification or reverse osmosis. This is because biological denitrification is usually found as a process in a wastewater treatment plant rather than as a stand-alone treatment of a nitrate

contaminated ground or surface water. Also, due to its inclusion as part of a full plant, the costs associated with biological denitrification are somewhat more difficult to ascertain relative to EDI and ion exchange. RO is simply too expensive to consider as an alternative in nitrate removal from surface and ground waters.

For the purposes of a cost comparison between EDI and ion exchange, in order to achieve (at minimum) WHO drinking water standards, it was necessary to compare similarly contaminated waters. As a result the comparisons have been performed for two typical 100 mg/L nitrate contaminated groundwaters and the costs of treating the complex waters.

The actual size up costs for treating a large flow, relative to those encountered in the bench scale unit, were difficult to determine. Thus, the costs associated with EDI were calculated by determining the average costs per cubic meter of the complex waters from the results obtained in the complex and recycle experiments. Disregarding selectivity the cost of treating the two complex waters at different voltages were compared.

From previous experimentation, higher voltages have been determined to require more energy per equivalence removed (operating costs) but the higher fluxes achieved results in a reduced membrane surface area (capital costs). Therefore a general sense of the most cost-effective treatment of the natural waters can be computed by determining the minimum value of the capital + operation & maintenance costs (total cost). The results of this analysis appear below.

It is understood that this method yields a rather inexact comparison due to the fact that the feed streams for each of these processes are somewhat different from each other, making concrete statements about costs difficult. However, it is the range of costs that was desired in order to determine if EDI is at all a reasonable alternative to ion-exchange.

10.2.1 Ion-Exchange Costs:

Of concern in the cost comparisons involving ion-exchange columns is the feed concentration of sulphate. Sulphate will compete for exchange sites with nitrate for traditional strong base anion exchange resins. The use of nitrate selective resins, at a greater cost, must be considered relative to the reduced performance imposed by a high sulphate concentration. In both cases the plants operated with general anion exchange resins despite the relatively high concentrations of sulphate (> 100mg/L).

Total costs for a 1 MGD plant at McFarland, California and Lansing, Michigan in 1985 and 1987 U.S. dollars were calculated to be the following (Canter, 1997):

Table 10.1 Ion-exchange costs for nitrate contaminated groundwater

Cost (cents/1000 gal)	California	Michigan
Capital Cost	25.1	28.2
O & M Cost	16.1	17.4
Total Cost	41.2	43.6

The capital costs of the plant were calculated over a 20 yr life cycle at 8% interest (Canter, 1997). The total cost in year 2000 Canadian dollars per cubic meter was approximately 0.28 \$/m³ and 0.30 \$/m³ for the California and Michigan waters respectively.

The composition of the McFarland, California and Lansing, Michigan groundwaters can be found in Appendix G. The average nitrate concentration of four test wells of the GW, for the California site, was approximately 100 mg/L as NO₃; sulphate 143 mg/L and the TDS were 400-500 mg/L.

The water was treated to below 45 mg/L but then blended with untreated feed to a concentration a few mg/L below 45 mg/L.

10.2.2 EDI Treatment Costs:

The costs associated with the treatment of these waters with the bench scale unit were estimated. They were relatively high given that the largest number of membrane pairs experimented upon was 5 and the overall mass of nitrate removed from the process stream was not that large. It is also necessary to know the membrane replacement schedule in order to know the total volume of water treated before incurring these costs. For the purposes of the cost comparison it was assumed that the membranes could operate for ten years (Ganzi, 1998) with periodic maintenance to ensure fouling is maintained at a minimum.

The total cost per cubic meter was calculated using Equation 10.1:

$$\text{Total Cost} = \text{Amortized Capital cost} + \text{Operation \& Maintenance} \quad (10.1)$$

The cost of all of the components used in fabricating the unit were known and the capital cost was calculated using Equation 10.2:

$$\text{Capital Cost} = (\text{Membrane} + \text{Resin} + \text{Casing} + \text{Electrodes} + \text{Pumps}) \quad (10.2) \\ / \text{ Total volume treated}$$

In practice EDI units operating in ultrapure water production typically contain 40-60 membrane pairs (Ganzi, 1998) depending on the process flow rate and packing arrangement. After a certain number of pairs, leakage of water through the anion & cation exchange membranes can become problematic due to the head required to pump through a large number of chambers. Therefore treatment costs were extrapolated for up to 40 membrane pairs for the bench scale unit.

This extrapolation was performed by following the trends observed in increasing the number of membrane pairs from 2 to 3 to 5 in the single and multi-species experimentation. Those trends were an approximate 10% decrease in flux and 5-10 % increase in energy requirement with a doubling of the number of membrane pairs. This in turn has a deleterious effect on the O & M costs since decreasing flux means a poorer volume of water treated to cubic meter of

membrane ratio. The result was that the fluxes and power requirements were extrapolated from 3 to 6,9,20 and 40 membrane pairs, with the flux at 40 membrane pairs estimated at approximately 65% of the 3 membrane pairs value.

The operation and maintenance cost was calculated using Equation 10.3:

$$\text{O \& M Cost} = (\text{Unit and Pumping Power per day}) \times \text{Maintenance Factor} \quad (10.3) \\ \text{/volume treated per day}$$

A breakdown of the capital costs and operation and maintenance costs for the bench scale unit can be found in Appendix G. Table 10.2 presents the costs associated with the bench scale unit at a 3 and 40 membrane pairs and three different applied voltages. Due to the similar fluxes and energy requirement the costs for treating either complex water were similar. Since the exactness of the cost analysis was difficult to determine the results were simply presented as an average of the two waters.

Table 10.2 Cost of treatment for complex waters (\$/m³)

	3 membrane pairs			40 membrane pairs		
	2.0 V	3.3 V	5.0 V	2.0 V	3.3 V	5.0 V
Capital	0.53	0.35	0.30	0.15	0.09	0.08
O & M	0.19	0.21	0.31	0.28	0.31	0.38
Total cost	0.72	0.57	0.61	0.43	0.40	0.47

It can be seen from the cost estimates for EDI operation that 3 membrane pairs per unit is far too small a number for cost effective operation. The costs per cubic meter were approximately 50% greater as compared to 40 membrane pairs per unit. Also of note was that as the voltage per membrane pair increased the capital cost went down. This was due to the larger fluxes, which meant less of a membrane surface area requirement. However the resulting increased power requirement at higher voltages resulted in greater operating costs. For the systems with 40 membrane pairs, operating at 5 volts per membrane pair was the least cost effective operating regime.

Of particular note was that at 40 membrane pairs the operation and maintenance costs were a greater percentage of total costs than at 3 membrane pairs (or conversely capital costs decreased as a percentage of total costs). The reason for this was that as the number of membrane pairs increased the only capital cost increase was due to the larger number of membranes (and amount of resin). The same electrodes pumps and casing can be used at this number of membrane pairs, with an increase in the power requirement of the pumps. This resulted in 2.0 V per membrane pair being close to as cost effective as 3.3 volts per membrane pair. An additional advantage of 2.0 volt per membrane pair operation was that selectivity was greatest at lower voltages, the choice could be made to operate at the lower applied potential.

Figure 10.1 demonstrates the trends observed when the number of membrane pairs was increased from 3 to 40. It can be seen from Figure 10.1 that after 10 membrane pairs the decrease in cost was gradual. Given our

confidence in these values it is difficult to say with certainty if there is any difference in overall cost between 10, 20 and 40 membrane pairs.

Thus a comparison of ion exchange and EDI treatment for a similarly contaminated groundwater yielded a treatment cost approximately 15-25% greater for EDI (30 vs 40 cents per cubic meter). Though the costs associated with the bench-scale unit were higher it is assumed that scale-up will increase the competitiveness of the EDI process as the proper size of pumps can be purchased and casing costs should go down as a percentage of capital costs with increased size.

Figure 10.1 Costs of EDI unit operation on complex feed at 3.3 volts per membrane pair

It would be advisable to operate the bench scale unit for a much longer period of time (say several months) of continuous operation with a nitrate contaminated groundwater in order to determine more closely the replacement schedule for both the resin and membranes. Until such time the cost estimate for EDI operation remains rather uncertain and a more precise comparison with ion exchange is unachievable.

If it is still reasonable to believe that the costs associated with EDI treatment are comparable to ion exchange, then a full-scale pilot plant operation treating 0.1 MGD ($380 \text{ m}^3/\text{day}$) should be examined in order to make a more exact determination. From the experimental results this would require approximately 420 square meters of membrane surface area contained in a 40 membrane pair configuration. This could be accomplished by a bank of ten or twelve 1 meter x 1 meter x 40 membrane pair units each treating a portion of the flow. The foot print left by such a pilot plant need only be in the range of 10-15 square meters of floor space.

11.0 Conclusions and Recommendations :

As a result of the experimentation performed with the EDI unit the following conclusions and recommendations can be made regarding the variation of the operating parameters:

- 1) **Feed flow rate:** An increase in feed flow rate from 250 mL/min to 500 mL/min resulted in lower fluxes and higher currents and therefore higher energy consumption per equivalence removed. Nitrate selectivity was unaffected. It is therefore recommended that flow rates of 250 mL/min or less be investigated in any further experimentation involving the EDI unit.
- 2) **Voltage per membrane pair:** Increased voltage resulted in higher fluxes but also higher energy consumption per equivalence. Nitrate selectivity was greatest at 2.0 volts per membrane pair (typically at current densities below 1.0 mA/cm², as found by Kesore et al. (1997)). As seen in the cost analysis, the nature of the feed stream affects which applied voltage is the most cost effective per volume of feed treated. Hence, considerations such as available space and the importance of nitrate selectivity need to be weighed in any individual application.
- 3) **Inter-membrane spacing:** Regardless of the feed stream increased spacing resulted in power performance of the EDI unit. It seems clear that what is needed is enough space to ensure resin placement and hence flow pathways but not so much space as to increase resistance

to current. There is also a greater possibility, with increased spacing, that resin settling will occur. It is therefore recommended that 1mm spacings or less be investigated in future experimentation.

- 4) **Resin type:** Both of the nitrate selective resins achieved higher nitrate fluxes at lower energy requirements than the general anion exchange resin. Also, nitrate selectivity was not observed in with the general anion exchange resin. It seems as if the physiochemical properties of the nitrate selective resins that allow for selectivity in ion exchange columns also allow for selectivity in an EDI system. It is recommended that future experimentation be restricted to nitrate selective resins alone.
- 5) **Number of cell pairs:** It can be seen from the cost analysis that there is a trade off between the high capital costs incurred at low operating voltages (large surface area needed) and the higher power costs associated with operating a smaller unit at a higher voltage. Increasing the number of cell pairs formed the basis of the extrapolation contained in the cost analysis (to obtain estimates of flux and energy requirement in order to determine treatment costs at 10, 20 and 40 membrane pairs). It is therefore recommended that an attempt be made to operate the unit at these numbers of pairs in order to verify the accuracy of the estimated treatment costs.

6) **Feed stream concentration:** At total anion concentrations above about 6 meq/L an increase in concentration no longer lowers the power requirement. As concentrations decrease below 1 meq/L the power requirement increases noticeably. Also, selectivity increases as total anionic concentration goes down. It is worth doing recycle experimentation on a given sample of nitrate-contaminated water to determine overall removal levels of all constituents when nitrate has reached its MAC level.

Not only the absolute concentrations of nitrate and competing anions are relevant to determine performance but also the level of TDS. Performance was better for the Ottawa-Carleton tap water than the Manotick groundwater. It would therefore be valid to perform some experiments where the levels of TDS are the only variable.

It is highly recommended that longer duration testing (months of continuous operation) on a complex feed stream be performed. This enables the determination of performance over time intervals that a real application will require. Also, this type of experimentation will aid in determining if any pretreatment of the feed needs to be performed to ensure steady long term performance.

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Appendix A

Ion Exchange Experiments

Ion Exchange Experiments

Inlet Concentration:

200 mg/L

Mass of resin :

100 grams

Flow rate:

250 mL/min

Bed Volumes	Outlet Concentration (mg/L)		
	Resin 1	Resin 2	General
0	3.6	2.2	1.5
20	3.5	3.1	2.1
40	3.5	3.8	4.2
60	6.5	3.6	3.6
80	5.3	3.9	3.5
100	4.5	3.3	4.9
120	8.0	1.2	4.7
140	7.2	5.5	4
160	9.2	30.6	7.1
180	10.2	62.3	10.4
200	22.3	79.5	3.8
220	66.9	102	5.6
240	195	154	6.2
260	199	183	14.3
280	199	200	89.9
300	198	202	184
320	200	199	198
340	202	200	199

Appendix B

Once-through Single Species Experiments

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	104.1	1.78E-04	2.87E-06	87	130
10	105.0	1.70E-04	2.75E-06	85	143
15	106.4	1.58E-04	2.55E-06	85	164
20	107.0	1.52E-04	2.48E-06	85	134
25	108.6	1.38E-04	2.23E-06	85	146
30	108.1	1.57E-04	2.51E-06	85	130
35	105.1	1.69E-04	2.73E-06	85	146
40	107.3	1.50E-04	2.42E-06	85	134
45	106.7	1.55E-04	2.50E-06	85	146
50	108.3	1.59E-04	2.58E-06	85	130
Average	106.5	1.57E-04	2.53E-06	84.9	145.1

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	102.0	1.97E-04	3.17E-06	88	119
10	106.9	1.58E-04	2.47E-06	88	130
15	105.3	1.68E-04	2.70E-06	85	135
20	108.5	1.57E-04	2.58E-06	84	139
25	105.8	1.63E-04	2.63E-06	85	139
30	107.0	1.53E-04	2.46E-06	86	153
35	107.3	1.50E-04	2.41E-06	86	153
40	107.8	1.50E-04	2.42E-06	86	153
45	105.7	1.64E-04	2.65E-06	85	138
50	108.7	1.73E-04	2.79E-06	85	131

Average 106.3 1.59E-04 2.56E-06 85.1 143.1

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	94.5	2.64E-04	4.26E-06	115	193
10	96.8	2.43E-04	3.92E-06	112	193
15	97.5	2.37E-04	3.83E-06	112	210
20	98.0	2.38E-04	3.74E-06	111	218
25	98.7	2.27E-04	3.65E-06	111	218
30	97.6	2.36E-04	3.61E-06	111	205
35	97.2	2.40E-04	3.87E-06	111	205
40	99.4	2.40E-04	3.70E-06	112	212
45	97.9	2.34E-04	3.78E-06	112	212
50	97.1	2.38E-04	3.74E-06	112	212

Average 97.7 2.35E-04 3.80E-06 111.6 210.5

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	94.0	2.69E-04	4.34E-06	115	190
10	98.2	2.31E-04	3.73E-06	111	217
15	97.5	2.37E-04	3.83E-06	112	210
20	99.1	2.23E-04	3.60E-06	111	221
25	98.2	2.31E-04	3.73E-06	111	213
30	99.5	2.20E-04	3.51E-06	111	227
35	98.9	2.25E-04	3.63E-06	111	219
40	97.1	2.38E-04	3.81E-06	112	209
45	97.8	2.35E-04	3.79E-06	112	212
50	96.2	2.49E-04	3.97E-06	111	205

Average 98.2 2.31E-04 3.73E-06 111.6 214.4

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	88.9	3.15E-04	5.07E-06	146	309
10	91.2	2.94E-04	4.74E-06	143	324
15	91.2	2.85E-04	4.60E-06	142	332
20	90.5	3.00E-04	4.84E-06	143	318
25	92.4	2.83E-04	4.57E-06	142	334
30	91.2	2.92E-04	4.73E-06	143	321
35	91.2	2.92E-04	4.73E-06	143	321
40	91.2	2.92E-04	4.73E-06	143	321
45	91.2	2.92E-04	4.73E-06	143	321
50	91.2	2.92E-04	4.73E-06	143	321

Average 91.9 2.88E-04 4.64E-06 142.6 330.4

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	89.2	3.12E-04	5.03E-06	145	310
10	90.1	3.10E-04	4.99E-06	142	311
15	90.8	2.97E-04	4.80E-06	141	316
20	90.5	3.00E-04	4.84E-06	140	315
25	90.6	2.99E-04	4.83E-06	141	314
30	90.3	3.02E-04	4.87E-06	140	315
35	93.6	2.72E-04	4.39E-06	140	343
40	92.0	2.87E-04	4.62E-06	140	335
45	91.4	2.92E-04	4.71E-06	140	320
50	90.6	2.99E-04	4.83E-06	140	315

Average 91.1 2.95E-04 4.75E-06 140.6 318.2

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 248

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	212.0	3.23E-04	5.20E-06	145	120
15	216.0	2.87E-04	4.62E-06	140	130
25	220.0	2.51E-04	4.05E-06	140	149
35	213.0	3.14E-04	5.06E-06	140	119
45	218.0	2.69E-04	4.34E-06	140	139
Average	216.6	2.82E-04	4.54E-06	139.9	133.2

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	94.5	2.64E-04	4.26E-06	115	193
10	96.8	2.43E-04	3.92E-06	112	210
15	97.5	2.37E-04	3.83E-06	111	218
20	98.0	2.36E-04	3.76E-06	111	205
25	98.7	2.27E-04	3.65E-06	112	212
30	97.6	2.36E-04	3.70E-06	112	212
35	97.2	2.40E-04	3.87E-06	111	205
40	98.3	2.30E-04	3.70E-06	112	212
45	97.9	2.34E-04	3.78E-06	112	212
50	97.9	2.33E-04	3.74E-06	111	212
Average	97.7	2.35E-04	3.80E-06	111.6	210.5

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 248

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	212.0	3.23E-04	5.20E-06	142	117
10	217.0	2.78E-04	4.45E-06	135	132
15	222.0	2.33E-04	3.76E-06	136	156
20	215.0	2.95E-04	4.70E-06	136	119
25	214.0	3.05E-04	4.91E-06	136	119
30	210.0	3.21E-04	5.19E-06	135	107
35	216.0	2.87E-04	4.62E-06	135	126
40	212.0	3.23E-04	5.20E-06	135	112
45	211.0	3.32E-04	5.35E-06	135	109
50	213.0	2.93E-04	4.77E-06	135	122
Average	214.7	2.99E-04	4.82E-06	135.7	122.5

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 248

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	191.0	5.11E-04	8.24E-06	205	178
10	202.0	4.12E-04	6.65E-06	196	190
15	197.0	4.57E-04	7.37E-06	196	190
20	203.0	4.03E-04	6.50E-06	195	215
25	203.0	4.03E-04	6.50E-06	195	215
30	198.0	4.48E-04	7.23E-06	195	230
35	206.0	3.76E-04	6.07E-06	195	230
40	204.0	3.94E-04	6.40E-06	194	192
45	198.0	4.48E-04	7.23E-06	194	192
50	196.0	4.68E-04	7.52E-06	193	188
Average	200.8	4.23E-04	6.82E-06	195.7	206.4

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 3 Initial Conc 248

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	185.0	5.65E-04	9.11E-06	260	307
10	188.0	5.73E-04	9.16E-06	256	316
15	192.0	5.02E-04	8.09E-06	256	340
20	186.0	5.58E-04	8.98E-06	255	307
25	192.0	5.02E-04	8.09E-06	255	339
30	190.0	5.30E-04	8.53E-06	256	307
35	186.0	5.56E-04	8.96E-06	256	307
40	193.0	4.98E-04	7.97E-06	255	316
45	188.0	5.38E-04	8.67E-06	255	316
50	192.0	5.07E-04	8.10E-06	255	316

Average 189.7 5.23E-04 8.43E-06 255.2 326.1

Single Species Experimentation

Run #1

Flow (mL/min) 250
 Spacing 1 mm
 Voltage 2.0
 Resin Num 1
 # of Pairs 3
 Initial Conc 372

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	324.0	4.30E-04	6.94E-06	182	113
10	329.0	3.85E-04	6.21E-06	180	125
15	331.0	3.67E-04	5.93E-06	178	129
20	335.0	3.62E-04	5.85E-06	176	132
25	330.0	3.76E-04	6.07E-06	178	126
30	328.0	3.94E-04	6.35E-06	178	125
35	334.0	3.41E-04	5.49E-06	176	138
40	330.0	3.73E-04	6.01E-06	177	127
45	331.0	3.67E-04	5.93E-06	177	128
50	328.0	3.97E-04	6.36E-06	178	125

Average 330.7 3.70E-04 5.97E-06 177.3 128.1

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 372

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	310.0	5.56E-04	8.96E-06	270	216
10	320.0	4.66E-04	7.52E-06	253	241
15	316.0	5.02E-04	8.09E-06	255	226
20	315.0	5.11E-04	8.24E-06	254	252
25	322.0	4.48E-04	7.23E-06	254	252
30	313.0	5.02E-04	8.09E-06	253	241
35	320.0	4.66E-04	7.52E-06	253	241
40	310.0	5.56E-04	8.96E-06	270	216
45	311.0	5.47E-04	8.82E-06	253	206
50	315.0	5.11E-04	8.24E-06	254	252

Average 316.1 5.01E-04 8.08E-06 254.6 226.8

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 372

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	330.0	3.76E-04	6.07E-06	175	124
15	340.0	2.87E-04	4.62E-06	170	158
25	342.0	2.69E-04	4.34E-06	169	168
35	336.0	3.23E-04	5.20E-06	170	141
45	336.0	3.23E-04	5.20E-06	169	140
Average	336.4	3.19E-04	5.14E-06	169.2	142.9

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 3 Initial Conc 372

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	290.0	7.35E-04	1.19E-05	300	272
15	305.0	6.00E-04	9.68E-06	294	326
20	298.0	6.63E-04	1.07E-05	294	347
25	309.0	5.65E-04	9.11E-06	294	303
35	300.0	6.45E-04	1.04E-05	293	308
45	301.0	6.36E-04	1.03E-05	294	308
Average	302.1	6.26E-04	1.01E-05	293.8	313.4

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 2 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	104.1	1.78E-04	2.87E-06	90	135
10	107.1	1.51E-04	2.44E-06	88	135
15	108.2	1.42E-04	2.28E-06	87	164
20	107.9	1.44E-04	2.33E-06	85	166
25	108.6	1.38E-04	2.23E-06	86	166
30	108.4	1.57E-04	2.54E-06	88	178
35	109.6	1.29E-04	2.08E-06	86	178
40	109.6	1.29E-04	2.08E-06	86	155
45	107.5	1.48E-04	2.38E-06	86	155
50	108.7	1.38E-04	2.20E-06	86	158
Average	108.2	1.42E-04	2.28E-06	86.3	163.2

Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 2.0
 Resin Num 2
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	104.5	1.75E-04	2.82E-06	92	140
10	108.6	1.35E-04	2.15E-06	90	172
15	109.6	1.29E-04	2.08E-06	90	186
20	109.6	1.29E-04	2.08E-06	89	172
25	108.6	1.38E-04	2.23E-06	89	174
30	108.2	1.21E-04	1.95E-06	89	183
35	108.6	1.38E-04	2.23E-06	89	183
40	108.9	1.35E-04	2.15E-06	89	183
45	109.5	1.30E-04	2.10E-06	89	183
50	108.6	1.21E-04	1.95E-06	89	183

Average 109.1 1.33E-04 2.15E-06 89.4 179.3

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 2 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	96.0	2.51E-04	4.05E-06	120	212
10	101.6	2.02E-04	3.15E-06	111	212
15	99.2	2.22E-04	3.58E-06	117	234
20	99.8	2.17E-04	3.40E-06	114	235
25	99.8	2.17E-04	3.50E-06	115	235
30	100.6	2.15E-04	3.40E-06	114	240
35	100.5	2.11E-04	3.40E-06	114	240
40	97.9	2.23E-04	3.77E-06	115	231
45	99.3	2.21E-04	3.57E-06	115	231
50	101.2	2.04E-04	3.30E-06	111	233
Average	100.0	2.15E-04	3.47E-06	115.3	238.4

Run #1
 Flow (mL/min) Spacing Voltage Resin # of Pairs Initial Conc
 250 1 mm 3.3 Num 2 3 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	95.0	2.60E-04	4.19E-06	118	202
15	100.2	2.13E-04	3.44E-06	114	237
25	97.9	2.34E-04	3.77E-06	115	218
35	100.6	2.10E-04	3.38E-06	114	241
45	99.3	2.21E-04	3.57E-06	114	229
Average	99.5	2.19E-04	3.53E-06	114.1	231.6

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 2 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	89.2	3.12E-04	5.03E-06	149	319
10	93.5	2.73E-04	4.31E-06	145	363
15	94.0	2.69E-04	4.34E-06	145	360
20	93.0	2.78E-04	4.35E-06	145	360
25	92.0	2.87E-04	4.62E-06	145	337
30	93.5	2.74E-04	4.41E-06	145	361
35	94.1	2.68E-04	4.32E-06	145	361
40	91.0	2.89E-04	4.55E-06	145	345
45	94.4	2.65E-04	4.28E-06	145	364
50	95.0	2.60E-04	4.19E-06	145	364
Average	93.5	2.73E-04	4.41E-06	145.4	354.9

Run #2
 Flow (mL/min) Spacing Voltage Resin # of Pairs Initial Conc
 250 1 mm 5.0 Num 2 3 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	90.2	3.03E-04	4.88E-06	150	330
10	93.0	2.79E-04	4.41E-06	149	349
15	92.6	2.81E-04	4.54E-06	147	348
20	94.1	2.68E-04	4.32E-06	146	363
25	90.2	3.03E-04	4.88E-06	146	321
30	93.6	2.72E-04	4.39E-06	146	340
35	94.1	2.68E-04	4.32E-06	146	363
40	92.6	2.81E-04	4.54E-06	146	348
45	91.4	2.92E-04	4.71E-06	146	333
50	93.0	2.79E-04	4.41E-06	146	349
Average	92.8	2.79E-04	4.51E-06	146.3	349.7

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin General # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	106.8	1.54E-04	2.49E-06	90	156
15	110.8	1.18E-04	1.91E-06	88	198
25	109.5	1.30E-04	2.10E-06	87	179
35	110.6	1.20E-04	1.94E-06	87	193
45	109.6	1.29E-04	2.08E-06	87	180

Average 110.2 1.23E-04 1.99E-06 87.8 189.9

Run #2
Flow (mL/min) 250
Spacing 1 mm
Voltage 2.0
Resin General
of Pairs 3
Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	107.1	1.51E-04	2.44E-06	92	162
15	110.5	1.21E-04	1.95E-06	90	198
25	110.6	1.20E-04	1.94E-06	89	198
35	109.5	1.30E-04	2.10E-06	90	185
45	110.2	1.24E-04	1.99E-06	89	192

Average **110.9** **1.17E-04** **1.89E-06** **89.3** **204.3**

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin General # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	99.5	2.20E-04	3.54E-06	126	255
10	104.2	1.77E-04	2.86E-06	124	293
15	103.8	1.81E-04	2.92E-06	120	294
20	102.6	1.93E-04	3.31E-06	119	288
25	102.1	1.96E-04	3.17E-06	120	272
30	103.4	1.85E-04	3.08E-06	119	283
35	101.8	1.99E-04	3.21E-06	118	263
40	102.6	1.92E-04	3.09E-06	119	275
45	101.9	1.98E-04	3.19E-06	120	269
50	103.9	1.84E-04	2.96E-06	119	285
Average	102.9	1.89E-04	3.05E-06	119.6	280.8

Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.3
 Resin General
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	97.8	2.35E-04	3.79E-06	118	223
10	102.4	1.94E-04	3.11E-06		
15	101.5	2.02E-04	3.25E-06	114	251
20	101.8	2.11E-04	3.32E-06		
25	102.8	1.90E-04	3.06E-06	114	266
30	102.9	1.89E-04	3.03E-06		
35	103.5	1.84E-04	2.96E-06	114	276
40	103.7	1.83E-04	2.93E-06		
45	103.9	1.80E-04	2.90E-06	114	281
50	102.9	1.83E-04	2.93E-06		

Average 102.8 1.90E-04 3.06E-06 114.1 267.1

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin General # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	92.6	2.81E-04	4.54E-06	152	360
15	99.0	2.24E-04	3.61E-06	149	443
25	98.6	2.28E-04	3.67E-06	149	436
35	98.2	2.31E-04	3.73E-06	149	430
45	96.5	2.46E-04	3.97E-06	148	400
Average	97.9	2.34E-04	3.77E-06	148.4	423.4

Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 5.0
 Resin General
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	93.5	2.73E-04	4.41E-06	151	368
10	95.4	2.56E-04	4.12E-06	145	368
15	94.3	2.66E-04	4.29E-06	147	368
20	96.4	2.47E-04	3.99E-06	143	368
25	93.2	2.76E-04	4.45E-06	149	360
30	94.8	2.62E-04	4.21E-06	145	360
35	96.0	2.51E-04	4.05E-06	149	396
40	93.9	2.70E-04	4.27E-06	147	396
45	97.6	2.37E-04	3.82E-06	149	420
50	95.9	2.41E-04	3.92E-06	149	420
Average	95.4	2.56E-04	4.14E-06	147.9	385.5

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin None # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	112.5	1.03E-04	1.66E-06	73	189
10	112.5	1.03E-04	1.66E-06	73	189
15	113.0	9.86E-05	1.59E-06	71	192
20	112.8	9.24E-05	1.53E-06	71	184
25	112.5	1.03E-04	1.66E-06	71	184
30	110.1	9.12E-05	1.50E-06	72	219
35	114.2	8.78E-05	1.42E-06	72	219
40	113.6	9.32E-05	1.50E-06	72	219
45	114.2	8.78E-05	1.42E-06	72	219
50	113.6	9.12E-05	1.50E-06	72	219

Average 113.2 9.72E-05 1.57E-06 71.4 198.8

Run #2
Flow (mL/min) 250
Spacing 1 mm
Voltage 2.0
Resin None
of Pairs 3
Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	112.2	1.06E-04	1.71E-06	76	192
10	115.8	7.35E-05	1.19E-06	73	229
15	114.5	8.51E-05	1.37E-06	73	229
20	113.9	9.45E-05	1.41E-06	72	241
25	115.1	7.97E-05	1.29E-06	72	241
30	113.8	9.11E-05	1.41E-06	72	219
35	114.2	8.78E-05	1.42E-06	72	219
40	111.9	1.09E-04	1.73E-06	72	241
45	115.1	7.97E-05	1.29E-06	72	241
50	114.6	8.27E-05	1.33E-06	72	241

Average **114.3** **8.65E-05** **1.40E-06** **72.7** **226.4**

Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 3.3
Resin None
of Pairs 3
Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	100.5	2.11E-04	3.40E-06	108	228
10	107.6	1.37E-04	2.19E-06	103	294
15	107.5	1.48E-04	2.38E-06	103	309
20	105.3	1.68E-04	2.70E-06	104	310
25	107.4	1.49E-04	2.40E-06	104	310
30	107.1	1.50E-04	2.41E-06	102	294
35	106.8	1.54E-04	2.49E-06	102	294
40	108.5	1.39E-04	2.25E-06	103	334
45	108.7	1.37E-04	2.21E-06	103	334
50	106.2	1.53E-04	2.56E-06	103	334
Average	107.2	1.50E-04	2.42E-06	103.3	306.7

Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.3
 Resin None
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	101.2	2.04E-04	3.30E-06	105	228
15	108.5	1.39E-04	2.24E-06	101	323
25	107.9	1.44E-04	2.32E-06	101	311
35	108.3	1.41E-04	2.27E-06	100	316
45	106.9	1.53E-04	2.47E-06	100	290
Average	107.6	1.47E-04	2.37E-06	100.8	305.3

Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 5.0
 Resin None
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	99.3	2.21E-04	3.57E-06	141	425
10	102.5	1.93E-04	3.11E-06	137	488
15	103.1	1.87E-04	3.02E-06	137	488
20	100.6	2.10E-04	3.38E-06	139	442
25	100.6	2.10E-04	3.38E-06	139	442
30	101.3	1.90E-04	3.02E-06	138	465
35	101.9	1.98E-04	3.19E-06	138	465
40	101.7	2.00E-04	3.22E-06	139	481
45	102.5	1.93E-04	3.11E-06	139	481
50	100.6	2.10E-04	3.38E-06	139	442
Average	101.8	1.99E-04	3.21E-06	137.8	462.4

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin None # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	94.0	2.69E-04	4.34E-06	145	360
10	100.2	2.78E-04	4.39E-06	145	360
15	101.1	2.05E-04	3.31E-06	139	452
20	99.8	2.17E-04	3.38E-06	139	442
25	101.5	2.02E-04	3.25E-06	139	460
30	99.6	2.19E-04	3.38E-06	139	442
35	100.6	2.10E-04	3.38E-06	139	442
40	100.9	2.17E-04	3.38E-06	139	442
45	99.8	2.17E-04	3.50E-06	138	424
50	102.2	1.95E-04	3.11E-06	138	424
Average	100.6	2.10E-04	3.39E-06	138.4	440.1

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 2 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	108.5	1.39E-04	2.24E-06	82	157
10	109.3	1.39E-04	2.24E-06	82	158
15	108.1	1.42E-04	2.30E-06	78	146
20	107.5	1.48E-04	2.38E-06	78	145
25	109.8	1.27E-04	2.05E-06	77	161
30	109.2	1.34E-04	2.11E-06	77	159
35	108.0	1.43E-04	2.31E-06	78	145
40	108.9	1.26E-04	2.02E-06	77	158
45	108.6	1.38E-04	2.23E-06	78	151
50	108.6	1.38E-04	2.23E-06	78	151

Average 108.8 1.36E-04 2.20E-06 78.0 152.9

Run #1
 Flow (mL/min) 250
 Spacing 2 mm
 Voltage 3.3
 Resin Num 1
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	99.4	2.20E-04	3.56E-06	109	220
15	100.1	2.14E-04	3.45E-06	108	224
25	101.4	2.03E-04	3.27E-06	108	237
35	100.2	2.13E-04	3.44E-06	108	225
45	102.4	1.94E-04	3.12E-06	109	250
Average	101.6	2.01E-04	3.24E-06	108.2	239.8

Run #2
 Flow (mL/min) Spacing Voltage Resin # of Pairs Initial Conc
 250 2 mm 3.3 Num 1 3 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	100.2	2.13E-04	3.44E-06	116	242
10	102.5	1.93E-04	3.11E-06	113	253
15	102.4	1.94E-04	3.12E-06	113	259
20	103.2	1.86E-04	3.01E-06	112	267
25	103.2	1.86E-04	3.01E-06	112	267
30	101.4	2.03E-04	3.30E-06	113	246
35	101.2	2.04E-04	3.30E-06	113	246
40	100.9	2.07E-04	3.34E-06	112	240
45	100.9	2.07E-04	3.34E-06	112	240
50	102.9	1.89E-04	3.05E-06	111	256
Average	102.0	1.97E-04	3.18E-06	112.4	254.0

Single Species Experimentation

Run #1

Flow (mL/min) 250
 Spacing 2 mm
 Voltage 5.0
 Resin Num 1
 # of Pairs 3
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	98.6	2.28E-04	3.67E-06	140	410
15	98.0	2.33E-04	3.76E-06	135	386
25	99.3	2.21E-04	3.57E-06	136	410
35	98.5	2.28E-04	3.69E-06	136	397
45	99.7	2.18E-04	3.51E-06	136	416
Average	98.6	2.28E-04	3.67E-06	135.7	397.7

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 2 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	109.9	1.90E-04	3.06E-06	87	122
10	112.3	1.67E-04	2.41E-06	85	122
15	110.2	1.85E-04	2.99E-06	85	122
20	109.8	1.91E-04	3.08E-06	85	122
25	110.2	1.85E-04	2.99E-06	85	122
30	111.4	1.69E-04	2.73E-06	85	122
35	112.9	1.49E-04	2.41E-06	85	152
40	111.2	1.85E-04	2.99E-06	85	122
45	110.2	1.85E-04	2.99E-06	85	122
50	111.2	1.85E-04	2.99E-06	85	122

Average 111.4 1.70E-04 2.74E-06 85.1 135.6

Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 3.3
Resin Num 1
of Pairs 2
Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	104.8	2.58E-04	4.16E-06	110	189
15	105.9	2.43E-04	3.92E-06	110	201
25	105.2	2.53E-04	4.08E-06	111	195
35	105.5	2.49E-04	4.01E-06	109	195
45	104.3	2.65E-04	4.27E-06	109	183
Average	105.6	2.47E-04	3.99E-06	109.8	197.3

Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.3
 Resin Num 1
 # of Pairs 2
 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	103.9	2.70E-04	4.36E-06	114	187
10	104.7	2.59E-04	4.18E-06	112	198
15	105.3	2.51E-04	4.05E-06	112	198
20	106.1	2.41E-04	3.88E-06	112	187
25	104.2	2.66E-04	4.29E-06	112	187
30	103.9	2.70E-04	4.36E-06	111	188
35	104.5	2.62E-04	4.23E-06	111	197
40	104.9	2.57E-04	4.11E-06	111	197
45	105.4	2.50E-04	4.03E-06	111	197
50	106.0	2.51E-04	4.03E-06	111.7	195.5

Average **105.1** **2.54E-04** **4.10E-06** **111.7** **195.5**

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 2 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	101.3	3.05E-04	4.92E-06	145	317
10	102.6	3.29E-04	5.31E-06	145	294
15	100.0	3.23E-04	5.20E-06	144	298
20	102.2	3.29E-04	5.31E-06	145	317
25	101.3	3.05E-04	4.92E-06	145	317
30	102.1	3.29E-04	5.31E-06	145	294
35	99.5	3.29E-04	5.31E-06	145	294
40	103.2	3.29E-04	5.31E-06	145	302
45	100.2	3.20E-04	5.16E-06	145	302
50	100.6	3.25E-04	5.25E-06	145	305

Average 101.2 3.07E-04 4.95E-06 144.6 315.0

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 5 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	97.5	1.42E-04	2.30E-06	82	153
10	98.1	1.49E-04	2.45E-06	82	151
15	97.0	1.45E-04	2.34E-06	82	151
20	96.5	1.43E-04	2.38E-06	81	155
25	98.1	1.39E-04	2.25E-06	81	155
30	98.6	1.48E-04	2.38E-06	82	148
35	95.6	1.53E-04	2.46E-06	81	141
40	96.2	1.49E-04	2.41E-06	82	148
45	96.5	1.48E-04	2.38E-06	82	148
50	97.5	1.42E-04	2.30E-06	82	153

Average 97.1 1.45E-04 2.33E-06 81.4 150.3

Single Species Experimentation

Run #1

Flow (mL/min) Spacing Voltage Resin # of Pairs Initial Conc

250 1 mm 3.3 Num 1 5 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	82.6	2.23E-04	3.59E-06	108	215
10	84.5	2.12E-04	3.34E-06	106	227
15	85.5	2.07E-04	3.34E-06	106	227
20	86.2	2.03E-04	3.26E-06	106	233
25	86.4	2.02E-04	3.26E-06	106	233
30	86.6	2.08E-04	3.34E-06	106	236
35	86.9	1.99E-04	3.22E-06	106	236
40	87.2	2.08E-04	3.34E-06	107	235
45	86.4	2.02E-04	3.26E-06	107	235
50	85.5	2.07E-04	3.34E-06	106	227
Average	86.0	2.04E-04	3.30E-06	106.2	230.9

Single Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 5 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	84.5	2.12E-04	3.43E-06	105	220
10	85.1	2.09E-04	3.37E-06	105	221
15	87.2	1.98E-04	3.19E-06	105	236
20	88.1	1.93E-04	3.11E-06	105	241
25	85.0	2.10E-04	3.38E-06	105	222
30	84.8	2.13E-04	3.44E-06	105	219
35	84.6	2.12E-04	3.42E-06	104	218
40	84.9	2.10E-04	3.39E-06	104	220
45	87.0	1.99E-04	3.21E-06	104	232
50	83.8	2.00E-04	3.23E-06	104	231

Average 85.9 2.05E-04 3.30E-06 104.4 226.6

Single Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 5 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
5	78.6	2.44E-04	3.94E-06	135	369
15	78.2	2.46E-04	3.97E-06	134	363
25	79.1	2.41E-04	3.89E-06	134	370
35	77.5	2.50E-04	4.03E-06	134	357
45	79.5	2.39E-04	3.86E-06	134	373
Average	77.9	2.48E-04	4.00E-06	134.2	361.2

Single Species Experimentation

Run #1

Flow (mL/min) 500 Spacing 1 mm Voltage 2.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	115.2	1.58E-04	2.54E-06	94	159
10	116.3	1.68E-04	2.74E-06	92	190
15	114.3	1.74E-04	2.80E-06	92	141
20	113.9	1.83E-04	2.93E-06	92	152
25	115.0	1.61E-04	2.60E-06	92	152
30	113.1	1.95E-04	3.11E-06	92	193
35	116.9	1.27E-04	2.05E-06	92	193
40	114.8	1.68E-04	2.72E-06	92	152
45	113.9	1.81E-04	2.92E-06	92	136
50	115.2	1.62E-04	2.61E-06	91	159
Average	114.8	1.64E-04	2.65E-06	92.0	151.8

Single Species Experimentation

Run #1

Flow (mL/min) 500 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	109.5	2.60E-04	4.19E-06	131	224
15	112.8	2.01E-04	3.24E-06	128	283
25	111.8	2.19E-04	3.53E-06	127	258
35	110.6	2.40E-04	3.87E-06	126	233
45	111.2	2.29E-04	3.70E-06	126	244
Average	112.0	2.15E-04	3.47E-06	126.6	263.5

Single Species Experimentation

Run #2

Flow (mL/min) 500 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	110.3	2.46E-04	3.96E-06	134	242
10	112.6	2.01E-04	3.30E-06	130	233
15	111.9	2.17E-04	3.50E-06	131	268
20	111.8	2.19E-04	3.53E-06	130	233
25	109.6	2.58E-04	4.16E-06	131	225
30	110.6	1.88E-04	3.01E-06	131	233
35	110.6	2.40E-04	3.87E-06	130	240
40	112.8	2.01E-04	3.24E-06	130	233
45	112.6	2.04E-04	3.30E-06	130	283
50	109.4	2.31E-04	3.73E-06	130	233

Average 111.8 2.18E-04 3.52E-06 130.3 267.7

Single Species Experimentation

Run #1

Flow (mL/min) 500 Spacing 1 mm Voltage 5.0 Resin Num 1 # of Pairs 3 Initial Conc 124

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	106.2	3.19E-04	5.15E-06	165	345
10	109.2	3.65E-04	5.61E-06	165	345
15	106.3	3.17E-04	5.12E-06	164	345
20	108.2	3.63E-04	5.58E-06	163	345
25	107.3	2.99E-04	4.83E-06	163	363
30	106.5	3.08E-04	4.92E-06	162	365
35	107.5	2.96E-04	4.77E-06	162	365
40	107.4	3.09E-04	4.93E-06	163	346
45	106.5	3.14E-04	5.06E-06	163	346
50	107.6	3.22E-04	5.15E-06	163	346

Average 107.6 2.95E-04 4.75E-06 163.1 370.3

Appendix C

Recycle Experiments

Recycle Experimentation**Run #1**

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Energy
250	1 mm	2.0	Num 1	12	
Time	Conc	Flux	Flux	Current	Energy
(min)	(mg/L)	(mg/cm²/s)	(meq/cm²/s)	(mA)	(J/meq)
0	134.0	2.59E-04	4.18E-06	95	98
10	128.0	1.52E-04	2.45E-06	93	162
30	120.9	1.39E-04	2.25E-06	83	158
50	114.4	1.33E-04	2.15E-06	80	159
70	108.2	1.32E-04	2.14E-06	78	156
90	102.1	5.61E-05	9.05E-07	75	354
110	99.5	8.17E-05	1.32E-06	72	235
130	95.7	1.90E-04	3.06E-06	69	97
150	86.8	5.28E-05	8.52E-07	67	338
170	84.4	7.20E-05	1.16E-06	65	241
190	81.0	5.72E-05	9.23E-07	63	291
210	78.4	1.05E-04	1.69E-06	61	156
230	73.5	1.03E-04	1.66E-06	59	153
250	68.7	4.93E-05	7.95E-07	57	308
270	66.4	6.96E-05	1.12E-06	56	213
290	63.2	3.84E-05	6.19E-07	54	375
310	61.4	7.82E-05	1.26E-06	53	179
330	57.8	6.47E-05	1.04E-06	51	210
350	54.8	2.24E-05	3.62E-07	50	595
370	53.7	4.78E-05	7.71E-07	49	271
390	51.5				

Recycle Experimentation						
Run #2	Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	
250	250	1 mm	2.0	Num 1	12	
Time	Conc	Flux	Flux	Current	Energy	
(min)	(mg/L)	(mg/cm ² /s)	(meq/cm ² /s)	(mA)	(J/meq)	
0	134.0	1.72E-04	2.77E-06	90.0	140	
10	130.0	1.46E-04	2.36E-06	87.5	160	
30	123.2	2.38E-04	3.84E-06	80.0	90	
50	112.1	1.51E-04	2.44E-06	77.0	136	
70	105.1	8.71E-05	1.41E-06	74.5	228	
90	101.0	6.34E-05	1.02E-06	72.0	303	
110	98.1	1.27E-04	2.05E-06	69.5	146	
130	92.2	1.01E-04	1.63E-06	66.5	175	
150	87.5	4.89E-05	7.89E-07	64.5	352	
170	85.2	3.78E-05	6.10E-07	62.5	441	
190	83.5	4.21E-05	6.78E-07	60.5	384	
210	81.5	1.36E-04	2.19E-06	58.0	114	
230	75.2	1.25E-04	2.01E-06	56.0	120	
250	69.4	4.93E-05	7.95E-07	54.0	292	
270	67.1	5.67E-05	9.15E-07	52.0	244	
290	64.5	7.90E-05	1.27E-06	50.0	169	
310	60.8	4.09E-05	6.59E-07	48.8	318	
330	58.9	6.51E-05	1.05E-06	47.9	196	
350	55.9	3.59E-05	5.80E-07	46.8	347	
370	54.2	4.95E-05	7.98E-07	45.9	247	
390	51.9					

Recycle Experimentation**Run #1**

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed			
250	1 mm	3.3	Num 1	12			
Time	Conc (mg/L)	Flux (mg/cm²/s)	Flux (meq/cm²/s)	Current (mA)	Energy		
0	134	3.44E-04	5.55E-06	138	176		
10	126	2.37E-04	3.82E-06	130	242		
30	115	1.94E-04	3.12E-06	120	273		
50	106	2.06E-04	3.33E-06	111	236		
70	96.4	1.89E-04	3.05E-06	95	221		
90	87.6	9.89E-05	1.60E-06	92	409		
110	83	1.51E-04	2.43E-06	86	251		
130	76	1.76E-04	2.84E-06	84	208		
150	67.8	7.53E-05	1.21E-06	79	462		
170	64.3	9.25E-05	1.49E-06	73	345		
190	60	6.45E-05	1.04E-06	70	477		
210	57	1.20E-04	1.94E-06	67	243		
230	51.4	9.46E-05	1.53E-06	64	295		
250	47	6.45E-05	1.04E-06	61	413		
270	44	7.53E-05	1.21E-06	59	342		
290	40.5	4.95E-05	7.98E-07	57	507		
310	38.2	5.81E-05	9.37E-07	56	424		
330	35.5	7.31E-05	1.18E-06	55	331		
350	32.1	2.37E-05	3.82E-07	53	986		
370	31	3.87E-05	6.24E-07	52	591		
390	29.2						

Recycle Experimentation						
Run #2						
Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed		
250	1 mm	3.3	Num 1	12		
Time	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy	
0	134	2.15E-04	3.47E-06	133.5	273	
10	129	3.44E-04	5.55E-06	128.5	164	
30	113	2.58E-04	4.16E-06	118	201	
50	101	4.30E-05	6.94E-07	107.5	1100	
70	99	2.04E-04	3.30E-06	97.5	210	
90	89.5	2.26E-04	3.64E-06	91	177	
110	79	1.40E-04	2.25E-06	85	268	
130	72.5	4.95E-05	7.98E-07	82.5	734	
150	70.2	9.03E-05	1.46E-06	77.5	378	
170	66	1.20E-04	1.94E-06	74	270	
190	60.4	1.57E-04	2.53E-06	69	193	
210	53.1	4.95E-05	7.98E-07	65	578	
230	50.8	5.38E-05	8.67E-07	62.5	512	
250	48.3	7.53E-05	1.21E-06	60.5	354	
270	44.8	6.67E-05	1.08E-06	59	389	
290	41.7	8.82E-05	1.42E-06	57	284	
310	37.6	3.23E-05	5.20E-07	56	764	
330	36.1	6.88E-05	1.11E-06	55	352	
350	32.9	7.10E-05	1.14E-06	54	335	
370	29.6	4.52E-05	7.28E-07	52	507	
390	27.5					

Recycle Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

Num 1

Litres in feed

12

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy
0	134	3.01E-04	4.86E-06	160	355
10	127	3.18E-04	5.13E-06	156	326
30	112.2	1.98E-04	3.19E-06	143	482
50	103	1.98E-04	3.19E-06	132	445
70	93.8	2.39E-04	3.85E-06	121	338
90	82.7	1.51E-04	2.43E-06	113	498
110	75.7	1.27E-04	2.05E-06	104	546
130	69.8	1.55E-04	2.50E-06	95	409
150	62.6	1.16E-04	1.87E-06	89	511
170	57.2	1.33E-04	2.15E-06	83	413
190	51	9.89E-05	1.60E-06	75	505
210	46.4	1.01E-04	1.63E-06	72	472
230	41.7	1.05E-04	1.70E-06	69	433
250	36.8	1.03E-04	1.66E-06	66	426
270	32	7.96E-05	1.28E-06	64	536
290	28.3	6.67E-05	1.08E-06	63	625
310	25.2	4.73E-05	7.63E-07	61	860
330	23	4.30E-05	6.94E-07	60	922
350	21	4.09E-05	6.59E-07	58	946
370	19.1	3.87E-05	6.24E-07	58	990
390	17.3				

Recycle Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time	Conc	Flux	Flux	Current	Energy
250	1 mm	5.0	Num 1	12	(min)	(mg/L)	(mg/cm2/s)	(meq/cm2/s)	(mA)	
					0	134	3.44E-04	5.55E-06	161	311
					10	126	2.71E-04	4.37E-06	156	383
					30	113.4	1.98E-04	3.19E-06	145	489
					50	104.2	1.96E-04	3.16E-06	137	465
					70	95.1	2.82E-04	4.54E-06	129	305
					90	82	1.05E-04	1.70E-06	118	747
					110	77.1	2.09E-04	3.36E-06	110	350
					130	67.4	1.55E-04	2.50E-06	101	435
					150	60.2	1.20E-04	1.94E-06	95	523
					170	54.6	1.01E-04	1.63E-06	88	580
					190	49.9	1.20E-04	1.94E-06	81	446
					210	44.3	8.60E-05	1.39E-06	78	601
					230	40.3	1.10E-04	1.77E-06	75	453
					250	35.2	9.46E-05	1.53E-06	72	507
					270	30.8	8.17E-05	1.32E-06	69	563
					290	27	6.02E-05	9.71E-07	68	747
					310	24.2	4.52E-05	7.28E-07	67	982
					330	22.1	4.09E-05	6.59E-07	64	1044
					350	20.2	3.01E-05	4.86E-07	63	1384
					370	18.8	3.44E-05	5.55E-07	61	1182
					390	17.2				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time	Conc	Flux	Flux	Current	Energy
			Num 1	12	(min)	(mg/L)	(mg/cm2/s)	(meq/cm2/s)	(mA)	(J/meq)
250	2.0				0	134	1.72E-04	2.77E-06	102	159
					10	130	1.51E-04	2.43E-06	99	175
					30	123	1.72E-04	2.77E-06	92	143
					50	115	1.61E-04	2.60E-06	85	140
					70	107.5	9.46E-05	1.53E-06	83	234
					90	103.1	8.39E-05	1.35E-06	80	256
					110	99.2	8.82E-05	1.42E-06	78	237
					130	95.1	1.74E-04	2.81E-06	76	116
					150	87	3.23E-05	5.20E-07	73	603
					170	85.5	5.38E-05	8.67E-07	71	351
					190	83	4.73E-05	7.63E-07	69	387
					210	80.8	7.74E-05	1.25E-06	66	227
					230	77.2	1.03E-04	1.66E-06	64	166
					250	72.4	7.31E-05	1.18E-06	63	228
					270	69	6.02E-05	9.71E-07	60	265
					290	66.2	5.81E-05	9.37E-07	58	268
					310	63.5	6.24E-05	1.01E-06	57	245
					330	60.6	4.73E-05	7.63E-07	55	311
					350	58.4	3.44E-05	5.55E-07	54	415
					370	56.8	4.52E-05	7.28E-07	53	311
					390	54.7				

Recycle Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time	Conc	Flux	Flux	Current	Energy
					(min)	(mg/L)	(mg/cm ² /s)	(meq/cm ² /s)	(mA)	(J/meq)
250	2.0	2.0	Num 1	12	0	134.0	1.29E-04	2.08E-06	103	214
					10	131.0	1.51E-04	2.43E-06	102	180
					30	124.0	1.40E-04	2.25E-06	95	180
					50	117.5	1.61E-04	2.60E-06	88	145
					70	110.0	8.17E-05	1.32E-06	84	276
					90	106.2	7.53E-05	1.21E-06	81	288
					110	102.7	8.17E-05	1.32E-06	79	258
					130	98.9	1.44E-04	2.32E-06	76	141
					150	92.2	6.67E-05	1.08E-06	75	300
					170	89.1	7.74E-05	1.25E-06	72	248
					190	85.5	5.38E-05	8.67E-07	69	343
					210	83.0	5.59E-05	9.02E-07	67	320
					230	80.4	7.96E-05	1.28E-06	65	219
					250	76.7	7.74E-05	1.25E-06	63	218
					270	73.1	5.59E-05	9.02E-07	61	291
					290	70.5	6.67E-05	1.08E-06	60	240
					310	67.4	6.88E-05	1.11E-06	58	224
					330	64.2	4.30E-05	6.94E-07	57	351
					350	62.2	3.66E-05	5.90E-07	55	401
					370	60.5	3.01E-05	4.86E-07	54	475
					390	59.1				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin Num 1	Litres in feed 12	Energy (J/meq)
250	2.54	3.3			
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	1.89E-04	3.05E-06	150	348
10	129.6	1.33E-04	2.15E-06	145	478
30	123.4	2.54E-04	4.09E-06	137	238
50	111.6	1.81E-04	2.91E-06	128	312
70	103.2	1.76E-04	2.84E-06	120	301
90	95.0	1.46E-04	2.36E-06	111	334
110	88.2	1.48E-04	2.39E-06	101	300
130	81.3	1.57E-04	2.53E-06	95	267
150	74.0	7.96E-05	1.28E-06	89	494
170	70.3	9.68E-05	1.56E-06	84	383
190	65.8	9.68E-05	1.56E-06	78	357
210	61.3	7.10E-05	1.14E-06	75	467
230	58.0	6.24E-05	1.01E-06	72	509
250	55.1	6.45E-05	1.04E-06	69	473
270	52.1	8.39E-05	1.35E-06	68	355
290	48.2	6.88E-05	1.11E-06	65	415
310	45.0	5.81E-05	9.37E-07	64	483
330	42.3	3.23E-05	5.20E-07	62	847
350	40.8	5.38E-05	8.67E-07	62	504
370	38.3	4.52E-05	7.28E-07	61	589
390	36.2				

Recycle Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Current	Energy
250	2.7mm	3.3	Num 1	12		
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)	
0	134.0	1.68E-04	2.71E-06	148	387	
10	130.1	2.13E-04	3.43E-06	143	295	
30	120.2	2.28E-04	3.68E-06	136	262	
50	109.6	1.83E-04	2.95E-06	125	301	
70	101.1	1.42E-04	2.29E-06	117	363	
90	94.5	1.25E-04	2.01E-06	109	385	
110	88.7	1.48E-04	2.39E-06	100	297	
130	81.8	1.31E-04	2.12E-06	93	310	
150	75.7	1.18E-04	1.91E-06	85	316	
170	70.2	1.12E-04	1.80E-06	81	317	
190	65.0	1.05E-04	1.70E-06	77	322	
210	60.1	8.39E-05	1.35E-06	74	388	
230	56.2	1.10E-04	1.77E-06	71	283	
250	51.1	6.67E-05	1.08E-06	69	452	
270	48.0	4.52E-05	7.28E-07	67	648	
290	45.9	6.24E-05	1.01E-06	65	455	
310	43.0	9.03E-05	1.46E-06	63	304	
330	38.8	4.73E-05	7.63E-07	61	563	
350	36.6	5.59E-05	9.02E-07	60	472	
370	34.0	4.09E-05	6.59E-07	59	635	
390	32.1					

Recycle Experimentation**Run #1****Flow (mL/min)** **Spacing**

250 2.00

Voltage
5.0**Resin**
Num 1**Litres in feed**
12

Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
0	134.0	3.01E-04	4.86E-06	172	381
10	127.0	2.54E-04	4.09E-06	168	441
30	115.2	2.02E-04	3.26E-06	157	517
50	105.8	1.68E-04	2.71E-06	147	583
70	98.0	2.11E-04	3.40E-06	139	439
90	88.2	1.31E-04	2.12E-06	126	642
110	82.1	1.27E-04	2.05E-06	117	615
130	76.2	1.55E-04	2.50E-06	110	472
150	69.0	1.23E-04	1.98E-06	99	539
170	63.3	1.03E-04	1.66E-06	93	598
190	58.5	8.60E-05	1.39E-06	87	678
210	54.5	8.39E-05	1.35E-06	85	672
230	50.6	9.25E-05	1.49E-06	81	582
250	46.3	7.96E-05	1.28E-06	78	654
270	42.6	8.82E-05	1.42E-06	76	576
290	38.5	7.31E-05	1.18E-06	73	670
310	35.1	6.24E-05	1.01E-06	71	762
330	32.2	5.59E-05	9.02E-07	68	816
350	29.6	6.02E-05	9.71E-07	67	740
370	26.8	3.44E-05	5.55E-07	65	1265
390	25.2				

Recycle Experimentation

Run #2

Flow (mL/min) Spacing

250

2.200

Voltage

5.0

Resin

Num 1

Litres in feed

12

Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	2.03E-04	3.27E-06	175	576
10	129.3	2.39E-04	3.85E-06	171	476
30	118.2	2.67E-04	4.31E-06	159	396
50	105.7	2.07E-04	3.33E-06	149	479
70	96.1	1.42E-04	2.30E-06	138	647
90	89.5	1.55E-04	2.49E-06	127	549
110	82.3	1.88E-04	3.04E-06	120	424
130	73.6	1.32E-04	2.14E-06	111	558
150	67.4	9.41E-05	1.52E-06	105	746
170	63.0	1.12E-04	1.81E-06	98	585
190	57.8	9.14E-05	1.47E-06	88	642
210	53.6	1.06E-04	1.72E-06	84	526
230	48.6	6.41E-05	1.03E-06	79	818
250	45.6	7.55E-05	1.22E-06	75	662
270	42.1	8.10E-05	1.31E-06	72	596
290	38.4	8.19E-05	1.32E-06	68	557
310	34.5	5.68E-05	9.16E-07	66	778
330	31.9	5.69E-05	9.18E-07	65	758
350	29.3	5.49E-05	8.85E-07	63	760
370	26.7	4.04E-05	6.51E-07	62	1016
390	24.8				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	
50	1 mm	2.0	Num 1	12	
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	2.87E-04	4.63E-06	104.5	97
10	127.3	1.33E-04	2.15E-06	101.8	204
30	121.1	1.64E-04	2.65E-06	92.4	150
50	113.5	1.23E-04	1.98E-06	89.8	195
70	107.8	1.21E-04	1.95E-06	86.8	191
90	102.2	6.90E-05	1.11E-06	84.2	325
110	99.0	7.72E-05	1.25E-06	80.6	279
130	95.4	1.22E-04	1.97E-06	78.0	170
150	89.7	1.27E-04	2.05E-06	77.1	162
170	83.8	6.45E-05	1.04E-06	74.1	306
190	80.8	4.86E-05	7.84E-07	71.9	394
210	78.5	1.05E-04	1.69E-06	69.5	177
230	73.7	8.52E-05	1.37E-06	67.9	212
250	69.7	7.71E-05	1.24E-06	65.0	225
270	66.1	7.06E-05	1.14E-06	63.8	241
290	62.8	3.82E-05	6.16E-07	61.6	430
310	61.1	7.52E-05	1.21E-06	59.3	210
330	57.6	6.33E-05	1.02E-06	58.1	245
350	54.6	2.12E-05	3.42E-07	57.0	717
370	53.6	4.88E-05	7.87E-07	55.0	300
390	51.4				

Recycle Experimentation

Run #2

Flow (mL/min)

100

Spacing

1 mm

Voltage

2.0

Resin

Num 1

Litres in feed

12

Time	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	1.89E-04	3.05E-06	102.6	145
10	129.6	1.20E-04	1.94E-06	100.6	223
30	124.0	2.17E-04	3.50E-06	92.8	114
50	113.9	1.35E-04	2.19E-06	87.0	171
70	107.6	8.17E-05	1.32E-06	83.4	272
90	103.8	1.12E-04	1.80E-06	81.4	194
110	98.6	9.25E-05	1.49E-06	77.8	224
130	94.3	1.14E-04	1.84E-06	75.1	176
150	89.0	8.60E-05	1.39E-06	74.2	230
170	85.0	4.09E-05	6.59E-07	71.3	465
190	83.1	6.45E-05	1.04E-06	69.6	288
210	80.1	7.53E-05	1.21E-06	66.1	234
230	76.6	1.10E-04	1.77E-06	64.4	157
250	71.5	7.31E-05	1.18E-06	61.6	225
270	68.1	6.67E-05	1.08E-06	59.8	239
290	65.0	7.74E-05	1.25E-06	57.0	196
310	61.4	6.02E-05	9.71E-07	55.1	244
330	58.6	4.52E-05	7.28E-07	54.6	322
350	56.5	5.38E-05	8.67E-07	53.4	265
370	54.0	5.59E-05	9.02E-07	52.8	252
390	51.4				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	_litres in feed	
50	1 mm	5.0	Num 1	12	
Time (min)	Conc (mg/L)	Flux (mg/cm2/s)	Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
0	134.0	2.90E-04	4.68E-06	189	435
10	127.3	2.27E-04	3.66E-06	185	543
30	116.7	2.50E-04	4.03E-06	172	457
50	105.1	2.56E-04	4.13E-06	160	415
70	93.1	1.89E-04	3.05E-06	146	516
90	84.4	1.45E-04	2.35E-06	137	629
110	77.6	1.26E-04	2.03E-06	127	674
130	71.8	1.54E-04	2.48E-06	117	507
150	64.6	1.17E-04	1.89E-06	110	627
170	59.1	1.46E-04	2.35E-06	103	472
190	52.4	1.11E-04	1.78E-06	94.5	570
210	47.2	9.21E-05	1.49E-06	90.8	657
230	43.0	1.01E-04	1.62E-06	88.4	585
250	38.3	1.04E-04	1.68E-06	85.8	550
270	33.4	8.01E-05	1.29E-06	84.2	701
290	29.7	6.57E-05	1.06E-06	82.2	835
310	26.7	4.41E-05	7.12E-07	81.1	1225
330	24.6	4.15E-05	6.69E-07	80.6	1295
350	22.7	3.59E-05	5.79E-07	79.5	1476
370	21.0	3.51E-05	5.67E-07	78.7	1493
390	19.4				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time	Conc	Flux	Flux	Current	Energy
	1 mm	5.0	Num 1	12	(min)	(mg/L)	(mg/cm2/s)	(meq/cm2/s)	(mA)	(J/meq)
					0	134.0	2.90E-04	4.68E-06	189	435
					10	127.3	2.27E-04	3.66E-06	185	543
					30	116.7	2.50E-04	4.03E-06	172	457
					50	105.1	2.56E-04	4.13E-06	160	415
					70	93.1	1.89E-04	3.05E-06	146	516
					90	84.4	1.45E-04	2.35E-06	137	629
					110	77.6	1.26E-04	2.03E-06	127	674
					130	71.8	1.54E-04	2.48E-06	117	507
					150	64.6	1.17E-04	1.89E-06	110	627
					170	59.1	1.46E-04	2.35E-06	103	472
					190	52.4	1.11E-04	1.78E-06	94.5	570
					210	47.2	9.21E-05	1.49E-06	90.8	657
					230	43.0	1.01E-04	1.62E-06	88.4	585
					250	38.3	1.04E-04	1.68E-06	85.8	550
					270	33.4	8.01E-05	1.29E-06	84.2	701
					290	29.7	6.57E-05	1.06E-06	82.2	835
					310	26.7	4.41E-05	7.12E-07	81.1	1225
					330	24.6	4.15E-05	6.69E-07	80.6	1295
					350	22.7	3.59E-05	5.79E-07	79.5	1476
					370	21.0	3.51E-05	5.67E-07	78.7	1493
					390	19.4				

**Recycle Experimentation
Run #1**

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
250	1 mm	2.0	NUCLEAR	12	0	134.0	2.15E-04	3.47E-06	95	118
					10	129.0	1.51E-04	2.43E-06	93	165
					30	122.0	1.29E-04	2.08E-06	83	172
					50	116.0	1.25E-04	2.01E-06	81	173
					70	110.2	1.05E-04	1.70E-06	79	200
					90	105.3	6.67E-05	1.08E-06	76	304
					110	102.2	9.03E-05	1.46E-06	74	219
					130	98.0	8.82E-05	1.42E-06	71	215
					150	93.9	1.01E-04	1.63E-06	69	182
					170	89.2	8.17E-05	1.32E-06	67	218
					190	85.4	5.38E-05	8.67E-07	65	322
					210	82.9	8.60E-05	1.39E-06	63	197
					230	78.9	7.96E-05	1.28E-06	61	206
					250	75.2	4.73E-05	7.63E-07	60	337
					270	73.0	5.38E-05	8.67E-07	58	289
					290	70.5	3.66E-05	5.90E-07	57	414
					310	68.8	8.17E-05	1.32E-06	56	182
					330	65.0	6.02E-05	9.71E-07	54	239
					350	62.2	6.02E-05	9.71E-07	54	237
					370	59.4	4.09E-05	6.59E-07	52	339
					390	57.5				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed			
250	1 mm	3.3		12			
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)		
0	134	2.58E-04	4.16E-06	136	232		
10	128	2.37E-04	3.82E-06	131	244		
30	117	1.94E-04	3.12E-06	121	275		
50	108	1.91E-04	3.09E-06	113	260		
70	99.1	2.06E-04	3.33E-06	98	208		
90	89.5	9.25E-05	1.49E-06	94	445		
110	85.2	1.35E-04	2.19E-06	88	286		
130	78.9	1.66E-04	2.67E-06	85	225		
150	71.2	8.39E-05	1.35E-06	81	425		
170	67.3	8.60E-05	1.39E-06	77	394		
190	63.3	9.03E-05	1.46E-06	74	360		
210	59.1	6.24E-05	1.01E-06	72	508		
230	56.2	8.17E-05	1.32E-06	70	377		
250	52.4	7.53E-05	1.21E-06	68	395		
270	48.9	7.96E-05	1.28E-06	66	362		
290	45.2	6.45E-05	1.04E-06	64	436		
310	42.2	4.95E-05	7.98E-07	62	552		
330	39.9	6.67E-05	1.08E-06	61	399		
350	36.8	5.81E-05	9.37E-07	59	443		
370	34.1	4.52E-05	7.28E-07	57	550		

Recycle Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	
250	1 mm	3.3		12	
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134	2.15E-04	3.47E-06	137	280
10	129	2.37E-04	3.82E-06	133	246
30	118	1.94E-04	3.12E-06	123	278
50	109	1.94E-04	3.12E-06	115	261
70	100	1.68E-04	2.71E-06	99	260
90	92.2	9.46E-05	1.53E-06	95	442
110	87.8	1.20E-04	1.94E-06	91	331
130	82.2	1.57E-04	2.53E-06	87	242
150	74.9	1.20E-04	1.94E-06	83	303
170	69.3	8.39E-05	1.35E-06	79	414
190	65.4	8.60E-05	1.39E-06	77	391
210	61.4	7.31E-05	1.18E-06	74	445
230	58.0	8.17E-05	1.32E-06	72	388
250	54.2	6.67E-05	1.08E-06	70	459
270	51.1	6.02E-05	9.71E-07	68	493
290	48.3	6.88E-05	1.11E-06	66	422
310	45.1	6.67E-05	1.08E-06	64	419
330	42.0	7.10E-05	1.14E-06	63	388
350	38.7	4.95E-05	7.98E-07	61	538
370	36.4	4.52E-05	7.28E-07	59	570
390	34.3				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Energy
250	1 mm	5.0	Num 2	12	(J/meq)
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	2.46E-04	3.98E-06	160.5	434
10	128.3	2.97E-04	4.80E-06	155.5	349
30	114.4	2.02E-04	3.25E-06	144.4	477
50	105.1	1.82E-04	2.93E-06	134.6	494
70	96.6	2.46E-04	3.97E-06	123.4	335
90	85.2	1.39E-04	2.24E-06	115.9	557
110	78.7	1.32E-04	2.13E-06	107.1	541
130	72.6	1.48E-04	2.38E-06	98.8	446
150	65.7	1.22E-04	1.97E-06	92.6	506
170	60.1	1.29E-04	2.08E-06	86.6	448
190	54.1	9.49E-05	1.53E-06	78.8	553
210	49.6	9.92E-05	1.60E-06	75.1	505
230	45.0	1.06E-04	1.71E-06	72.6	457
250	40.1	9.19E-05	1.48E-06	70.0	508
270	35.8	7.09E-05	1.14E-06	67.8	638
290	32.5	6.04E-05	9.74E-07	66.3	731
310	29.7	4.10E-05	6.61E-07	65.3	1062
330	27.8	3.40E-05	5.48E-07	63.7	1249
350	26.3	3.05E-05	4.93E-07	62.6	1367
370	24.8	3.17E-05	5.12E-07	61.5	1293

Recycle Experimentation				Resin		Litres in feed	
Run #1				12		12	
Flow (mL/min)	Spacing	Voltage					
250	1 mm	2.0					
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)		
0	134.0	1.60E-04	2.57E-06	95.0	159		
10	130.3	1.52E-04	2.45E-06	93.4	164		
30	123.2	1.05E-04	1.70E-06	83.3	211		
50	118.3	1.27E-04	2.05E-06	81.1	170		
70	112.4	1.07E-04	1.73E-06	79.1	196		
90	107.4	6.80E-05	1.10E-06	76.0	298		
110	104.2	7.11E-05	1.15E-06	73.4	276		
130	100.9	9.08E-05	1.46E-06	71.1	209		
150	96.7	8.49E-05	1.37E-06	69.0	217		
170	92.8	8.50E-05	1.37E-06	67.6	212		
190	88.8	3.81E-05	6.14E-07	65.0	455		
210	87.0	9.03E-05	1.46E-06	64.1	189		
230	82.8	6.74E-05	1.09E-06	62.0	245		
250	79.7	3.45E-05	5.56E-07	60.4	468		
270	78.1	4.24E-05	6.83E-07	59.4	374		
290	76.1	3.95E-05	6.37E-07	58.3	394		
310	74.3	7.43E-05	1.20E-06	56.7	204		
330	70.9	5.23E-05	8.43E-07	55.6	284		
350	68.4	4.07E-05	6.56E-07	54.5	357		
370	66.5	2.10E-05	3.39E-07	53.0	672		
390	65.6						

Recycle Experimentation
Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed				
250	1 mm	3.3	0.012	12	Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)
					0	134	2.15E-04	3.47E-06
					10	129	2.37E-04	3.82E-06
					30	118	1.51E-04	2.43E-06
					50	111	1.94E-04	3.12E-06
					70	102	1.78E-04	2.88E-06
					90	93.7	1.38E-04	2.22E-06
					110	87.3	1.44E-04	2.32E-06
					130	80.6	7.10E-05	1.14E-06
					150	77.3	1.23E-04	1.98E-06
					170	71.6	8.17E-05	1.32E-06
					190	67.8	9.89E-05	1.60E-06
					210	63.2	7.96E-05	1.28E-06
					230	59.5	6.45E-05	1.04E-06
					250	56.5	7.10E-05	1.14E-06
					270	53.2	6.67E-05	1.08E-06
					290	50.1	5.38E-05	8.67E-07
					310	47.6	4.95E-05	7.98E-07
					330	45.3	4.09E-05	6.59E-07
					350	43.4	5.16E-05	8.32E-07
					370	41	4.52E-05	7.28E-07
					390	38.9		
					Current (mA)	Energy (J/meq)		
					136	277		
					132	245		
					123	358		
					114	258		
					98.5	243		
					94.5	302		
					89.0	272		
					86.0	533		
					83.0	298		
					78.5	423		
					76.0	338		
					73.5	406		
					71.5	488		
					69.5	431		
					66.5	439		
					65.0	532		
					63.5	565		
					62.0	668		
					61.0	520		
					59.5	580		

Recycle Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
250	1 mm	3.3	3.3	12	0	134	1.72E-04	2.77E-06	137	350
					10	130	2.58E-04	4.16E-06	133	226
					30	118	1.29E-04	2.08E-06	123	418
					50	112	1.94E-04	3.12E-06	116	263
					70	103	1.78E-04	2.88E-06	100	247
					90	94.7	1.33E-04	2.15E-06	95.5	315
					110	88.5	1.35E-04	2.19E-06	91.0	296
					130	82.2	7.74E-05	1.25E-06	87.0	494
					150	78.6	1.31E-04	2.12E-06	83.5	280
					170	72.5	6.24E-05	1.01E-06	80.0	564
					190	69.6	9.68E-05	1.56E-06	77.5	352
					210	65.1	8.60E-05	1.39E-06	75.0	384
					230	61.1	6.24E-05	1.01E-06	73.0	515
					250	58.2	6.88E-05	1.11E-06	71.0	454
					270	55	4.30E-05	6.94E-07	69.0	706
					290	53	7.74E-05	1.25E-06	67.0	381
					310	49.4	4.09E-05	6.59E-07	64.5	695
					330	47.5	4.95E-05	7.98E-07	63.5	565
					350	45.2	4.30E-05	6.94E-07	61.5	629
					370	43.2	3.87E-05	6.24E-07	60.5	688
					390	41.4				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
250	1 mm	5.0	CMC-25	12	0	134.0	1.91E-04	3.09E-06	160.5	559
					10	129.6	3.00E-04	4.84E-06	157.1	349
					30	115.6	1.81E-04	2.92E-06	145.9	537
					50	107.2	1.85E-04	2.99E-06	137.3	494
					70	98.5	2.32E-04	3.75E-06	125.9	361
					90	87.7	1.26E-04	2.03E-06	119.4	631
					110	81.9	1.22E-04	1.96E-06	110.3	605
					130	76.2	1.41E-04	2.27E-06	101.8	482
					150	69.7	1.29E-04	2.08E-06	96.3	497
					170	63.7	1.25E-04	2.02E-06	90.1	480
					190	57.8	1.02E-04	1.64E-06	81.9	538
					210	53.1	9.64E-05	1.56E-06	78.8	545
					230	48.6	1.14E-04	1.84E-06	76.2	444
					250	43.3	9.15E-05	1.48E-06	73.5	535
					270	39.1	7.02E-05	1.13E-06	71.9	683
					290	35.8	5.37E-05	8.65E-07	70.2	872
					310	33.3	1.60E-05	2.58E-07	69.8	2913
					330	32.6	2.28E-05	3.68E-07	68.8	2009
					350	31.5	3.66E-05	5.91E-07	67.7	1231
					370	29.8	3.81E-05	6.14E-07	67.1	1175
					390	28.0				

Run #1		Resin		Litres in feed	
Flow (mL/min)	250	Spacing	1 mm	Voltage	2.0
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	1.04E-04	1.67E-06	91.3	235
10	131.6	1.01E-04	1.62E-06	89.8	238
30	126.9	1.09E-04	1.75E-06	80.1	197
50	121.9	1.07E-04	1.72E-06	77.2	193
70	116.9	1.12E-04	1.80E-06	75.3	180
90	111.7	4.83E-05	7.79E-07	73.1	403
110	109.5	5.29E-05	8.53E-07	69.9	353
130	107.0	7.55E-05	1.22E-06	68.3	241
150	103.5	7.09E-05	1.14E-06	65.7	247
170	100.2	9.18E-05	1.48E-06	62.6	182
190	95.9	2.24E-05	3.62E-07	60.2	716
210	94.9	8.06E-05	1.30E-06	59.9	198
230	91.1	5.70E-05	9.19E-07	56.3	264
250	88.5	2.14E-05	3.46E-07	54.4	677
270	87.5	3.11E-05	5.01E-07	53.0	455
290	86.0	2.86E-05	4.62E-07	51.6	481
310	84.7	6.94E-05	1.12E-06	49.7	191
330	81.5	6.01E-05	9.69E-07	48.3	214
350	78.7	4.68E-05	7.55E-07	47.4	270
370	76.5	1.01E-05	1.63E-07	46.1	1217
390	76.0				

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing	Voltage	Resin	Litres in feed	Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
250	1 mm	3.3	3.3	12	0	134	1.29E-04	2.08E-06	135.5	462
					10	131	1.72E-04	2.77E-06	131.5	336
					30	123	1.51E-04	2.43E-06	122.5	358
					50	116	1.51E-04	2.43E-06	113.5	332
					70	109	1.29E-04	2.08E-06	98.5	336
					90	103	1.25E-04	2.01E-06	95.0	335
					110	97.2	1.03E-04	1.66E-06	90.8	387
					130	92.4	1.08E-04	1.73E-06	85.1	348
					150	87.4	1.08E-04	1.73E-06	83.8	343
					170	82.4	7.53E-05	1.21E-06	79.3	463
					190	78.9	9.68E-05	1.56E-06	77.5	352
					210	74.4	6.88E-05	1.11E-06	75.0	479
					230	71.2	4.95E-05	7.98E-07	73.6	655
					250	68.9	5.81E-05	9.37E-07	71.6	542
					270	66.2	4.73E-05	7.63E-07	68.5	637
					290	64	4.09E-05	6.59E-07	66.3	714
					310	62.1	4.52E-05	7.28E-07	65.4	637
					330	60	4.73E-05	7.63E-07	63.9	594
					350	57.8	4.30E-05	6.94E-07	63.4	649
					370	55.8	4.09E-05	6.59E-07	61.9	666
					390	53.9				

Recycle Experimentation				Voltage	Resin	Litres in feed	Energy (J/meq)
Run #2	Flow (mL/min)	Spacing					
250	250	1 mm		3.3	12		
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)		
0	134	1.72E-04	2.77E-06	135.5	347		
10	130	1.72E-04	2.77E-06	132.8	340		
30	122	1.29E-04	2.08E-06	121.3	414		
50	116	1.29E-04	2.08E-06	112.9	385		
70	110	1.29E-04	2.08E-06	97.5	333		
90	104	1.29E-04	2.08E-06	94.6	323		
110	98	1.27E-04	2.05E-06	89.9	312		
130	92.1	1.10E-04	1.77E-06	87.1	349		
150	87	1.08E-04	1.73E-06	84.2	345		
170	82	8.17E-05	1.32E-06	79.3	427		
190	78.2	9.25E-05	1.49E-06	77.1	367		
210	73.9	9.46E-05	1.53E-06	74.5	347		
230	69.5	5.81E-05	9.37E-07	73.1	554		
250	66.8	6.67E-05	1.08E-06	71.3	471		
270	63.7	6.88E-05	1.11E-06	68.0	435		
290	60.5	5.16E-05	8.32E-07	65.7	560		
310	58.1	4.52E-05	7.28E-07	65.0	633		
330	56	4.95E-05	7.98E-07	63.3	564		
350	53.7	3.87E-05	6.24E-07	62.7	713		
370	51.9	4.52E-05	7.28E-07	61.6	600		
390	49.8						

Recycle Experimentation

Run #1

Flow (mL/min)	Spacing 1 mm	Voltage 5.0	Resin 12	Litres in feed 12	
Time (min)	Conc (mg/L)	Flux (mg/cm ² /s)	Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
0	134.0	1.35E-04	2.18E-06	160.5	792
10	130.9	2.52E-04	4.06E-06	155.5	412
30	119.2	1.62E-04	2.61E-06	141.5	582
50	111.6	1.70E-04	2.74E-06	131.8	518
70	103.7	2.45E-04	3.95E-06	119.6	326
90	92.4	1.13E-04	1.82E-06	113.4	669
110	87.1	1.29E-04	2.09E-06	103.7	534
130	81.1	1.33E-04	2.14E-06	95.7	481
150	74.9	1.39E-04	2.24E-06	89.5	429
170	68.5	1.20E-04	1.94E-06	83.8	465
190	62.9	5.39E-05	8.69E-07	75.3	932
210	60.4	6.76E-05	1.09E-06	72.5	715
230	57.2	9.44E-05	1.52E-06	70.9	500
250	52.8	5.91E-05	9.53E-07	68.3	771
270	50.1	5.06E-05	8.16E-07	66.9	882
290	47.7	5.86E-05	9.46E-07	65.3	742
310	45.0	8.64E-06	1.39E-07	64.3	4960
330	44.6	1.84E-05	2.96E-07	63.9	2321
350	43.8	3.84E-05	6.19E-07	62.2	1082
370	42.0	4.15E-05	6.69E-07	62.4	1002
390	40.0				

Appendix D

Once-through Multi-Species Experiments

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.67	2.96E-06	1.77	2.06E-06	5.02E-06	140	203.6
20	1.70	2.69E-06	1.81	1.72E-06	4.41E-06	139	222.4
30	1.71	2.60E-06	1.76	2.15E-06	4.75E-06	137	226.8
40	1.67	2.96E-06	1.79	1.87E-06	4.83E-06	138	200.7
50	1.69	2.77E-06	1.83	1.52E-06	4.30E-06	136	210.8
Average	1.69	2.77E-06	1.81	1.72E-06	4.49E-06	137.8	214.6

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin
Num 1

3

of Pairs

3

Initial Conc
Nitrate

2.00

Initial Conc
Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.67	2.96E-06	1.79	1.88E-06	4.84E-06	141	205.1
20	1.73	2.42E-06	1.77	2.06E-06	4.48E-06	140	248.9
30	1.74	2.33E-06	1.84	1.43E-06	3.76E-06	139	256.6
40	1.68	2.87E-06	1.77	2.06E-06	4.93E-06	140	210.0
50	1.66	3.05E-06	1.82	1.61E-06	4.66E-06	139	196.2
Average	1.70	2.70E-06	1.80	1.81E-06	4.51E-06	139.8	224.5

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.58	3.76E-06	1.72	2.51E-06	6.27E-06	198	376.8
20	1.55	4.03E-06	1.65	3.14E-06	7.17E-06	191	339.2
30	1.62	3.41E-06	1.70	2.69E-06	6.09E-06	192	403.8
40	1.63	3.32E-06	1.71	2.60E-06	5.91E-06	192	414.7
50	1.55	4.03E-06	1.67	2.96E-06	6.99E-06	191	339.2
Average	1.58	3.76E-06	1.68	2.88E-06	6.64E-06	192.4	368.1

Multi-Species Experimentation

Run #2

Flow (mL/min)
250Spacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate 2.00Initial Conc
Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.55	4.03E-06	1.66	3.05E-06	7.08E-06	192	341.0
20	1.57	3.85E-06	1.69	2.78E-06	6.63E-06	190	353.1
30	1.59	3.67E-06	1.68	2.87E-06	6.54E-06	189	368.4
40	1.62	3.41E-06	1.67	2.96E-06	6.36E-06	188	395.4
50	1.59	3.67E-06	1.71	2.60E-06	6.27E-06	189	368.4
Average	1.59	3.69E-06	1.69	2.75E-06	6.44E-06	189.8	369.1

Multi-Species Experimentation
Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 5.0
Resin Num 1 3
of Pairs 3
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.53	4.21E-06	1.55	4.03E-06	8.51E-06	258	619.2
20	1.50	4.48E-06	1.50	4.48E-06	8.69E-06	250	638.3
30	1.53	4.21E-06	1.53	4.21E-06	8.24E-06	248	661.3
40	1.53	4.21E-06	1.52	4.30E-06	8.51E-06	245	625.5
50	1.51	4.39E-06	1.52	4.30E-06	8.69E-06	245	600.0

Average 1.52 4.34E-06 1.53 4.17E-06 8.51E-06 248.8 617.0

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin
Num 1

3

of Pairs

3

Initial Conc
Nitrate

2.00

Initial Conc
Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
5	1.55	4.03E-06	1.57	3.85E-06	7.71E-06	258	720.0
10	1.57	3.85E-06	1.59	3.67E-06	7.62E-06	250	681.8
15	1.55	4.03E-06	1.56	3.94E-06	8.24E-06	248	620.0
20	1.56	3.94E-06	1.52	4.30E-06	7.89E-06	245	653.3
25	1.55	4.03E-06	1.57	3.85E-06	7.44E-06	245	683.7
30	1.58	3.78E-06	1.60	3.58E-06			
35	1.55	4.03E-06					
40	1.55	4.03E-06					
45	1.58	3.78E-06					
50	1.57	3.85E-06					

Average 1.55 4.01E-06 1.58 3.78E-06 7.80E-06 248.8 668.1

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

NU-70

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.69	2.05E-06	1.82	1.61E-06	4.30E-06	143	228.8
15	1.70	2.69E-06	1.82	1.61E-06	4.30E-06	143	228.8
20	1.69	2.72E-06	1.81	1.72E-06	4.23E-06	143	245.1
30	1.72	2.51E-06	1.82	1.61E-06	4.75E-06	142	219.9
40	1.69	2.78E-06	1.78	1.97E-06	4.75E-06	142	219.9
50	1.71	2.60E-06	1.82	1.61E-06	4.21E-06	142	235.0
Average	1.74	2.33E-06	1.83	1.52E-06	3.85E-06	142	262.2

Average **1.72** **2.55E-06** **1.81** **1.67E-06** **4.22E-06** **142.2** **240.9**

Multi-Species Experimentation
Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 3.33
Resin Num 2
of Pairs 3
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.59	3.67E-06	1.73	2.42E-06	5.91E-06	198	405.7
20	1.61	3.49E-06	1.69	2.78E-06	6.45E-06	197	384.0
30	1.59	3.67E-06	1.72	2.51E-06	6.27E-06	197	374.9
40	1.58	3.76E-06	1.68	2.87E-06	6.18E-06	196	423.4
50	1.63	3.32E-06	1.70	2.69E-06	6.45E-06	197	374.9

Average 1.61 3.45E-06 1.70 2.66E-06 6.11E-06 197.1 410.4

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 2

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.62	3.41E-06	1.73	2.42E-06	5.82E-06	196	412.2
20	1.60	3.58E-06	1.69	2.78E-06	6.36E-06	196	391.6
30	1.64	3.23E-06	1.74	2.33E-06	5.56E-06	195	432.9
40	1.63	3.32E-06	1.75	2.24E-06	5.56E-06	195	421.2
50	1.61	3.49E-06	1.68	2.87E-06	6.36E-06	195	399.6

Average

1.61

3.47E-06

1.71

2.57E-06

6.04E-06

195.4

404.7

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

Rohm and Haas

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.54	4.12E-06	1.59	3.67E-06	7.80E-06	255	665.2
15	1.56	3.91E-06	1.59	3.67E-06	7.58E-06	254	692.7
20	1.57	3.85E-06	1.60	3.58E-06	7.44E-06	252	703.3
30	1.49	4.57E-06	1.58	3.76E-06	8.33E-06	251	590.6
40	1.57	3.85E-06	1.58	3.76E-06	7.62E-06	250	697.7
50	1.59	3.67E-06	1.56	3.94E-06	7.62E-06	250	731.7

Average

1.56

3.97E-06

1.58

3.79E-06

7.77E-06

251.7

683.6

Multi-Species Experimentation

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
2.0Resin
Gardline# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.75	2.24E-06	1.82	1.61E-06	3.85E-06	142	272.6
20	1.77	2.06E-06	1.81	1.72E-06	3.78E-06	141	294.3
30	1.74	2.33E-06	1.78	1.97E-06	4.30E-06	141	260.3
40	1.76	2.15E-06	1.84	1.43E-06	3.58E-06	141	282.0
50	1.76	2.15E-06	1.85	1.34E-06	3.49E-06	141	282.0
Average	1.75	2.22E-06	1.82	1.59E-06	3.82E-06	141.0	274.1

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

3

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.71	2.60E-06	1.71	2.69E-06	5.65E-06	198	479.5
15	1.67	2.96E-06	1.70	2.69E-06	5.29E-06	196	522.1
20	1.68	2.87E-06	1.69	2.60E-06	6.00E-06	196	460.7
30	1.70	2.69E-06	1.71	2.69E-06	5.47E-06	196	505.3
40	1.66	3.05E-06	1.67	2.96E-06	5.11E-06	196	540.1
50	1.69	2.78E-06	1.70	2.69E-06			
	1.71	2.60E-06	1.72	2.51E-06			
Average	1.68	2.86E-06	1.69	2.76E-06	5.62E-06	196.2	493.0

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

3.33 mm

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.68	2.87E-06	1.69	2.78E-06	5.65E-06	194	484.5
20	1.68	2.87E-06	1.69	2.78E-06	5.65E-06	194	484.5
30	1.67	2.96E-06	1.70	2.69E-06	5.65E-06	193	467.4
40	1.70	2.69E-06	1.67	2.96E-06	5.65E-06	193	514.2
50	1.69	2.78E-06	1.68	2.87E-06	5.65E-06	192	495.0

Average

1.68

2.89E-06

1.68

2.83E-06

5.71E-06

193.3

481.2

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

3

of Pairs

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate Conc (mg/L)	Flux (meq/cm ² /s)	Chloride Conc (mg/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.58	3.76E-06	1.64	3.23E-06	6.99E-06	249	711.4
20	1.57	3.85E-06	1.60	3.58E-06	7.44E-06	248	692.1
30	1.56	3.94E-06	1.64	3.23E-06	7.17E-06	248	676.4
40	1.60	3.58E-06	1.58	3.76E-06	7.35E-06	247	741.0
50	1.59	3.67E-06	1.62	3.41E-06	7.08E-06	247	722.9

Average

1.59

3.69E-06

1.61

3.49E-06

7.19E-06

247.8

722.4

Multi-Species Experimentation

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 2.0 Resin NONE # of Pairs 3 Initial Conc Nitrate 2.00 Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
5	1.80	1.75E-06	1.80	1.79E-06	3.56E-06		
10	1.78	1.97E-06	1.79	1.88E-06	3.85E-06	130	283.6
15	1.79	1.84E-06	1.81	1.70E-06	3.63E-06	128	319.1
20	1.81	1.70E-06	1.77	2.06E-06	3.76E-06	128	323.4
25	1.77	1.77E-06	1.83	1.52E-06	3.29E-06	128	323.4
30	1.83	1.52E-06	1.83	1.52E-06	3.05E-06	128	361.4
35	1.82	1.60E-06	1.79	1.52E-06	3.21E-06	128	323.4
40	1.81	1.70E-06	1.85	1.34E-06	3.05E-06	128	323.4
45	1.80	1.77E-06	1.85	1.34E-06	3.11E-06	127	323.4
50	1.77	2.06E-06	1.85	1.34E-06	3.41E-06	127	265.0
Average	1.80	1.81E-06	1.81	1.67E-06	3.48E-06	128.2	307.5

Multi-Species Experimentation
Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 3.33
Resin NONE
of Pairs 3
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.74	2.33E-06	1.76	2.15E-06	4.48E-06	190	584.0
15	1.72	2.51E-06	1.73	2.29E-06	4.80E-06	190	584.0
20	1.73	2.42E-06	1.71	2.60E-06	5.02E-06	189	559.4
25	1.74	2.33E-06	1.73	2.29E-06	4.62E-06	189	559.4
30	1.77	2.06E-06	1.72	2.51E-06	4.57E-06	189	656.7
35	1.73	2.42E-06	1.73	2.29E-06	4.71E-06	189	559.4
40	1.72	2.51E-06	1.75	2.24E-06	4.75E-06	189	539.5
45	1.74	2.33E-06	1.73	2.29E-06	4.62E-06	189	559.4
50	1.72	2.51E-06	1.72	2.51E-06	5.02E-06	189	539.5
Average	1.74	2.35E-06	1.74	2.37E-06	4.72E-06	189.3	580.2

Multi-Species Experimentation

Run #2

Flow (mL/min)
250Spacing
1 mmVoltage
3.33Resin
NONE# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.76	2.15E-06	1.76	2.15E-06	4.30E-06	187	622.7
15	1.73	2.15E-06	1.73	2.15E-06	4.30E-06	186	530.9
20	1.72	2.51E-06	1.76	2.15E-06	4.66E-06	186	594.6
30	1.75	2.24E-06	1.74	2.33E-06	4.57E-06	186	675.7
40	1.78	1.97E-06	1.77	2.06E-06	4.03E-06	186	594.6
50	1.75	2.24E-06	1.75	2.24E-06	4.48E-06	186	594.6
Average	1.75	2.26E-06	1.76	2.19E-06	4.45E-06	186.1	592.6

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

NONE

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate Conc (mg/L)	Flux (meq/cm ² /s)	Chloride Conc (mg/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.63	3.05E-06	1.65	3.14E-06	6.18E-06	234	825.9
20	1.63	3.32E-06	1.62	3.41E-06	6.72E-06	233	755.7
30	1.65	3.41E-06	1.66	3.05E-06	6.45E-06	233	735.8
40	1.64	3.23E-06	1.61	3.49E-06	6.72E-06	234	780.0
50	1.67	2.96E-06	1.65	3.14E-06	6.09E-06	233	847.3

Average

1.64

3.23E-06

1.63

3.31E-06

6.53E-06

233.6

780.2

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

2.0

Voltage

2.0

Resin
Num 1

Num 1

of Pairs

3

Initial Conc
Nitrate

2.00

Initial Conc
Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.76	2.15E-06	1.86	1.25E-06	3.41E-06	136	272.0
20	1.72	2.51E-06	1.87	1.16E-06	3.67E-06	134	229.7
30	1.69	2.78E-06	1.78	1.97E-06	4.75E-06	134	207.5
40	1.69	2.78E-06	1.84	1.43E-06	4.21E-06	133	205.9
50	1.76	2.15E-06	1.85	1.34E-06	3.49E-06	133	266.0

Average

1.74

2.36E-06

1.84

1.47E-06

3.83E-06

134.0

247.0

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

2.5mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.67	2.96E-06	1.76	2.15E-06	5.11E-06	188	455.3
15	1.69	2.78E-06	1.75	2.21E-06	5.00E-06	188	457.4
20	1.64	3.23E-06	1.74	2.33E-06	5.56E-06	188	417.4
25	1.63	3.32E-06	1.75	2.25E-06	5.57E-06	187	467.0
30	1.68	2.87E-06	1.76	2.15E-06	5.02E-06	187	467.0
40	1.68	2.87E-06	1.68	2.87E-06	5.73E-06	187	467.0
50	1.70	2.69E-06	1.75	2.24E-06	4.93E-06	187	498.2
Average	1.67	2.95E-06	1.73	2.40E-06	5.35E-06	187.6	457.8

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

3.33

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.65	3.14E-06	1.74	2.33E-06	5.47E-06	187	427.0
20	1.64	3.23E-06	1.76	2.15E-06	5.38E-06	186	412.9
30	1.65	3.14E-06	1.74	2.33E-06	5.47E-06	186	424.7
40	1.65	3.14E-06	1.78	1.97E-06	5.11E-06	186	424.7
50	1.61	3.49E-06	1.73	2.42E-06	5.91E-06	186	381.2
Average	1.65	3.14E-06	1.74	2.30E-06	5.44E-06	186.3	427.2

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

2.00

Voltage

5.0

Resin
Num 1

1

of Pairs

3

Initial Conc
Nitrate

2.00

Initial Conc
Chloride

2.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.63	3.32E-06	1.66	3.05E-06	6.36E-06	238	771.9
15	1.60	3.39E-06	1.59	3.07E-06	6.46E-06	235	705.0
20	1.62	3.41E-06	1.65	3.14E-06	6.54E-06	235	742.1
25	1.61	3.42E-06	1.64	3.15E-06	6.57E-06	235	733.3
30	1.59	3.67E-06	1.58	3.76E-06	7.44E-06	235	687.8
35	1.60	3.58E-06	1.61	3.49E-06	7.08E-06	234	702.0
40	1.61	3.57E-06	1.62	3.48E-06	7.05E-06	235	705.0
45	1.63	3.32E-06	1.56	3.94E-06	7.26E-06	235	762.2
Average	1.61	3.47E-06	1.62	3.40E-06	6.87E-06	235.2	731.0

Multi-Species Experimentation

Run #1

Flow (mL/min)
1 mmSpacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.77	4.12E-06	1.84	2.87E-06	6.99E-06	210	364.9
20	1.81	3.41E-06	1.83	3.05E-06	6.45E-06	210	441.7
30	1.79	3.76E-06	1.81	3.41E-06	7.17E-06	209	397.7
40	1.82	3.23E-06	1.86	2.51E-06	5.73E-06	209	464.0
50	1.76	4.30E-06	1.84	2.87E-06	7.17E-06	208	346.3
Average	1.79	3.80E-06	1.84	2.95E-06	6.75E-06	209.2	398.3

Multi-Species Experimentation

Run #2

Flow (mL/min)

Spacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
5	1.82	3.22E-06	1.83	3.05E-06	7.35E-06	224	373.0
10	1.76	4.30E-06	1.83	3.05E-06	7.35E-06	224	373.0
15	1.75	4.18E-06	1.85	2.69E-06	6.45E-06	224	426.2
20	1.79	3.76E-06	1.85	2.69E-06	6.45E-06	224	426.2
30	1.80	3.58E-06	1.83	3.05E-06	6.63E-06	223	445.6
40	1.76	4.30E-06	1.85	2.69E-06	6.99E-06	224	373.0
50	1.78	3.94E-06	1.82	3.23E-06	7.17E-06	223	405.0
Average	1.78	3.92E-06	1.83	2.99E-06	6.91E-06	223.7	411.6

Multi-Species Experimentation

Run #1

Flow (mL/min)

Spacing
1 mm

Voltage
5.0

Resin
Num 1

of Pairs
3

Initial Conc
Nitrate
2.00

Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.77	4.12E-06	1.82	3.23E-06	7.35E-06	278	725.2
20	1.79	3.76E-06	1.78	3.94E-06	7.71E-06	277	791.4
30	1.77	4.12E-06	1.82	3.23E-06	7.35E-06	278	725.2
40	1.78	3.94E-06	1.77	4.12E-06	8.06E-06	278	758.2
50	1.79	3.76E-06	1.81	3.41E-06	7.17E-06	277	791.4

Average 1.78 3.86E-06 1.80 3.64E-06 7.51E-06 277.3 779.5

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Sulphate

2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.68	2.87E-06	1.78	1.97E-06	4.84E-06	141	211.5
20	1.67	2.96E-06	1.81	1.72E-06	4.68E-06	140	203.6
30	1.72	2.51E-06	1.77	2.06E-06	4.57E-06	140	240.0
40	1.69	2.78E-06	1.77	2.06E-06	4.84E-06	139	215.2
50	1.71	2.60E-06	1.80	1.79E-06	4.39E-06	139	230.1
Average	1.70	2.70E-06	1.79	1.89E-06	4.59E-06	139.8	223.6

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.59	3.92E-06	1.67	2.96E-06	6.45E-06	194	397.6
15	1.61	3.49E-06	1.67	2.96E-06	6.45E-06	194	397.6
20	1.57	3.85E-06	1.65	3.14E-06	6.99E-06	193	358.7
30	1.60	3.58E-06	1.66	3.05E-06	6.63E-06	194	387.6
40	1.59	3.67E-06	1.67	2.96E-06	6.63E-06	193	376.2
50	1.57	3.85E-06	1.64	3.23E-06	7.08E-06	193	358.7
Average	1.59	3.64E-06	1.66	3.02E-06	6.66E-06	193.3	380.6

Multi-Species Experimentation

Run #2

Flow (mL/min) 250 Spacing 1 mm Voltage 3.33 Resin Num 1 # of Pairs 3 Initial Conc Nitrate 2.00 Initial Conc 2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.60	3.58E-06	1.63	3.32E-06	6.90E-06	197	393.6
15	1.60	3.58E-06	1.63	3.32E-06	6.90E-06	197	393.6
20	1.59	3.67E-06	1.67	2.96E-06	6.63E-06	196	382.1
30	1.62	3.41E-06	1.67	2.96E-06	6.36E-06	195	410.1
40	1.59	3.67E-06	1.66	3.05E-06	6.72E-06	196	382.1
50	1.57	3.85E-06	1.62	3.41E-06	7.26E-06	195	362.4

Average 1.59 3.63E-06 1.65 3.18E-06 6.81E-06 196.0 386.9

Multi-Species Experimentation

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
5.0Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Sulphate
2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.52	4.30E-06	1.52	4.30E-06	8.60E-06	250	625.0
20	1.52	4.30E-06	1.50	4.48E-06	8.78E-06	248	620.0
30	1.53	4.21E-06	1.54	4.12E-06	8.33E-06	247	630.6
40	1.52	4.30E-06	1.53	4.21E-06	8.51E-06	247	617.5
50	1.54	4.12E-06	1.52	4.30E-06	8.42E-06	247	644.3

Average 1.53 4.21E-06 1.52 4.26E-06 8.47E-06 247.7 632.7

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

1.77

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.73	2.42E-06	1.81	1.70E-06	4.12E-06	145	257.8
15	1.73	2.42E-06	1.73	2.42E-06	4.57E-06	144	288.0
20	1.76	2.15E-06	1.73	2.42E-06	4.57E-06	143	245.1
30	1.72	2.51E-06	1.77	2.06E-06	4.66E-06	144	238.3
40	1.71	2.60E-06	1.77	2.06E-06	4.39E-06	143	245.1
50	1.72	2.51E-06	1.79	1.88E-06			
Average	1.73	2.44E-06	1.77	2.06E-06	4.50E-06	143.9	254.7

Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

100%

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.62	3.41E-06	1.69	2.78E-06	6.18E-06	199	418.5
20	1.60	3.58E-06	1.67	2.96E-06	6.54E-06	198	395.6
30	1.63	3.32E-06	1.70	2.69E-06	6.00E-06	198	427.7
40	1.60	3.58E-06	1.69	2.78E-06	6.36E-06	198	395.6
50	1.65	3.14E-06	1.68	2.87E-06	6.00E-06	198	452.1

Average 1.62 3.37E-06 1.69 2.75E-06 6.11E-06 198.2 422.8

Multi-Species Experimentation

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

100%

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.63	3.32E-06	1.70	2.69E-06	6.00E-06	200	432.0
15	1.59	3.27E-06	1.67	2.96E-06	6.36E-06	199	418.5
20	1.62	3.41E-06	1.72	2.51E-06	5.91E-06	199	418.5
25	1.60	3.35E-06	1.69	2.78E-06	6.27E-06	198	405.7
30	1.62	3.41E-06	1.69	2.78E-06	6.27E-06	198	405.7
40	1.61	3.49E-06	1.67	2.96E-06	6.54E-06	197	393.6
50	1.60	3.58E-06	1.67	2.96E-06	6.54E-06	197	393.6
Average	1.62	3.43E-06	1.69	2.77E-06	6.20E-06	198.7	415.4

Multi-Species Experimentation

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
5.0Resin
0.012# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
2.00

Time (min)	Nitrate		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.59	3.67E-06	1.56	3.94E-06	7.62E-06	250	731.7
15	1.59	3.70E-06	1.55	4.03E-06	7.72E-06	250	743.3
20	1.57	3.85E-06	1.54	4.12E-06	7.97E-06	250	697.7
30	1.56	3.94E-06	1.53	4.21E-06	8.15E-06	249	679.1
40	1.58	3.76E-06	1.56	3.94E-06	7.71E-06	249	711.4
50	1.57	3.85E-06	1.57	3.85E-06	7.71E-06	249	694.9
Average	1.57	3.88E-06	1.55	4.01E-06	7.90E-06	249.2	691.2

Multi-Species Experimentation

Run #1

Flow (mL/min)

Spacing
2 mmVoltage
2.0Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.84	2.87E-06	1.89	1.97E-06	4.84E-06	161	241.5
20	1.83	3.05E-06	1.87	2.33E-06	5.38E-06	160	225.9
30	1.83	3.05E-06	1.89	1.97E-06	5.02E-06	159	224.5
40	1.86	2.51E-06	1.92	1.43E-06	3.94E-06	160	274.3
50	1.84	2.87E-06	1.89	1.97E-06	4.84E-06	160	240.0

Average 1.85 2.71E-06 1.89 1.93E-06 4.64E-06 159.8 256.2

Multi-Species Experimentation

Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.33
 Resin Num 1 3
 Initial Conc Nitrate 100
 Initial Conc Chloride 100

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	0.83	1.52E-06	0.83	1.52E-06	3.05E-06	112	526.5
20	0.78	1.97E-06	0.86	1.25E-06	3.23E-06	111	403.2
30	0.78	1.97E-06	0.85	1.34E-06	3.32E-06	111	403.2
40	0.76	2.15E-06	0.84	1.43E-06	3.58E-06	112	373.0
50	0.76	2.15E-06	0.83	1.52E-06	3.67E-06	112	373.0
Average	0.78	1.96E-06	0.84	1.43E-06	3.40E-06	111.4	413.1

Multi-Species Experimentation

Run #2

Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Initial Conc Nitrate	Initial Conc Chloride
250	1 mm	3.33	Num 1	3	100	100

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	0.80	1.97E-06	0.86	1.25E-06	3.23E-06	113	410.5
20	0.79	1.88E-06	0.82	1.61E-06	3.49E-06	112	426.2
30	0.77	2.06E-06	0.85	1.34E-06	3.41E-06	113	392.7
40	0.78	1.97E-06	0.84	1.43E-06	3.41E-06	112	406.9
50	0.80	1.79E-06	0.85	1.34E-06	3.14E-06	113	451.5

Average	0.79	1.87E-06	0.84	1.40E-06	3.28E-06	112.3	432.1
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Multi-Species Experimentation

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

Initial Conc

Chloride

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	2.50	4.18E-06	2.61	3.49E-06	7.97E-06	258	412.4
20	2.53	4.21E-06	2.61	3.49E-06	7.71E-06	257	437.0
30	2.51	4.39E-06	2.60	3.58E-06	7.97E-06	256	417.5
40	2.53	4.21E-06	2.63	3.32E-06	7.53E-06	256	435.3
50	2.55	4.03E-06	2.63	3.32E-06	7.35E-06	256	454.7
Average	2.53	4.23E-06	2.62	3.37E-06	7.60E-06	256.3	434.3

Multi-Species Experimentation

Average	Initial Conc	Initial Conc	Initial Conc
Flow (mL/min)	2.00	2.00	2.00
250	2.00	2.00	2.00

Resin Num1 3

Voltage 2.0

Spacing 1 mm

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm2/s)	Chloride Conc (meq/L)	Flux (meq/cm2/s)	Sulphate Conc (meq/L)	Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
10	1.77	2.06E-06	1.83	1.52E-06	1.80	1.79E-06	5.38E-06	175	365.2
20	1.76	2.15E-06	1.80	1.79E-06	1.78	1.97E-06	5.91E-06	174	348.0
30	1.81	1.70E-06	1.82	1.61E-06	1.83	1.52E-06	4.84E-06	174	439.6
40	1.75	2.24E-06	1.85	1.34E-06	1.80	1.79E-06	5.38E-06	173	332.2
50	1.75	2.24E-06	1.83	1.52E-06	1.83	1.52E-06	5.29E-06	173	332.2
Average	1.77	2.02E-06	1.83	1.53E-06	1.81	1.73E-06	5.29E-06	174	373

Multi-Species Experimentation

Run #1	Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Initial Conc	Initial Conc	Initial Conc
250	1 mm	3.33	Num1	3	2.00	2.00	2.00	2.00

Time (min)	Nitrate		Chloride		Sulphate		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.68	2.87E-06	1.74	2.33E-06	1.71	2.60E-06	7.80E-06	257	641.9
20	1.72	2.51E-06	1.75	2.24E-06	1.69	2.78E-06	7.53E-06	256	730.7
30	1.69	2.78E-06	1.76	2.15E-06	1.71	2.60E-06	7.53E-06	255	657.4
40	1.72	2.51E-06	1.72	2.51E-06	1.74	2.33E-06	7.35E-06	255	727.8
50	1.68	2.87E-06	1.76	2.15E-06	1.72	2.51E-06	7.53E-06	255	636.9
Average	1.69	2.76E-06	1.74	2.35E-06	1.71	2.57E-06	7.68E-06	256	666

Multi-Species Experimentation

Run #2	Flow (mL/min)	Spacing	Voltage	Resin Num1	# of Pairs	Initial Conc	Initial Conc	Initial Conc
	250	1 mm	3.33		3	2.00	2.00	2.00

Time (min)	Nitrate		Chloride		Sulphate		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.69	2.78E-06	1.75	2.24E-06	1.72	2.51E-06	7.53E-06	256	660.0
20	1.68	2.87E-06	1.71	2.60E-06	1.72	2.51E-06	7.97E-06	254	634.4
30	1.67	2.96E-06	1.75	2.24E-06	1.70	2.69E-06	7.89E-06	254	615.1
40	1.71	2.60E-06	1.72	2.51E-06	1.71	2.60E-06	7.71E-06	254	700.0
50	1.68	2.87E-06	1.76	2.15E-06	1.72	2.51E-06	7.53E-06	253	631.9

Multi-Species Experimentation

Average Flow (mL/min)	Spacing	Voltage	Resin Num1	# of Pairs	Initial Conc	Initial Conc	Initial Conc
250	1 mm	5.0	Num1	3	2.00	2.00	2.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Sulphate Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.63	3.32E-06	1.67	2.96E-06	1.66	3.05E-06	9.32E-06	297	963
20	1.64	3.23E-06	1.68	2.87E-06	1.67	2.96E-06	9.05E-06	296	987
30	1.67	2.96E-06	1.67	2.96E-06	1.64	3.23E-06	9.14E-06	296	1076
40	1.61	3.49E-06	1.69	2.78E-06	1.68	2.87E-06	9.14E-06	295	908
50	1.66	3.05E-06	1.68	2.87E-06	1.64	3.23E-06	9.14E-06	295	1041
Average	1.64	3.22E-06	1.68	2.85E-06	1.65	3.10E-06	9.16E-06	296	992

Multi-Species Experimentation

Run #1	Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Initial Conc	Initial Conc	Initial Conc
250	1 mm	2.0	2.00	3	2.00	2.00	2.00	2.00

Time (min)	Nitrate Conc (meq/L)	Nitrate Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Chloride Flux (meq/cm ² /s)	Sulphate Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.80	1.79E-06	1.85	1.34E-06	1.82	1.61E-06	4.75E-06	178	427.2
20	1.79	1.88E-06	1.87	1.16E-06	1.83	1.52E-06	4.57E-06	177	404.6
30	1.81	1.70E-06	1.83	1.52E-06	1.82	1.61E-06	4.84E-06	177	447.2
40	1.80	1.79E-06	1.88	1.08E-06	1.83	1.52E-06	4.39E-06	177	424.8
50	1.78	1.97E-06	1.86	1.25E-06	1.84	1.43E-06	4.66E-06	177	386.2
Average	1.79	1.88E-06	1.85	1.32E-06	1.83	1.53E-06	4.74E-06	177	407

Multi-Species Experimentation

Run #1	Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Initial Conc	Initial Conc	Initial Conc
250	1 mm	3.33		3	2.00	2.00	2.00	2.00

Time (min)	Nitrate		Chloride		Sulphate		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm2/s)	Conc (mg/L)	Flux (meq/cm2/s)	Conc (mg/L)	Flux (meq/cm2/s)			
10	1.72	2.51E-06	1.76	2.15E-06	1.74	2.33E-06	6.99E-06	257	733.6
20	1.71	2.60E-06	1.76	2.15E-06	1.74	2.33E-06	7.08E-06	256	705.5
30	1.67	2.96E-06	1.76	2.15E-06	1.73	2.42E-06	7.53E-06	255	617.6
40	1.72	2.51E-06	1.77	2.06E-06	1.70	2.69E-06	7.26E-06	255	727.8
50	1.70	2.69E-06	1.76	2.15E-06	1.75	2.24E-06	7.08E-06	255	679.3
Average	1.71	2.58E-06	1.76	2.17E-06	1.74	2.35E-06	7.10E-06	256	712

Multi-Species Experimentation

Run #2 Initial Conc Initial Conc Initial Conc
 Flow (mL/min) Spacing Voltage Resin # of Pairs
 250 1 mm 3.33 2.00 2.00 2.00

Time (min)	Nitrate		Chloride		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.72	2.51E-06	1.77	2.06E-06	1.75	2.24E-06	6.81E-06	259	739.3
20	1.69	2.78E-06	1.74	2.33E-06	1.76	2.15E-06	7.26E-06	259	667.7
30	1.70	2.69E-06	1.75	2.24E-06	1.72	2.51E-06	7.44E-06	258	687.3
40	1.69	2.78E-06	1.72	2.51E-06	1.71	2.60E-06	7.89E-06	258	665.1
50	1.72	2.51E-06	1.78	1.97E-06	1.74	2.33E-06	6.81E-06	257	733.6
Average	1.71	2.58E-06	1.76	2.16E-06	1.74	2.36E-06	7.10E-06	258	720

Multi-Species Experimentation

Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 5.0
 Resin
 # of Pairs 3
 Initial Conc 2.00
 Initial Conc 2.00
 Initial Conc 2.00

Time (min)	Nitrate		Chloride		Sulphate		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.68	2.87E-06	1.72	2.51E-06	1.66	3.05E-06	8.42E-06	300	1125
20	1.64	3.23E-06	1.74	2.33E-06	1.69	2.78E-06	8.33E-06	300	1000
30	1.65	3.14E-06	1.69	2.78E-06	1.67	2.96E-06	8.87E-06	298	1022
40	1.63	3.32E-06	1.72	2.51E-06	1.69	2.78E-06	8.60E-06	299	970
50	1.69	2.78E-06	1.70	2.69E-06	1.66	3.05E-06	8.51E-06	298	1154
Average	1.66	3.07E-06	1.71	2.60E-06	1.68	2.85E-06	8.51E-06	310	1091

Extended Duration

Multi-Species Experimentation

Run #2

Flow (mL/min)

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
0.5	1.71	2.60E-06	1.81	1.70E-06	4.30E-06	138	228.4
1	1.67	2.96E-06	1.80	1.79E-06	4.75E-06	138	200.7
2	1.68	2.87E-06	1.83	1.68E-06	4.39E-06	137	209.5
3	1.70	2.69E-06	1.78	1.97E-06	4.66E-06	137	219.2
5	1.71	2.60E-06	1.82	1.81E-06	4.41E-06	136	226.8
6	1.73	2.42E-06	1.81	1.70E-06	4.12E-06	136	241.8
7	1.70	2.69E-06	1.79	1.88E-06	4.37E-06	136	217.6
8	1.68	2.87E-06	1.79	1.87E-06	4.74E-06	136	204.0
9	1.69	2.76E-06	1.81	1.69E-06	4.07E-06	136	210.6
10	1.71	2.60E-06	1.78	1.97E-06	4.57E-06	136	225.1
11	1.73	2.42E-06	1.82	1.81E-06	4.03E-06	136	241.8
12	1.72	2.51E-06	1.84	1.43E-06	3.94E-06	136	233.1
Average	1.69	3.05E-06	1.81	1.70E-06	4.15E-06	136	192.0

Average **1.70** **2.70E-06** **1.81** **1.73E-06** **4.43E-06** **136** **218**

Multi-Species Experimentation
Run #2
Flow (mL/min) 250
Spacing 1 mm
Voltage 2.0
Resin Num 1 3
of Pairs 3
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
1	1.67	2.96E-06	1.80	1.79E-06	4.75E-06	138	200.7
3	1.70	2.69E-06	1.78	1.97E-06	4.66E-06	137	219.2
5	1.73	2.42E-06	1.81	1.70E-06	4.12E-06	136	241.8
7	1.68	2.87E-06	1.79	1.87E-06	4.74E-06	136	204.0
9	1.71	2.60E-06	1.78	1.97E-06	4.57E-06	136	225.1
11	1.72	2.51E-06	1.84	1.43E-06	3.94E-06	136	233.1
12	1.69	3.05E-06	1.81	1.79E-06	4.75E-06	136	200.7
Average	1.70	2.70E-06	1.81	1.73E-06	4.43E-06	136	218

Multi-Species Experimentation

Run #1

Flow (mL/min) 250
Spacing 1 mm
Voltage 3.33

Resin Num 1
of Pairs 3

Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
0.5	1.59	3.67E-06	1.71	2.60E-06	6.27E-06	192	374
1	1.59	3.67E-06	1.71	2.60E-06	6.27E-06	192	374
3	1.58	3.76E-06	1.74	2.33E-06	6.09E-06	192	365
5	1.60	3.58E-06	1.69	2.78E-06	6.36E-06	192	384
7	1.64	3.23E-06	1.69	2.78E-06	6.00E-06	192	426
9	1.59	3.67E-06	1.69	2.78E-06	6.45E-06	192	224.8
11	1.63	3.32E-06	1.73	2.42E-06	5.73E-06	191	247.8
12	1.69	3.97E-06	1.71	2.58E-06	6.55E-06	192	337
Average	1.61	3.54E-06	1.71	2.58E-06	6.12E-06	192	337

Multi-Species Experimentation
 Run #2
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.33
 Resin Num 1
 # of Pairs 3
 Initial Conc Nitrate 2.00
 Initial Conc Chloride 2.00

Extended Duration

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
1	1.62	3.41E-06	1.64	3.23E-06	6.63E-06	192	404
3	1.64	3.23E-06	1.75	2.24E-06	5.47E-06	190	422
5	1.66	3.05E-06	1.62	3.41E-06	6.45E-06	189	444
7	1.56	3.94E-06	1.72	2.51E-06	6.45E-06	188	341
9	1.68	2.87E-06	1.65	3.14E-06	6.00E-06	135	202.5
11	1.63	3.32E-06	1.69	2.78E-06	6.09E-06	135	175.1
Average	1.61	3.48E-06	1.70	2.69E-06	6.17E-06	171	313

Multi-Species Experimentation
 Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 5.0
 Resin Num 1
 # of Pairs 3
 Initial Conc Nitrate 2.00
 Initial Conc Chloride 2.00

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
1	1.50	4.48E-06	1.53	4.21E-06	8.69E-06	245	588
2	1.51	4.39E-06	1.52	4.30E-06	8.69E-06	245	600
3	1.48	4.66E-06	1.54	4.12E-06	8.78E-06	244	563
5	1.53	4.21E-06	1.54	4.12E-06	8.33E-06	244	623
7	1.52	4.30E-06	1.52	4.30E-06	8.60E-06	245	613
9	1.51	4.39E-06	1.53	4.21E-06	8.69E-06	244	598
11	1.50	4.48E-06	1.51	4.39E-06	8.87E-06	243	233
12	1.49	4.57E-06	1.52	4.30E-06	8.87E-06	243	230

Average 1.51 4.37E-06 1.53 4.26E-06 8.62E-06 244 513

Multi-Species Experimentation
Run #2
Flow (mL/min) 250
Spacing 1 mm
Voltage 5.0
Resin Num 1
of Pairs 3
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (hours)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
0.5	1.50	4.18E-06	1.51	3.70E-06	7.87E-06	244	588
1	1.56	3.94E-06	1.57	3.85E-06	7.80E-06	244	665
2	1.53	4.21E-06	1.56	3.71E-06	7.92E-06	244	620
3	1.48	4.66E-06	1.59	3.67E-06	8.33E-06	244	563
4	1.56	3.94E-06	1.57	3.71E-06	7.65E-06	243	653
5	1.49	4.57E-06	1.56	3.94E-06	8.51E-06	243	572
6	1.57	3.85E-06	1.59	3.71E-06	7.56E-06	243	673
7	1.53	4.21E-06	1.57	3.85E-06	8.06E-06	243	620
8	1.53	4.21E-06	1.59	3.71E-06	7.92E-06	243	613
9	1.48	4.66E-06	1.52	4.30E-06	8.96E-06	243	561
10	1.52	4.30E-06	1.53	4.18E-06	8.68E-06	244	553
11	1.52	4.30E-06	1.51	4.39E-06	8.69E-06	244	244
12	1.47	4.75E-06	1.52	4.30E-06	9.05E-06	244	244
Average	1.52	4.29E-06	1.56	3.97E-06	8.26E-06	243	523

Appendix E

Once-through Complex Water Experiments

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.75	2.24E-06	1.84	1.43E-06	3.67E-06	162	311.0
15	1.72	2.51E-06	1.80	1.70E-06	4.21E-06	161	276.0
20	1.72	2.51E-06	1.83	1.52E-06	4.03E-06	161	276.0
25	1.75	2.24E-06	1.79	1.88E-06	4.12E-06	160	240.0
30	1.68	2.87E-06	1.82	1.61E-06	4.48E-06	160	240.0
35	1.73	2.42E-06	1.79	1.89E-06	4.31E-06	160	240.0
40	1.73	2.42E-06	1.82	1.61E-06	4.03E-06	160	284.4
45	1.73	2.42E-06	1.85	1.72E-06	4.15E-06	160	297.2
50	1.71	2.60E-06	1.82	1.61E-06	4.21E-06	160	264.8
Average	1.73	2.46E-06	1.82	1.63E-06	4.09E-06	160.7	282.6

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.74	2.33E-06	1.82	1.61E-06	3.94E-06	162	299.1
15	1.73	2.42E-06	1.82	1.61E-06	4.03E-06	162	288.0
20	1.74	2.33E-06	1.80	1.79E-06	4.12E-06	161	286.5
25	1.72	2.33E-06	1.78	1.79E-06	4.12E-06	161	297.2
30	1.70	2.69E-06	1.78	1.97E-06	4.66E-06	160	256.0
35	1.71	2.60E-06	1.77	2.06E-06	4.66E-06	160	264.8
40	1.74	2.33E-06	1.78	1.97E-06	4.30E-06	160	295.4
45	1.72	2.33E-06	1.80	1.79E-06	4.30E-06	160	276.0
50	1.74	2.33E-06	1.82	1.61E-06	3.94E-06	160	295.4
Average	1.72	2.48E-06	1.80	1.81E-06	4.29E-06	160.7	279.5

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.59	3.67E-06	1.70	2.69E-06	6.27E-06	229	457.5
15	1.60	3.58E-06	1.71	2.69E-06	6.27E-06	229	457.5
20	1.59	3.67E-06	1.68	2.87E-06	6.54E-06	228	444.4
25	1.62	3.41E-06	1.70	2.87E-06	6.00E-06	227	503.9
30	1.64	3.23E-06	1.69	2.78E-06	6.00E-06	227	503.9
35	1.62	3.41E-06	1.72	2.87E-06	6.09E-06	227	503.9
40	1.64	3.23E-06	1.68	2.87E-06	6.09E-06	227	503.9
45	1.60	3.67E-06	1.71	2.60E-06	6.00E-06	227	503.9
50	1.62	3.41E-06	1.71	2.60E-06	6.00E-06	227	477.4
Average	1.62	3.42E-06	1.70	2.66E-06	6.08E-06	227.6	476.7

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
5	1.62	3.41E-06	1.70	2.69E-06	6.10E-06	231	485.8
10	1.62	3.41E-06	1.69	2.78E-06	6.18E-06	231	485.8
15	1.60	3.38E-06	1.69	2.87E-06	6.25E-06	230	471.3
20	1.61	3.49E-06	1.68	2.87E-06	6.36E-06	230	471.3
25	1.59	3.47E-06	1.69	2.95E-06	6.42E-06	230	471.3
30	1.59	3.67E-06	1.72	2.51E-06	6.18E-06	230	448.3
35	1.60	3.58E-06	1.69	2.84E-06	6.42E-06	230	496.8
40	1.63	3.32E-06	1.66	3.05E-06	6.36E-06	230	496.8
45	1.59	3.27E-06	1.70	2.89E-06	6.16E-06	230	471.3
50	1.64	3.23E-06	1.73	2.42E-06	5.65E-06	230	510.6
Average	1.61	3.52E-06	1.69	2.76E-06	6.28E-06	230.0	468.4

Complex-(Ottawa-Carleton)**Run #1****Flow (mL/min)****250****Spacing****1 mm****Voltage****5.0****Resin****Num 1****# of Pairs****3****Initial Conc****Nitrate****2.00****Initial Conc****Chloride****2.00**

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.54	4.12E-06	1.56	3.94E-06	8.06E-06	280	730.4
20	1.53	4.21E-06	1.54	4.12E-06	8.33E-06	281	717.4
30	1.57	3.85E-06	1.58	3.76E-06	7.62E-06	280	781.4
40	1.53	4.21E-06	1.56	3.94E-06	8.15E-06	280	714.9
50	1.55	4.03E-06	1.57	3.85E-06	7.89E-06	279	744.0
Average	1.54	4.09E-06	1.57	3.85E-06	7.95E-06	280.0	736.4

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm2/s)	Chloride Conc (meq/L)	Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
10	1.57	3.85E-06	1.54	4.12E-06	7.97E-06	278	775.8
20	1.56	3.94E-06	1.55	4.03E-06	7.97E-06	277	755.5
30	1.56	3.94E-06	1.59	3.67E-06	7.62E-06	276	752.7
40	1.55	4.03E-06	1.53	4.21E-06	8.24E-06	275	733.3
50	1.56	3.94E-06	1.55	4.03E-06	7.97E-06	275	750.0
Average	1.56	3.95E-06	1.55	4.03E-06	7.98E-06	276.2	752.4

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 2

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.75	2.24E-06	1.82	1.61E-06	3.76E-06	160	320.0
15	1.74	2.10E-06	1.84	1.43E-06	3.76E-06	159	293.5
20	1.74	2.33E-06	1.85	1.34E-06	3.32E-06	158	344.7
30	1.78	1.97E-06	1.82	1.61E-06	3.85E-06	158	303.4
40	1.75	2.24E-06	1.83	1.52E-06	4.21E-06	158	252.8
50	1.70	2.69E-06					
Average	1.74	2.29E-06	1.83	1.53E-06	3.82E-06	158.7	300.7

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Nupur

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.75	2.24E-06	1.80	1.79E-06	4.03E-06	164	314.9
20	1.77	2.06E-06	1.81	1.70E-06	3.76E-06	163	340.2
30	1.75	2.24E-06	1.78	1.97E-06	4.21E-06	163	313.0
40	1.73	2.42E-06	1.85	1.34E-06	3.76E-06	163	289.8
50	1.74	2.33E-06	1.85	1.34E-06	3.67E-06	162	299.1
Average	1.74	2.31E-06	1.82	1.64E-06	3.95E-06	163.0	305.0

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

NUT

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.66	3.05E-06	1.75	2.24E-06	5.29E-06	232	545.3
15	1.64	3.23E-06	1.72	2.11E-06	5.34E-06	231	545.0
20	1.60	3.58E-06	1.73	2.42E-06	6.00E-06	231	461.5
30	1.63	3.32E-06	1.74	2.33E-06	5.65E-06	231	499.0
40	1.67	2.96E-06	1.75	2.24E-06	5.20E-06	230	557.0
50	1.63	3.32E-06	1.73	2.42E-06	5.73E-06	230	496.8
Average	1.64	3.20E-06	1.73	2.44E-06	5.64E-06	231.0	519.4

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)
250

Spacing
1 mm

Voltage
5.0

Resin
Num

of Pairs
3

Initial Conc
Nitrate
2.00

Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.59	3.67E-06	1.57	3.85E-06	7.53E-06	280	819.5
20	1.58	3.76E-06	1.63	3.32E-06	7.08E-06	281	802.9
30	1.62	3.41E-06	1.60	3.58E-06	6.99E-06	280	884.2
40	1.54	4.12E-06	1.56	3.94E-06	8.06E-06	280	730.4
50	1.58	3.76E-06	1.58	3.76E-06	7.53E-06	279	797.1
Average	1.58	3.75E-06	1.59	3.67E-06	7.43E-06	280.0	805.5

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

3

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.79	1.88E-06	1.77	2.06E-06	3.94E-06	146	333.7
20	1.81	1.70E-06	1.74	2.33E-06	4.03E-06	146	368.8
30	1.79	1.88E-06	1.83	1.52E-06	3.41E-06	145	331.4
40	1.74	2.33E-06	1.78	1.97E-06	4.30E-06	145	267.7
50	1.77	2.06E-06	1.81	1.70E-06	3.76E-06	145	302.6
Average	1.78	1.98E-06	1.78	1.95E-06	3.93E-06	145.4	320.0

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

3

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.81	1.70E-06	1.75	2.24E-06	3.94E-06	152	384.0
20	1.79	1.88E-06	1.82	1.61E-06	3.49E-06	152	347.4
30	1.79	1.88E-06	1.74	2.33E-06	4.21E-06	151	345.1
40	1.73	2.42E-06	1.73	2.42E-06	4.84E-06	151	268.4
50	1.81	1.70E-06	1.80	1.79E-06	3.49E-06	151	381.5
Average	1.79	1.84E-06	1.77	2.09E-06	3.93E-06	151.2	359.3

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

SEI-100

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.70	2.69E-06	1.77	2.06E-06	4.66E-06	210	578.7
20	1.72	2.51E-06	1.76	2.15E-06	4.66E-06	209	596.5
30	1.69	2.78E-06	1.69	2.78E-06	5.56E-06	209	538.8
40	1.72	2.51E-06	1.73	2.42E-06	4.93E-06	208	593.7
50	1.74	2.33E-06	1.70	2.69E-06	5.02E-06	208	639.4
Average	1.71	2.57E-06	1.72	2.48E-06	5.05E-06	208.9	585.7

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

(Gardner)

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.56	3.94E-06	1.62	3.41E-06	7.35E-06	255	695.5
20	1.62	3.41E-06	1.55	4.03E-06	7.44E-06	254	802.1
30	1.60	3.58E-06	1.66	3.05E-06	6.63E-06	254	762.0
40	1.55	4.03E-06	1.57	3.85E-06	7.89E-06	253	674.7
50	1.59	3.67E-06	1.60	3.58E-06	7.26E-06	253	740.5
Average	1.58	3.76E-06	1.60	3.56E-06	7.33E-06	253.8	727.8

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)
1.00

Spacing
1 mm

Voltage
2.0

Resin
Num 1

of Pairs
3

Initial Conc
Nitrate
2.00

Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.85	2.69E-06	1.88	2.15E-06	4.84E-06	175	280.0
20	1.88	2.15E-06	1.86	2.51E-06	4.66E-06	174	348.0
30	1.85	2.69E-06	1.84	2.87E-06	5.56E-06	174	278.4
40	1.85	2.69E-06	1.87	2.33E-06	5.02E-06	175	280.0
50	1.84	2.87E-06	1.87	2.33E-06	5.20E-06	174	261.0
Average	1.86	2.53E-06	1.87	2.35E-06	4.88E-06	174.4	301.3

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
5	1.84	2.87E-06	1.86	2.51E-06	5.38E-06	269	671.8
10	1.82	3.23E-06	1.83	3.05E-06	6.27E-06	268	595.0
20	1.83	3.05E-06	1.84	2.87E-06	5.91E-06	267	627.6
30	1.76	4.30E-06	1.82	3.23E-06	7.53E-06	267	444.6
40	1.78	3.94E-06	1.82	3.23E-06	7.17E-06	266	483.2
50							
Average	1.80	3.56E-06	1.84	2.91E-06	6.47E-06	267.3	549.8

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)
2.00

Spacing
1 mm

Voltage
5.0

Resin
Num 1

of Pairs
3

Initial Conc
Nitrate
2.00

Initial Conc
Chloride
2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
5	1.77	4.12E-06	1.78	3.94E-06	8.06E-06	301	785.2
10	1.77	4.12E-06	1.78	3.94E-06	8.06E-06	301	785.2
15	1.77	4.12E-06	1.78	3.94E-06	8.06E-06	301	785.2
20	1.79	3.76E-06	1.76	4.30E-06	8.06E-06	300	857.1
25	1.79	3.76E-06	1.78	3.94E-06	8.06E-06	301	785.2
30	1.80	3.58E-06	1.82	3.23E-06	6.81E-06	301	903.0
35	1.79	4.12E-06	1.78	3.94E-06	8.06E-06	301	785.2
40	1.77	4.12E-06	1.75	4.48E-06	8.60E-06	301	785.2
45	1.77	4.12E-06	1.76	4.30E-06	8.60E-06	301	785.2
50	1.76	4.30E-06	1.76	4.30E-06	8.60E-06	301	752.5
Average	1.77	4.10E-06	1.77	4.10E-06	8.20E-06	300.8	793.1

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

2.0

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

4.00

Initial Conc

Chloride

4.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	3.67	2.96E-06	3.72	2.51E-06	5.47E-06	209	304.0
20	3.69	2.78E-06	3.70	2.69E-06	5.47E-06	209	323.6
30	3.66	3.05E-06	3.70	2.69E-06	5.73E-06	208	293.6
40	3.70	2.69E-06	3.67	2.96E-06	5.65E-06	208	332.8
50	3.65	3.14E-06	3.73	2.42E-06	5.56E-06	207	283.9
Average	3.66	3.07E-06	3.71	2.64E-06	5.70E-06	208.1	294.3

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

Initial Conc

Chloride

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	3.49	4.57E-06	3.55	4.03E-06	8.42E-06	303	494.2
20	3.48	4.66E-06	3.53	4.21E-06	8.87E-06	302	464.2
30	3.49	4.57E-06	3.56	3.94E-06	8.51E-06	302	473.3
40	3.46	4.84E-06	3.54	4.12E-06	8.96E-06	302	447.0
50	3.49	4.57E-06	3.56	3.94E-06	8.51E-06	303	474.8
Average	3.49	4.57E-06	3.54	4.12E-06	8.69E-06	302.3	474.1

Complex-(Ottawa-Carleton)**Run #1****Flow (mL/min)****250****Spacing****1 mm****Voltage****5.0****Resin****Num 1****# of Pairs****3****Initial Conc****Nitrate****4.00****Initial Conc****Chloride****4.00**

Time (min)	Nitrate		Chloride		Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)				
10	3.42	5.20E-06	3.44	5.02E-06	1.02E-05	1.02E-05	381	788.3
20	3.40	5.38E-06	3.39	5.47E-06	1.08E-05	1.08E-05	380	760.0
30	3.41	5.29E-06	3.42	5.20E-06	1.05E-05	1.05E-05	380	772.9
40	3.44	5.02E-06	3.40	5.38E-06	1.04E-05	1.04E-05	380	814.3
50	3.41	5.29E-06	3.45	4.93E-06	1.02E-05	1.02E-05	380	772.9
Average	3.42	5.22E-06	3.42	5.20E-06	1.04E-05	1.04E-05	380.0	783.6

Complex Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 2.0
 Resin Num 1
 # of Pairs 3
 Initial Conc Nitrate 4.00
 Initial Conc Chloride 4.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	3.68	2.87E-06	3.72	2.51E-06	5.38E-06	249	373.5
20	3.65	3.14E-06	3.72	2.51E-06	5.65E-06	250	342.9
30	3.70	2.69E-06	3.70	2.69E-06	5.38E-06	250	400.0
40	3.71	2.60E-06	3.69	2.78E-06	5.38E-06	248	410.5
50	3.72	2.51E-06	3.70	2.69E-06	5.20E-06	248	425.1
Average	3.68	2.85E-06	3.72	2.55E-06	5.40E-06	249.1	378.4

Complex-
Run #1

Flow (mL/min)
250

Spacing
1 mm

Voltage
3.3

Resin
Num 1

of Pairs
3

Initial Conc
Nitrate
4.00

Initial Conc
Chloride
4.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm2/s)	Chloride Conc (meq/L)	Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
5	3.57	4.03E-06	3.59	3.67E-06	7.71E-06	390	692.6
10	3.55	4.03E-06	3.59	3.67E-06	7.71E-06	390	692.6
15	3.59	4.12E-06	3.62	3.41E-06	7.53E-06	389	675.8
20	3.54	4.12E-06	3.62	3.41E-06	7.53E-06	389	675.8
30	3.56	3.94E-06	3.57	3.85E-06	7.80E-06	387	702.9
40	3.57	3.58E-06	3.58	3.76E-06	7.35E-06	387	773.2
50	3.59	3.67E-06	3.59	3.67E-06	7.35E-06	388	756.3
Average	3.57	3.84E-06	3.59	3.69E-06	7.54E-06	388.1	724.6

(Main)

Complex- Run #2 Flow (mL/min) 250 Spacing 1 mm Voltage 3.3 Resin Num 1 # of Pairs 3 Initial Conc Nitrate 4.00 Initial Conc Chloride 4.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm2/s)	Chloride Conc (meq/L)	Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
10	3.58	3.76E-06	3.58	3.76E-06	7.53E-06	391	744.0
20	3.62	3.41E-06	3.60	3.58E-06	6.99E-06	393	826.5
30	3.58	3.76E-06	3.61	3.49E-06	7.26E-06	392	745.9
40	3.63	3.32E-06	3.57	3.85E-06	7.17E-06	391	844.6
50	3.60	3.58E-06	3.56	3.94E-06	7.53E-06	391	781.2
Average	3.60	3.61E-06	3.58	3.76E-06	7.38E-06	391.9	780.6

Complex-(Ottawa-Carleton)
Run #1
Flow (mL/min) 250
Spacing 1 mm
Voltage 2.0
Resin Num 1
of Pairs
Initial Conc Nitrate 2.00
Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.60	2.15E-06	1.68	1.72E-06	3.87E-06	150	300.0
15	1.62	2.04E-06	1.71	1.56E-06	3.60E-06	150	315.8
20	1.60	2.15E-06	1.73	1.41E-06	3.56E-06	149	299.9
25	1.61	2.10E-06	1.74	1.40E-06	3.49E-06	149	305.6
30	1.57	2.31E-06	1.72	1.37E-06	3.68E-06	149	277.2
35	1.59	2.20E-06	1.75	1.34E-06	3.55E-06	149	290.7
40	1.58	2.26E-06	1.73	1.45E-06	3.71E-06	148	281.9
45	1.58	2.23E-06	1.74	1.42E-06	3.65E-06	148	281.9
50	1.57	2.31E-06	1.68	1.72E-06	4.03E-06	149	277.2
Average	1.59	2.19E-06	1.73	1.48E-06	3.66E-06	148.9	293.6

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min) 250

Spacing 1 mm

Voltage 3.33

Resin Num 1

of Pairs

Initial Conc Nitrate 2.00

Initial Conc Chloride 2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
5	1.39	2.78E-06	1.53	2.51E-06	5.29E-06	208	454.2
10	1.43	3.06E-06	1.55	2.42E-06	5.48E-06	208	486.1
15	1.42	2.90E-06	1.57	2.31E-06	5.22E-06	207	510.6
20	1.42	3.12E-06	1.5	2.42E-06	5.54E-06	207	476.1
25	1.42	3.12E-06	1.56	2.37E-06	5.48E-06	207	475.4
30	1.39	3.06E-06	1.53	2.51E-06	5.57E-06	206	487.7
35	1.40	3.23E-06	1.58	2.26E-06	5.48E-06	206	457.3
40	1.41	3.17E-06	1.56	2.27E-06	5.43E-06	206	469.0
45	1.42	3.12E-06	1.57	2.31E-06	5.43E-06	208	477.7
Average	1.42	3.10E-06	1.56	2.36E-06	5.46E-06	207.3	479.3

Complex-(Ottawa-Carleton)

Run #2

Flow (mL/min)

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

2

Initial Conc

Nitrate

2.00

Chloride

2.00

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.40	3.23E-06	1.54	2.47E-06	5.70E-06	203	450.7
20	1.45	2.96E-06	1.56	2.37E-06	5.32E-06	203	491.6
30	1.38	3.33E-06	1.59	2.20E-06	5.54E-06	202	434.0
40	1.39	3.28E-06	1.54	2.47E-06	5.75E-06	202	441.1
50	1.38	3.33E-06	1.55	2.42E-06	5.75E-06	201	431.8
Average	1.40	3.21E-06	1.55	2.43E-06	5.63E-06	202.3	452.4

Complex-(Ottawa-Carleton)

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

5.0

Resin

Num 1

of Pairs

5

Initial Conc

Nitrate

2.00

Chloride

2.00

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.31	3.71E-06	1.31	3.71E-06	7.42E-06	255	739.1
20	1.32	3.66E-06	1.33	3.60E-06	7.26E-06	256	752.9
30	1.34	3.55E-06	1.34	3.55E-06	7.10E-06	254	769.7
40	1.33	3.60E-06	1.36	3.44E-06	7.04E-06	255	761.2
50	1.35	3.49E-06	1.34	3.55E-06	7.04E-06	254	781.5

Average

1.33

3.59E-06

1.34

3.56E-06

7.15E-06

255.0

764.3

Appendix F

Cycling Experiments

Cycling Experiments-Power Alternating, Flow constant

Run #1	Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Initial Conc	Initial Conc	Cycling
	250	1 mm	3.33	Num 1	3	Nitrate	Chloride	
						2.00	2.00	
	Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
		Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
	6	1.93	6.27E-07	1.95	4.48E-07	1.08E-06	0	0
	11	1.55	4.03E-06	1.65	3.14E-06	7.17E-06	198	352
	16	1.96	3.58E-07	1.97	2.69E-07	6.27E-07	0	0
	21	1.63	3.32E-06	1.71	2.60E-06	5.91E-06	197	426
	26	1.96	3.58E-07	1.97	2.69E-07	6.27E-07	0	0
	31	1.55	4.03E-06	1.69	2.78E-06	6.81E-06	198	352
	36	1.95	4.48E-07	1.97	2.69E-07	7.17E-07	0	0
	41	1.6	3.58E-06	1.75	2.24E-06	5.82E-06	197	394
	46	1.94	5.38E-07	1.95	4.48E-07	9.86E-07	0	0
	51	1.64	3.23E-06	1.69	2.78E-06	6.00E-06	199	442
	56	1.94	5.38E-07	1.96	3.58E-07	8.96E-07	0	0

Power - Off
Power - On
Total

Cycling Experiments-Power Alternating, Flow constant

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.33 Resin Num 1 # of Pairs 3 Initial Conc Nitrate 2.00 Initial Conc Chloride 2.00 Cycling 1 min

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.78	1.97E-06	1.86	1.25E-06	3.23E-06	195	708.4
20	1.81	1.70E-06	1.85	1.34E-06	3.05E-06	194	816.0
30	1.81	1.70E-06	1.86	1.25E-06	2.96E-06	196	824.4
40	1.78	1.97E-06	1.84	1.43E-06	3.41E-06	194	704.7
50	1.81	1.70E-06	1.86	1.25E-06	2.96E-06	195	820.2

Average 1.80 1.77E-06 1.86 1.28E-06 3.06E-06 195.0 397.2

Cycling Experiments-Power Alternating, Flow constant

Run #2	Initial Conc			Initial Conc			Cycling	
Flow (mL/min)	Spacing	Voltage	Resin	# of Pairs	Nitrate	Chloride	1 min	
250	1 mm	3.33	Num 1	3	2.00	2.00		
Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)	
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)				
	1.79	1.88E-06	1.85	1.34E-06				
	1.82	1.61E-06	1.84	1.43E-06				
	1.79	1.88E-06	1.83	1.52E-06				
	1.81	1.70E-06	1.87	1.16E-06				
10	1.79	1.88E-06	1.85	1.34E-06	3.23E-06	198	753.5	
20	1.82	1.61E-06	1.84	1.43E-06	3.05E-06	198	879.1	
30	1.79	1.88E-06	1.83	1.52E-06	3.41E-06	196	745.9	
40	1.81	1.70E-06	1.87	1.16E-06	2.87E-06	197	828.6	
50	1.79	1.88E-06	1.85	1.34E-06	3.23E-06	196	745.9	
Average	1.79	1.85E-06	1.85	1.36E-06	3.22E-06	197.1	383.0	

Cycling Experiments-Power Alternating, Flow constant

Run #1

Flow (mL/min)

Spacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate

2

Initial Conc
Chloride

2

Cycling
1 sec

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.80	1.79E-06	1.86	1.25E-06	3.05E-06	200	799.2
20	1.78	1.97E-06	1.88	1.08E-06	3.05E-06	198	719.3
30	1.81	1.70E-06	1.84	1.43E-06	3.14E-06	197	828.6
40	1.78	1.97E-06	1.83	1.52E-06	3.49E-06	196	712.0
50	1.80	1.79E-06	1.85	1.34E-06	3.14E-06	196	783.2
Average	1.80	1.76E-06	1.85	1.34E-06	3.11E-06	197.4	404.7

Cycling Experiments—Power Alternating, Flow constant

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2Initial Conc
Chloride
2Cycling
30 sec

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm ² /s)	Conc (mg/L)	Flux (meq/cm ² /s)			
10	1.82	1.61E-06	1.85	1.34E-06	2.96E-06	199	883.6
20	1.80	1.79E-06	1.87	1.16E-06	2.96E-06	197	787.2
30	1.78	1.97E-06	1.84	1.43E-06	3.41E-06	198	719.3
40	1.77	2.06E-06	1.87	1.16E-06	3.23E-06	197	684.5
50	1.82	1.61E-06	1.84	1.43E-06	3.05E-06	196	870.2

Average **1.79** **1.91E-06** **1.85** **1.33E-06** **3.25E-06** **197.1** **377.5**

Cycling Experiments-Power Alternating, Flow constant

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
2Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00Cycling
1 min

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm2/s)	Conc (mg/L)	Flux (meq/cm2/s)			
10	1.82	1.61E-06	1.88	1.08E-06	2.69E-06	134	357
20	1.83	1.52E-06	1.89	9.86E-07	2.51E-06	135	381
30	1.84	1.43E-06	1.88	1.08E-06	2.51E-06	135	405
40	1.86	1.25E-06	1.90	8.96E-07	2.15E-06	134	459
50	1.84	1.43E-06	1.89	9.86E-07	2.42E-06	133	399

Average	1.85	1.37E-06	1.90	9.16E-07	2.29E-06	134.1	212
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Cycling Experiments-Power Alternating, Flow constant

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.33 Resin Num 1 # of Pairs 3 Initial Conc Nitrate 2 Initial Conc Chloride 2 Cycling 5 sec

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm ² /s)	Conc (mg/L)	Flux (meq/cm ² /s)			
10	1.79	1.88E-06	1.82	1.61E-06	3.49E-06	200	761.1
20	1.81	1.70E-06	1.86	1.25E-06	2.96E-06	199	837.1
30	1.79	1.88E-06	1.82	1.61E-06	3.49E-06	198	753.5
40	1.83	1.52E-06	1.86	1.25E-06	2.78E-06	198	930.8
50	1.80	1.79E-06	1.85	1.34E-06	3.14E-06	197	787.2

Average 1.81 1.72E-06 1.85 1.37E-06 3.10E-06 198.7 415.5

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
3.33Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00Cycling
"10s-10s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm2/s)	Conc (mg/L)	Flux (meq/cm2/s)			
10	1.71	2.60E-06	1.78	1.97E-06	4.57E-06	195	537.4
20	1.68	2.87E-06	1.77	2.06E-06	4.93E-06	194	484.5
30	1.72	2.51E-06	1.76	2.15E-06	4.66E-06	196	559.4
40	1.74	2.33E-06	1.76	2.15E-06	4.48E-06	194	596.3
50	1.69	2.78E-06	1.75	2.24E-06	5.02E-06	195	502.7
Average	1.71	2.58E-06	1.77	2.10E-06	4.68E-06	195.0	272.0

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.33 Resin Num 1 # of Pairs 3 Nitrate 2.00 Chloride 2.00 Cycling "5s-5s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (mg/L)	Flux (meq/cm ² /s)	Conc (mg/L)	Flux (meq/cm ² /s)			
10	1.69	2.78E-06	1.75	2.24E-06	5.02E-06	195	502.7
20	1.72	2.51E-06	1.76	2.15E-06	4.66E-06	194	553.7
30	1.67	2.96E-06	1.72	2.51E-06	5.47E-06	196	474.7
40	1.70	2.69E-06	1.74	2.33E-06	5.02E-06	194	516.8
50	1.70	2.69E-06	1.73	2.42E-06	5.11E-06	195	519.5

Average 1.70 2.72E-06 1.74 2.34E-06 5.06E-06 195.0 257.5

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min)

250

Spacing
1 mmVoltage
5Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00Cycling
"10s-10s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.62	3.41E-06	1.64	3.23E-06	6.63E-06	195	615.8
20	1.63	3.32E-06	1.65	3.14E-06	6.45E-06	194	629.2
30	1.69	2.78E-06	1.69	2.78E-06	5.56E-06	196	758.7
40	1.63	3.32E-06	1.66	3.05E-06	6.36E-06	194	629.2
50	1.65	3.14E-06	1.62	3.41E-06	6.54E-06	195	668.6
Average	1.64	3.19E-06	1.65	3.10E-06	6.28E-06	195.0	330.7

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min)
250Spacing
1 mmVoltage
5Resin
Num 1# of Pairs
3Initial Conc
Nitrate
2.00Initial Conc
Chloride
2.00Cycling
"2s-2s"

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm ² /s)	Chloride Conc (meq/L)	Flux (meq/cm ² /s)	Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
10	1.60	3.58E-06	1.66	3.05E-06	6.63E-06	195	585
20	1.58	3.76E-06	1.67	2.96E-06	6.72E-06	194	554
30	1.62	3.41E-06	1.67	2.96E-06	6.36E-06	196	619
40	1.58	3.76E-06	1.63	3.32E-06	7.08E-06	194	554
50	1.56	3.94E-06	1.60	3.58E-06	7.53E-06	195	532
Average	1.59	3.69E-06	1.64	3.25E-06	6.94E-06	195.0	285

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min)

250

Spacing

1 mm

Voltage

3.33

Resin

Num 1

of Pairs

3

Initial Conc

Nitrate

2.00

Initial Conc

Chloride

2.00

Cycling

"2s-2s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm ² /s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm ² /s)	Conc (meq/L)	Flux (meq/cm ² /s)			
10	1.64	3.23E-06	1.74	2.33E-06	5.56E-06	195	433
20	1.70	2.69E-06	1.76	2.15E-06	4.84E-06	194	517
30	1.63	3.32E-06	1.73	2.42E-06	5.73E-06	196	423
40	1.68	2.87E-06	1.75	2.24E-06	5.11E-06	194	485
50	1.65	3.14E-06	1.71	2.60E-06	5.73E-06	195	445

Average

1.66

3.07E-06

1.73

2.41E-06

5.48E-06

195.0

229

Cycling Experiments-Flow and Power Alternating

Flow (mL/min) 250 Spacing 1 mm Voltage 2 Resin Num 1 # of Pairs 3 Nitrate 2.00 Chloride 2.00 Cycling "2s-2s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.71	2.60E-06	1.80	1.79E-06	4.39E-06	195	323
20	1.72	2.51E-06	1.83	1.52E-06	4.03E-06	194	333
30	1.75	2.24E-06	1.82	1.61E-06	3.85E-06	196	376
40	1.74	2.33E-06	1.83	1.52E-06	3.85E-06	194	358
50	1.71	2.60E-06	1.82	1.61E-06	4.21E-06	195	323

Average 1.73 2.46E-06 1.82 1.62E-06 4.08E-06 195.0 171

Cycling Experiments-Flow and Power Alternating

Run #1

Flow (mL/min) 250 Spacing 1 mm Voltage 3.33 Resin Num 1 # of Pairs 3 Initial Conc Nitrate 2.00 Initial Conc Chloride 2.00 Cycling "10s-5s"

Time (min)	Nitrate		Chloride		Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
	Conc (meq/L)	Flux (meq/cm2/s)	Conc (meq/L)	Flux (meq/cm2/s)			
10	1.66	3.05E-06	1.75	2.24E-06	5.29E-06	195	458
20	1.69	2.78E-06	1.73	2.42E-06	5.20E-06	194	500
30	1.65	3.14E-06	1.71	2.60E-06	5.73E-06	196	448
40	1.68	2.87E-06	1.74	2.33E-06	5.20E-06	194	485
50	1.65	3.14E-06	1.73	2.42E-06	5.56E-06	195	445

Average 1.66 3.02E-06 1.73 2.38E-06 5.40E-06 195.0 232

Cycling Experiments-Flow and Power Alternating

Run #1
 Flow (mL/min) 250
 Spacing 1 mm
 Voltage 3.33
 Resin Num 1
 # of Pairs 3
 Initial Conc Nitrate 2.00
 Initial Conc Chloride 2.00
 Cycling "5s-10s"

Time (min)	Nitrate Conc (meq/L)	Flux (meq/cm2/s)	Chloride Conc (meq/L)	Flux (meq/cm2/s)	Total Flux (meq/cm2/s)	Current (mA)	Energy (J/meq)
10	1.67	2.96E-06	1.72	2.51E-06	5.47E-06	195	472
15	1.69	2.97E-06	1.69	2.51E-06	5.48E-06	194	500
20	1.69	2.78E-06	1.76	2.15E-06	4.93E-06	194	500
25	1.69	2.67E-06	1.74	2.15E-06	4.82E-06	196	540
30	1.71	2.60E-06	1.69	2.78E-06	5.38E-06	196	540
40	1.64	3.23E-06	1.73	2.42E-06	5.65E-06	194	431
50	1.69	2.78E-06	1.74	2.33E-06	5.11E-06	195	503
Average	1.67	2.92E-06	1.72	2.47E-06	5.39E-06	195.0	240

Appendix G

Cost Analysis

**Bench Scale Unit
Capital Costs**

	# of Membrane Pairs				
	3	6	9	20	40
Membrane Cost (\$)	13.95	27.9	41.85	93	186
Casing (\$)	20	20	20	25	30
Total (\$):	184	198	212	268	376

Bench Scale Unit
O & M Costs

Power: 0.10 \$/KWh

Maintanance factor: 1.2

	# of Membrane Pairs				
	3	6	9	20	40
Volts	210	210	210	210	210
Current	140	140	140	140	140
Flow (G/s)	0.82	0.82	0.82	0.82	0.82
Pumps(J/s)	3.8	7.5	12.4	26	52
Life (day)	330	330	330	330	330
Power Cost: (\$/s)	1.29E-07	2.55E-07	4.14E-07	8.78E-07	1.76E-06
(\$/d)	0.011	0.022	0.036	0.076	0.152
(\$/yr)	0.12	0.24	0.42	0.84	1.68

**Bench Scale Unit
O & M Costs**

Power: 0.10\$/kWh Maintenance factor: 1.2

		# of Membrane Pairs				
		3	6	9	20	40
Vol	333	100	200	300	667	1333
Current		200	200	200	200	200
Power (J/s)		198	396	594	1188	2376
Pumps(J/s)		4.8	9.4	14.4	30	60
Life (days)		750	1500	2250	4500	9000
Power Cost: (\$/s)		1.89E-07	3.72E-07	5.67E-07	1.20E-06	2.41E-06
(\$/d)		0.016	0.032	0.049	0.104	0.208
(\$/m ³)		0.213	0.43	0.675	1.37	2.81

**Bench Scale Unit
O & M Costs**

Power: 0.10 \$/KWh Maintenance factor: 1.2

	# of Membrane Pairs				
	3	6	9	20	40
Current	300	300	300	300	300
Power (J/s)	6.4	11.9	19	33	65
Pumps(J/s)	3.03E-07	5.81E-07	9.03E-07	1.75E-06	3.47E-06
Power Cost: (\$/s)	0.026	0.050	0.078	0.151	0.300
Power Cost: (\$/d)					
Power Cost: (\$/ms)					