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The removal of perchlorate from waters using ion-exchange resins

Adriano Rosa Vieira
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THE REMOVAL OF PERCHLORATE FROM WATERS
USING ION-EXCHANGE RESINS

by

Adriano Rosa Vieira

Bachelor of Science
Federal University of Ouro Preto, Minas Gerais - Brazil
1996

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering Degree
Department of Civil and Environmental Engineering
Howard R. Hughes College of Engineering

The Graduate College
University of Nevada, Las Vegas
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The Removal of Perchlorate from Waters by Ion-Exchange Resins

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Civil and Environmental Engineering

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Examination Committee Member

ABSTRACT

The Removal Of Perchlorate From Waters Using Ion-Exchange Resins

by

Adriano Rosa Vieira

**Dr. Jacimaria Ramos Batista, Examination Committee Chair
Assistant Professor of Environmental Engineering
University of Nevada, Las Vegas**

This thesis investigates the feasibility of using several types of ion-exchange resins to remove perchlorate from waters. The capability of the resins to remove perchlorate, as well as their regeneration efficiency, were evaluated using both synthetic solutions and perchlorate-contaminated water from the Las Vegas Valley. For synthetic solutions, styrenic strong base resins showed high perchlorate removal efficiency but regeneration efficiency was low. Acrylic strong-base resins showed satisfactory perchlorate removal, but they regenerate better than the styrenic counterpart. Acrylic weak base resin showed satisfactory perchlorate removal efficiency and very high regeneration efficiency when regenerated with NaCl or caustic solutions. High concentrations of humic substances and sulfate, present in the perchlorate-contaminated groundwater, significantly affected perchlorate removal by the majority of the resins tested. Despite the affinity of the tested resins for sulfate, perchlorate was removed from the water by pushing sulfate out of the resin.

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CHAPTER 1

STATEMENT OF THE PROBLEM

1.1 Introduction

The recent discovery of perchlorate (ClO_4^-), an important component in rocket fuel and explosives, in several groundwater wells in Nevada, California, and Utah has generated substantial interest in potential treatment technologies to remove this contaminant from water supplies. The American Water Works Association Research Foundation (1998) estimates that water supplies of approximately 12 million people are contaminated with perchlorate. In Nevada, perchlorate contamination is related to two chemical plants: the former Pacific Engineering & Production Company of Nevada (PEPCON) and the Kerr McGee Chemical Corporation (KMCC). Very little is known about the health effects of perchlorate in humans, but it is acknowledged that perchlorate interferes with the ability of the thyroid gland to utilize iodine to produce thyroid hormones required for normal body metabolism, growth, and development. The current knowledge on perchlorate effects on the human body is the result of the use of this chemical to treat Grave's disease (hyperthyroidism). Perchlorate is known in the medical field as the most effective drug for blocking the uptake of iodine by the thyroid.

Biological and physicochemical treatment technologies are currently under investigation for their potential to economically remove perchlorate from waters.

Technologies under investigation include (a) ion exchange, (b) biodegradation, (c) membrane filtration, and (d) ozone/granular activated carbon. The data published to date indicate that ion exchange and biodegradation are the two most promising technologies for perchlorate removal. Biological bioreactors under investigation for perchlorate removal include (a) fixed membrane-immobilized biofilm, (b) sand/activated carbon column packed bed reactor, and (c) autohydrogenotrophic biofilm reactor.

Although perchlorate is readily biodegradable, the water industry does not feel comfortable adding biodegradation to the water treatment train, since one of the major goals of water treatment is the elimination, by disinfection, of microbial pathogens. Therefore, the implementation of perchlorate biodegradation for drinking water systems may encounter resistance from the water industry. On the other hand, the drinking-water utilities are already familiar with the use of ion exchange in their plants, and would probably welcome this technology. Because of its acceptability by the water industry, ion exchange is perhaps the technology most likely to be used for perchlorate removal from drinking waters. In homes and business, ion exchange processes have been used for water softening for many decades. This history helps the acceptance of this technology by the public.

Ion exchange, however, is only a separation technology and the final disposal or treatment of the regenerant solution from the ion exchange process should be taken into consideration. This thesis evaluates the feasibility of using several types of ion exchange resins to remove perchlorate from waters. In addition, this research examines ion exchange systems that would generate regenerant solutions that are amenable to biodegradation.

1.2 Specific Objectives

The specific objectives of this research are:

1. To evaluate the ability of strong-base anionic exchange resins to remove perchlorate from synthetic perchlorate solutions.
2. To evaluate the ability of weak-base anionic exchange resins to remove perchlorate from synthetic perchlorate solutions.
3. To investigate whether both weak- and strong base anionic exchange resins, loaded with perchlorate, can be regenerated.
4. To examine ion exchange systems that generate regeneration solutions that are amenable to biodegradation.
5. To investigate the competition of several anions with perchlorate, in synthetic solution, for the exchange sites in the ion exchange resin beads.
6. To examine the potential of ion exchange to remove perchlorate from a “real” water from a contaminated site in the Las Vegas Valley using different types of resins.

CHAPTER 2

LITERATURE REVIEW

2.1 Perchlorate

Perchlorate is produced, on large scale, as solid salts of ammonium, sodium, and potassium by the chemical industry for an extensive range of applications such as oxidizer in solid propellants for rockets, air bag inflators, missiles, fireworks and particular munitions, and the production of matches (Susarla *et al*, 1999). In 1997, perchlorate was detected in several drinking water sources in the United States, generating great interest in the development of technologies to remove this compound from waters.

In 1893, the first commercial perchlorate plant was constructed in Mansbo, Sweden. By 1904, after experiencing and solving diverse production problems, the plant was able to produce ammonium perchlorate on an effective regular basis (Schilt, 1979). Not longer after Sweden, the manufacture of perchlorate began in other countries such as France, Switzerland, Germany, and the United States. During the First and Second World Wars, perchlorate production was pushed to high levels. Differing from the period after the Word War I, when perchlorate production decreased, in the 1950's the production of ammonium perchlorate increased because of the development of the rocket industry and the usage of perchlorate as a rocket fuel component (Schilt, 1979).

Because of its shelf life, ammonium perchlorate must be periodically dislodged from the country's missile and rocket inventory and substituted with fresh supply. Therefore, since the 1950's, large volumes of perchlorate-containing unregulated wastes have been disposed of at several sites located in Nevada, Utah and California. In Nevada, perchlorate contamination is related to two chemical plants: the former Pacific Engineering & Production Company of Nevada (PEPCON), and the Kerr McGee Chemical Corporation (KMCC). The former PEPCON plant started to produce perchlorate in 1958 and operated until May 4, 1988 when an explosion destroyed the plant. The KMCC has been producing perchlorate from 1945 to the present.

2.1.1 Chemistry, Structure, and Properties of Perchlorate Ion

Lee and Carpenter (1959) used X-ray diffraction measurements on crystalline hydronium perchlorate to verify that the perchlorate ion has nearly perfect tetrahedral geometry (Schilt, 1979). They also measured an average chlorine-to-oxygen bond distance of 1.42 angstroms (Å). The oxygen-to-oxygen average distance is 2.43 angstroms (Å). The molal volume of the perchlorate ion (ClO_4^-), calculated using the LeBas method (LaGrega *et. al.*, 1994) is $54.2 \text{ cm}^3/\text{g-mol}$. By using the same method and for comparison purposes, the molal volumes of other anions of interest were also calculated: sulfate (SO_4^{2-}) equals $58.8 \text{ cm}^3/\text{g-mol}$, nitrate (NO_3^-) equals $40.5 \text{ cm}^3/\text{g-mol}$, chlorate (ClO_3^-) equals $46.8 \text{ cm}^3/\text{g-mol}$, and chloride (Cl^-) equals $24.6 \text{ cm}^3/\text{g-mol}$. Thus, the molal volume of perchlorate is slightly smaller than that of sulfate, but larger than those of chlorate, nitrate and chloride.

Basing their determination upon Raman and infrared spectra of aqueous solution, Symons and Waddington (1975) estimated the average hydration number of the perchlorate ion to be four. It appears that each oxygen atom may be hydrogen bonded to a separate water molecule (Schilt, 1979). The crystal radius of the perchlorate ion was determined from results of solvation studies of alkali-metal perchlorates as being equal to 1.85 Å (Salmon, 1971), that is significantly higher than the radius of sulfate, 1.49 Å (Wald, 1962). Figure 2.1 shows the chemical structure of perchlorate with the four oxygen atoms at the vertices and the chlorine atom at the center. The perchlorate ion limiting conductance in water was measured as being 67.32 ± 0.06 S-cm³/equivalent (Jones, 1945). It is important to know the limiting conductance of perchlorate because several analytical measurements and procedures are based on the electrochemical properties of the ion.

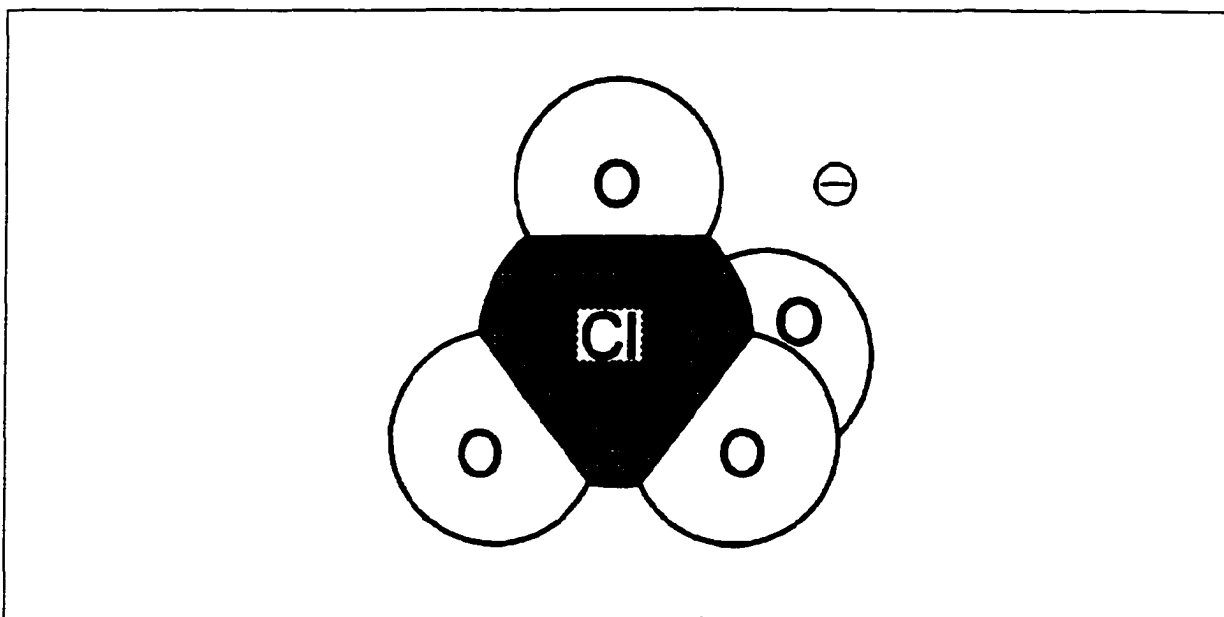


Figure 2.1 Chemical structure of perchlorate (Source: EPA, 1998).

Two different groups of investigators have conducted experiments to measure the standard enthalpy of formation of the perchlorate ion in infinitely dilute aqueous solution at 25°C; their results -30.53 ± 0.20 kcal/mole (Efimov and Medvedev, 1975) and -30.87 ± 0.07 kcal/mole (Kirpichev et al., 1975) are very similar (Schilt, 1979). The negative value of the enthalpy of formation for perchlorate ion indicates that the reaction occurs spontaneously. The enthalpies of formation for sodium and potassium perchlorates were calculated by Vorob'ev (1960) as -90.68 kcal/mole (-379.7 kJ/mole) and -101.9 kcal/mole (-426.6 kJ/mole) respectively. Potassium and sodium perchlorates were found to undergo endothermic phase change at 306°C and 304°C, melt at 575°C and 468°C and decompose at 620°C and 561°C respectively (Khorunzhii et al., 1972). The Gibbs free energy of formation (ΔG°_f) for perchlorate and chlorate in aqueous solution is -8.5 and -8.0 kJ/mol, respectively (Barrow, 1988). The low charge density of perchlorate reduces

its affinity for cations and its extent of hydration. Consequently, the extremely high solubilities of perchlorate salts in aqueous and non-aqueous media are due to its low association with cations (Urbansky, 1998). The ammonium and the alkali metal salts of perchlorate usually are promptly soluble in water. Sodium perchlorate is a remarkable example; its solubility in water is extremely high (2,096 g/L). On the other hand, potassium perchlorate is the notable exception, with solubility approximately equals to 20.6 g/L (Schilt, 1979). The physical properties of ammonium and alkali metal perchlorates, at 25 °C are shown in Table 2.1

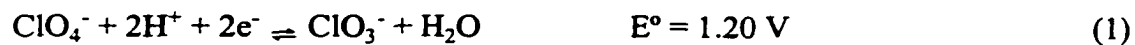
Table 2.1 Physical properties of some perchlorate compounds, at 25 °C						
Physical Properties	Perchlorates					
	NH ₄	Li	Na	K	Rb	Cs
Molecular Weight (g/mol)	117.49	106.40	122.44	138.55	184.92	232.36
Density	1.952	2.429	2.499	2.530	2.900	3.327
Solubility in water (g/L)	249.22	597.10	2,096.0	20.62	13.38	20.00
ΔH°_f (kJ/mole)	-290.65	-384.22	-385.94	-433.75	-435.01	-435.01
Source: Modified from Schilt (1979).						

Table 2.2 summarizes some of the properties of the perchlorate ion.

Table 2.2 Some properties of perchlorate ion.			
Property	Value	Technique	Reference
ClO_4^- limiting conductance in water	67.32 ± 0.06 $\text{S-cm}^3/\text{eq.}$	NA	Jones, 1945
Perfect tetrahedral geometry	NA	X-ray diffraction measurements	Lee and Carpenter, 1959
Average chlorine-to-oxygen bond distance	1.42Å	NA	Lee and Carpenter, 1959
Average oxygen-to-oxygen bond distance	2.43Å	NA	Lee and Carpenter, 1959
Sodium perchlorate enthalpy of formation	-379.66 kJ/mole	NA	Vorob'ev, 1960
Potassium perchlorate enthalpy of formation	-426.90 kJ/mole	NA	Vorob'ev, 1960
Perchlorate crystal radius	1.85Å	Solvation studies of alkali metal perchlorates	Salmon, 1971
Hydration number of perchlorate	4	Raman and infrared spectra of aqueous solution	Symons and Waddington, 1975
Perchlorate standard enthalpy of formation (dilute aqueous solution at 25°C)	-127.82 \pm 0.84 kJ/mole	NA	Efimov and Medvedev, 1975
	-129.25 \pm 0.29 kcal/mole	NA	Kirpichev <i>et al.</i> , 1975
Molar ionic volume	44.5 cm^3/mol at 25°C	NA	Schilt, 1979
	54.2 cm^3/mol	LeBas	This thesis, calculated as per LaGrega <i>et al.</i> , 1994

In 1989, Emsley measured the standard reduction potentials for the half-reactions of perchlorate (equations 1 and 2). From a thermodynamic point of view, the measured

standard reduction potentials for equations 1 and 2 indicate that reductions to chlorate or chloride are very favorable processes (Urbansky, 1998).



Equations 3 to 5 show the reduction of perchlorate to chloride with the respective standard free energies of formation, ΔG° in kJ/mol (Gurol and Kim, 1999).



The oxidizing strength and standard reduction potential (E°), where the species is reduced to chloride and under standard conditions in 1M acid, decrease as follows (EPA, 1998): $\text{ClO}_4^- > \text{ClO}_3^- > \text{HClO}_2 > \text{HOCl} > \text{Cl}_2$.

Whit decreasing pH, the reduction potential for the oxo-anions is increased. Thus, the oxo-anions are stronger oxidizing agents in acidic solutions. Equations 6 and 7 show the reduction of Cl(VII) to Cl(V) in solution with pH = 0 (acidic condition) and pH = 14 (alkaline condition), respectively:

In 1.0M H^+ (aq) solution (pH = 0):



In 1.0M OH^- (aq) solution (pH = 14):



The principle of Le Chatelier explains the pH effect on the reactions. When hydrogen ion is abundant (reaction 6), it acts as a reactant. In consequence, the equilibrium is driven to the right. When the hydroxide anion is a product of the reaction (reaction 7), it reduces the driving force for this reaction to take place. The positive value of E° indicates that the Reaction 7 is still spontaneous, but with a smaller driving force (EPA, 1998) because of its smaller E° value when compared to Reaction 6.

Because the water-oxygen couple has standard oxidation potential of -1.229 V (Emsley, 1989), it would be expected that perchloric acid would oxidize water to oxygen, looking only at the thermodynamics (Urbansky, 1998). However, that is not observed because of the slow kinetics of this process. As a result, perchlorate persistent behavior in nature is thoroughly dominated by its kinetics and not by its thermodynamics.

2.1.2 Health Effects of Perchlorate

The primary concern related to consuming perchlorate-contaminated water relates to its potential effect on the functioning of the thyroid gland as it competes for the iodine ion. In the 50's, perchlorate salts were used in large dosages to treat Grave's disease (hyperthyroidism). It is widely known that the thyroid hormones are required for normal body metabolism, growth, and development. Therefore, the lack of iodine can

cause hypothyroidism or cretinism (i.e. mental retardation). The latter condition usually develops in babies while the former condition appears in adults (Lamm, 1998).

The thyroid hormones, produced by the thyroid glands, circulate in the blood and regulate tissue metabolism, especially the synthesis of protein. To produce the thyroid hormones, known as thyroxine (T_4) and triiodothyronine (T_3), the thyroid gland concentrates iodine from the blood and iodinates tyrosine [monoiodotyrosine (MIT) and diiodotyrosine (DIT)] and subsequently generates the thyroid hormones within the large glycoprotein thyroglobulin (Tg). Then T_4 and T_3 hormones are hydrolyzed and secreted into the blood (Figure 2.2). The thyroid gland stores a large amount of preformed hormones (Lamm, 1998).

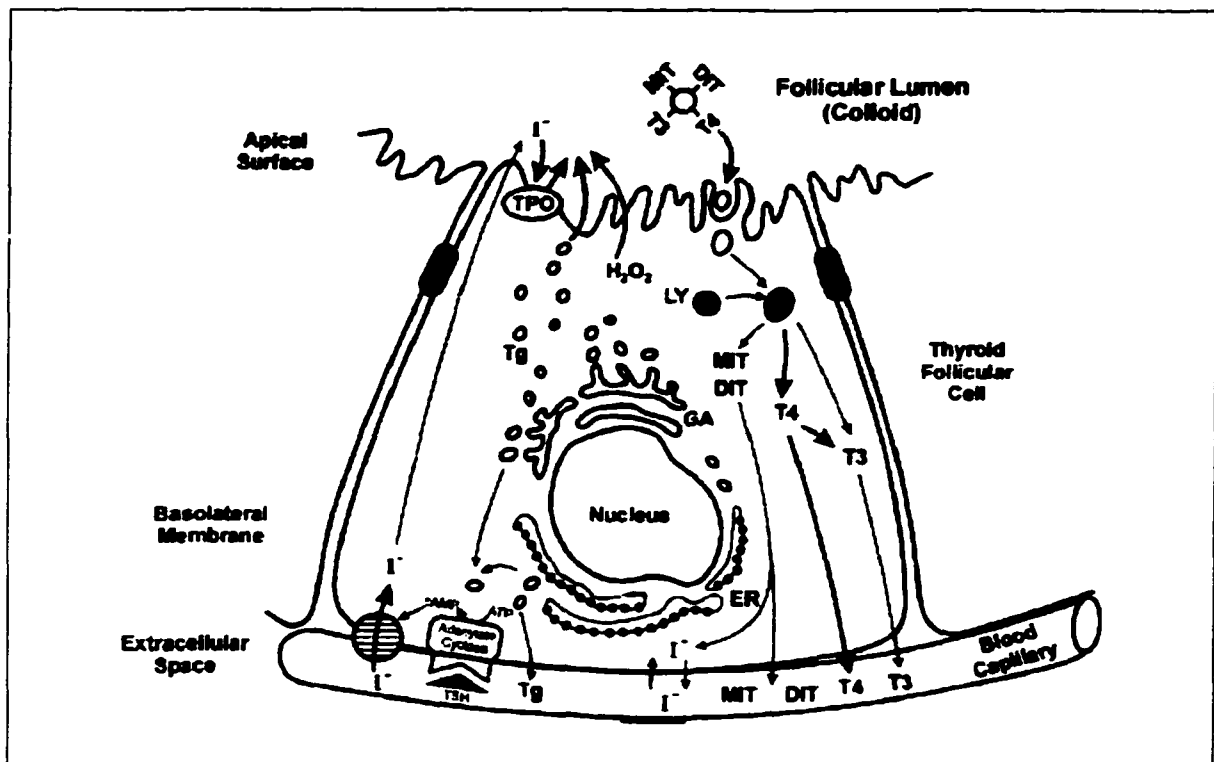


Figure 2.2 Schematic representation of thyroid hormone biosynthesis and secretion (Source: EPA, 1998).

Blocking the synthesis of T_4 and T_3 or the uptake of iodine are the two ways by which an anti-thyroid-hormone drug (e.g. perchlorate) can act. In the case of perchlorate, its effect is well-studied and it is a competitive inhibitor for iodine uptake by the thyroid gland resulting in reduced thyroid hormone production, although it does not directly affect the synthesis of thyroid hormones T_4 and T_3 (Wolff, 1998). In addition, perchlorate is known in the medical field as the most effective drug for blocking the uptake of iodine. In 1992, Eichler investigated the half-life ($T_{1/2}$) of perchlorate in the human body. He concluded that perchlorate passes rapidly through the body and the average retention time ($T_{1/2}$) is about 6 hours. The thionamides (such as carbimazole, MMI (Tapazol) or PTU) are the anti-thyroid-hormone drugs that act by blocking hormone synthesis. In extreme cases of hyperthyroidism (thyrotoxicosis) both types of drugs might be given simultaneously (Lamm, 1998).

Until recently, hyperthyroidism had been treated with potassium perchlorate. Hyperthyroidism or thyrotoxicosis results from an autoimmune condition known as Graves's disease (EPA, 1998). Graves's disease is an autoimmune disorder in which patients carry immunoglobulins in their blood that attach to the thyroid stimulating hormone (TSH) receptors on thyroid cells and behave like TSH to incite DNA production and cell divisions leading to a hyperthyroid condition. In the 1950s, perchlorate was widely used for treating Graves's disease. By inhibiting the uptake of iodine into the thyroid, perchlorate inhibits the excessive synthesis and secretion of thyroid hormones (TH) and causes a discharge of accumulated iodine in the gland (EPA draft report, 1998). In the early to mid 1960s, perchlorate use diminished, after a few cases of fatal aplastic anemia in patients treated with very high doses of perchlorate

(600-1600 mg/day) for long duration (months). In patients receiving less than 600 mg/day perchlorate, no case of fatal aplastic anemia had been reported up to 1968 (Roccke and Vogt, 1968).

Currently, potassium perchlorate is still used diagnostically to test thyroid hormones (TSH, T₃ and T₄) production in some clinical settings (EPA, 1998).

To date, the toxicological information available to estimate the potential health effects of perchlorate are notably insufficient. Most of the prior data on perchlorate effects on humans come from studies with patients with Graves's disease. In 1992 the EPA Superfund Technical Support Center issued a provisional reference dose (RfD). This RfD was revised in 1995. A study in which single doses of potassium perchlorate caused the release of iodine from the thyroids of patients with Graves's disease was the basis for the provisional RfD values (EPA, 1998). The RfD's calculation is based on an estimation of a daily human exposure that will result in no injurious non-cancer effects over a lifetime. Based on the RfD and standard assumptions for ingestion rate and body weight, the reported range in the ground water clean-up guidance was calculated as 4 - 18 µg/L. The California Department of Health Services (CA-DHS), based on those parameters, adopted its provisional action level of 18 µg/L (EPA, 1998).

2.1.3 Occurrences of Perchlorate

The Region 9 Office of the U. S. Environmental Protection Agency (USEPA, 1999) estimates that within the past two and half years, perchlorate has been found in the water supplies of over 15 million people in California, Nevada, and Arizona (Figure 2.3) and in surface and groundwater throughout the United States (AR, IA, IN, KS, MD, NM,

NY, PA, TX, UT, WV). In the USA, perchlorate contamination is usually related with the manufacturing or use of perchlorate salts. Figure 2.4 shows the States with environmental releases of perchlorate and Figure 2.5 shows the States with identified perchlorate manufactures or users.

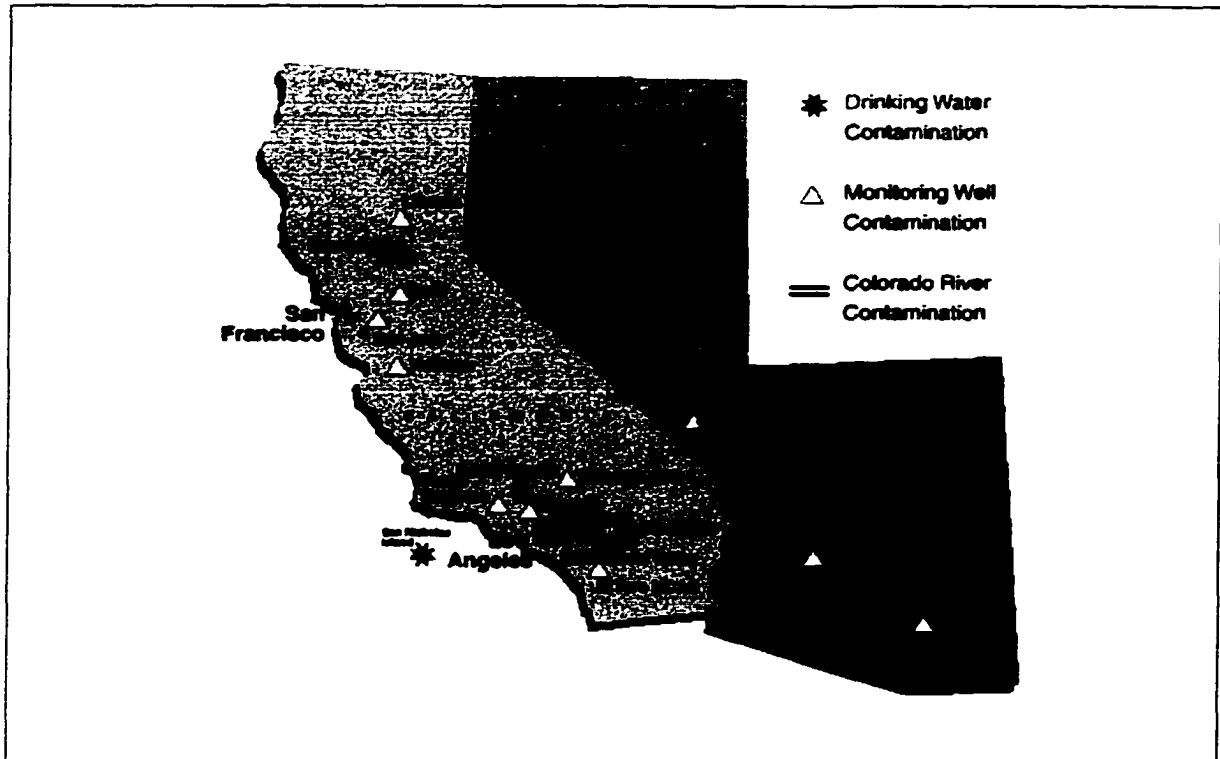


Figure 2.3 Perchlorate occurrences in EPA Region 9 (Source: EPA, 1999).

In 1985, Region 9 Office of the USEPA first became aware of the potential contamination issues with perchlorate. At that time, samples measured with a colorimetric method reported contamination in 14 wells, with concentrations ranging from 0.11 to 2.6 mg/L (EPA, 1998). Before 1997 there was no reliable method for measuring perchlorate concentrations below 0.40 mg/L. In the beginning of the 1990s, samples from monitoring wells at a California Superfund site showed perchlorate at

detectable concentration levels (> 1 mg/L). Based on these occurrences, EPA Region 9 requested assessment of the toxicology data from the EPA Superfund Technical Center. In consequence, the EPA Superfund Technical Center issued a provisional Reference Dose (RfD) in 1992 and a revised provisional RfD in 1995 (EPA, 1998).

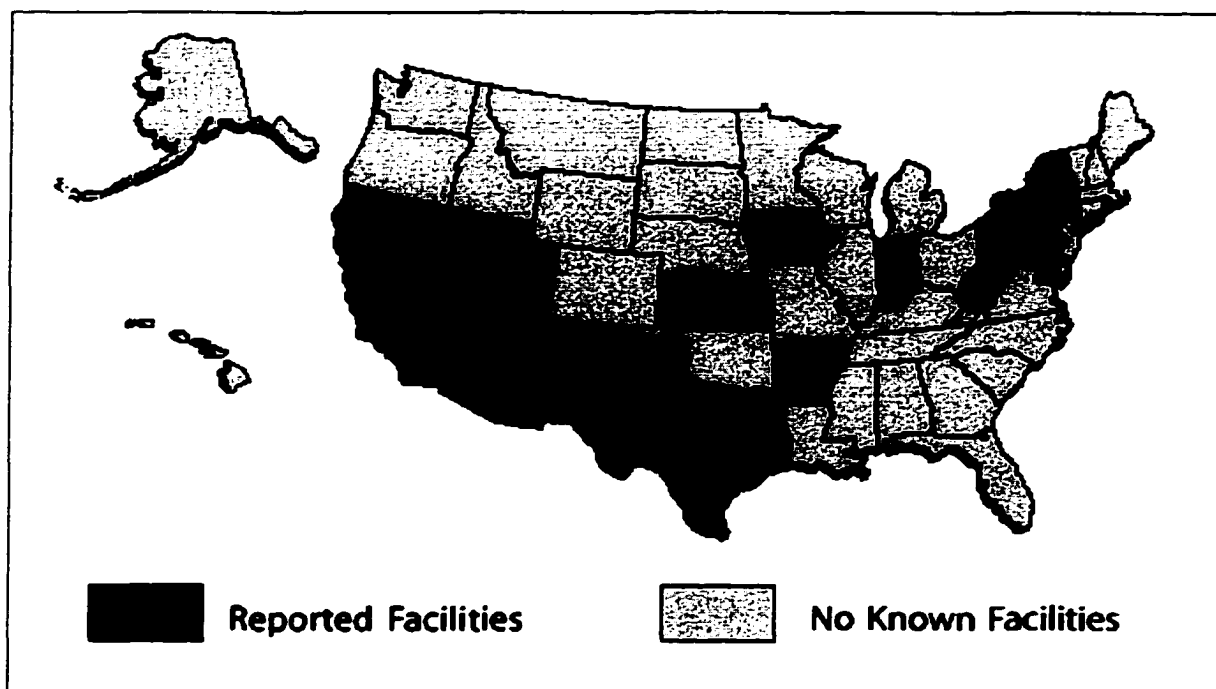


Figure 2.4 States with environmental releases of perchlorate (Source: EPA, 1999).

In January 1997, the Sanitation and Radiation Laboratory Branch (SRLB) was requested by the California Department of Health Services' Division of Drinking Water and Environmental Management to test perchlorate in drinking water wells substantially influenced by groundwater moving from the Aerojet facility close to Sacramento. Because of the $18 \mu\text{g/L}$ provisional action level, Region 9 of EPA implied that a reporting limit of at least $4 \mu\text{g/L}$ would be needed, but at that time no procedures were available for measuring perchlorate at such low levels. An ion chromatograph method

In drinking water wells, perchlorate was first found in eastern Sacramento County (up to 0.260 mg/L) near the Aerojet General Corporation's facility, in March 1997. Within several months following the March 1997 development of the low-level detection method, perchlorate had been found in several drinking water wells. In Los Angeles County, perchlorate has been detected up to 159 µg/L in a number of drinking water wells (California Department of Health Services, 1998). In this area, several sites have been identified as potential sources of contamination: an Aerojet facility (Azusa), the Whittaker-Berbut site in Santa Clarita, and the Jet Propulsion Laboratory in Pasadena.

Perchlorate was also found in some Riverside County drinking water wells (up to 29 µg/L), in some San Bernardino County drinking water wells (up to 325 µg/L) and in 24 agricultural wells (up to 221 µg/L). In this area, perchlorate contamination is in a trichloroethylene (TCE) plume associated with past operations of the Lockheed Propulsion Company (California Department of Health Services, 1998).

Close to an inactive well near an extinct fireworks site by Rialto, perchlorate was found at concentrations up to 270 µg/L. The Regional Water Quality Control Board listed several locations with perchlorate groundwater contamination (California Department of Health Services, 1998): (a) An explosive manufacturing facility near Lincoln (CA), with perchlorate concentrations up to 67 mg/L, (b) United Technologies in Santa Clara (CA), with perchlorate concentrations up to 180 mg/L, (c) Whittaker Ordnance Facility near Hollister in San Benito County (CA), with perchlorate concentrations up to 0.09 mg/L, (d) An agricultural well in the vicinity of Hollister with perchlorate at 0.034 mg/L (34 µg/L), and a private well with 0.81 mg/L.

In Arizona, the Environmental Protection Agency has been conducting perchlorate concentration analysis along the Colorado River with results ranging from non-detectable to 9 µg/L. Other sampling conducted in several places of Arizona, including, municipalities, Lake Havasu, Jose De Sonita River, Salt River, Verde River, and close to some industrial parks ranged from non-detectable to 6 µg/L (Arizona Department of Environmental Quality, 2000)

In Utah and Texas perchlorate releases also have been detected (EPA,1999). In Utah, perchlorate concentrations range from 4 to 200 µg/L. These perchlorate levels were found in groundwater wells on the property of a rocket motor manufacturer Alliant Techsystems. At the Utah Copper mines in Magna, also in the state of Utah, a level of 13 µg/L was measured (Urbansky, 1998).

In Nevada, the state with the largest perchlorate concentration identified to date, perchlorate contamination is related to two ammonium perchlorate manufacturing facilities, the Pacific Engineering & Production Company of Nevada (PEPCON) and The Kerr McGee Chemical Corporation (KMCC). These facilities are located in Henderson, in an area called the Basic Management Industrial (BMI) complex. Water samples collected 300 m from the former PEPCON site, a rocket fuel plant that exploded in 1988, contain perchlorate concentrations as high as 630 mg/L. Samples from wells close to the site show concentrations ranging from 51.4 to 630 mg/L (Urbansky, 1998). Groundwater samples collected from 50 wells in the KMCC surroundings and located approximately 1.6 km from the abandoned PEPCON site contain perchlorate concentrations up to 3,700 mg/L. It is known that potassium perchlorate, used as a solid oxidant for rocket propulsion, was the original source for a portion of the contamination,

but it is important to emphasize that most of the contamination appears to originate from the legal discharge decades ago of unregulated waste effluents containing high levels of ammonium perchlorate (Urbansky, 1998). Figure 2.6 shows the contaminated area as well as the location of two facilities responsible for the contamination in Southern Nevada. The perchlorate-contaminated groundwater from Henderson, NV, seeps into the Las Vegas Wash which in turn drains into Lake Mead and the Colorado River down to Arizona and California. Lake Mead is the major water source for the 1.2 million inhabitants of the Las Vegas metropolitan area. Perchlorate levels in Lake Mead vary by location but have not exceeded 18 $\mu\text{g/L}$ to date.

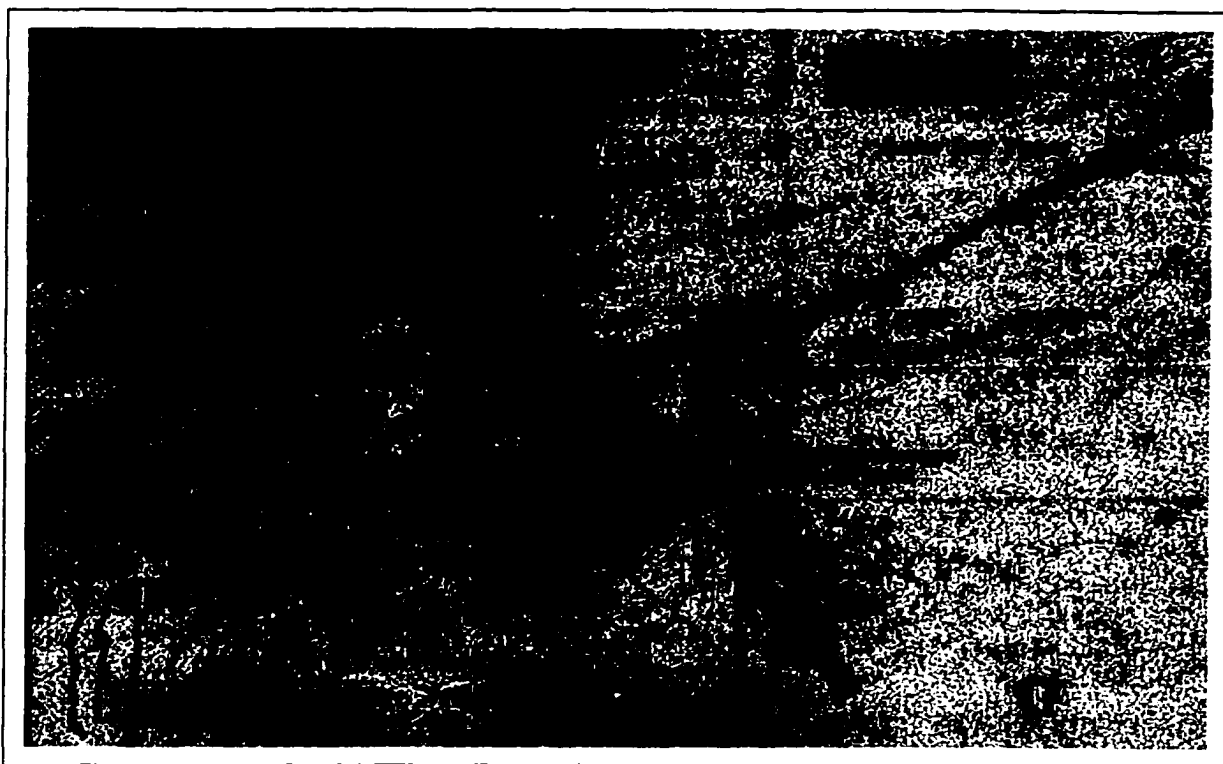


Figure 2.6 PEPCON and KMCC locations by the Las Vegas Wash (Source: modified from The Las Vegas Review Journal, May 3, 1998).

Boralessa and Batista (2000) analyzed frozen samples dating from 1993 to 1999 collected from the Las Vegas Wash, which is a stream that feeds into Lake Mead and drains the BMI complex area. The researchers found that in 1993 the perchlorate concentrations in the Las Vegas Wash averaged 400 $\mu\text{g/L}$ and progressively increased to an average of 800 $\mu\text{g/L}$ by the year of 1995. In the later years, the perchlorate concentrations stabilized at this level (800 $\mu\text{g/L}$). In addition, the researchers analyzed frozen samples from Lake Mead. At the point where the Las Vegas Wash discharges into Lake Mead, called the Las Vegas Bay, perchlorate concentrations are rapidly diluted and varied from 100 to 200 $\mu\text{g/L}$. In the interior sections of Lake Mead perchlorate concentrations of 10-15 $\mu\text{g/L}$ were measured (Boralessa and Batista, 2000).

The Southern Nevada Water Authority (SNWA) has measured perchlorate concentrations of 11 $\mu\text{g/L}$ in the Las Vegas tap water (Urbansky, 1998). In agreement with the SNWA findings, samples measured at the Environmental Engineering Laboratory at the University of Nevada Las Vegas also showed perchlorate concentrations ranging between 10 and 14 $\mu\text{g/L}$ for Las Vegas tap water.

2.1.3.1 Natural Occurrences of Perchlorate

There are indications that perchlorate may occur naturally in the environment. Investigations of the occurrence of perchlorate in natural nitrate deposits in Chile have been conducted (Schilt, 1979 and Susarla et al., 1999). Seawater samples from several locations in the globe have been analyzed for the presence of perchlorate (Schilt, 1979). Despite all these investigations, the natural occurrence of perchlorate is still questionable.

In 1886, Beckurts reported the discovery of small amounts of perchlorate in natural deposits of nitrates in Chile (Schilt, 1979). Some years later several groups of researchers concerned with the possible harmful effects of perchlorate present in Chilean nitrate used as fertilizer confirmed the same findings of Beckurts. In 1896, Sjollem found potassium perchlorate present in Chile saltpeter in amounts up to 6.79%. In 1914, Maschhaupt investigated the presence of perchlorate in crude and refined saltpeter and found a content of 1.5% and 1.0% respectively (Schilt, 1979), indicating that the presence of perchlorate is more likely to be due to the natural occurrence of perchlorate than to the manufacturing process of the fertilizer. In agreement with these observations, Susarla et al. (1999) suggested that the source of perchlorate-contaminated fertilizers is natural minerals used in the manufacturing process of nitrates. To date, it is not known how perchlorate is produced by natural means.

In addition, Susarla et al. (1999) also investigated the presence of perchlorate in some other compounds. Langbenite, the single most important source of potassium sulfate for all major manufacturers, has shown perchlorate amounts up to 1.86%, urea with concentrations up to 0.25% and Chilean nitrate with concentrations up to 3.64%.

Bass-Becking et al. (1958) reported the discovery of perchlorate in seawater. Perchlorate levels varying from 10 to 1000 mg/L were found in samples collected at diverse localities. However their study have been strongly refuted by other researchers instead of being verified. Greenhalgh and Riley (1960) reported non-detectable concentration of perchlorate in over 30 surface and deep-water samples collected from both northern and southern hemispheres in an extensive study ended in 1960. In addition, they attributed the results of Bass-Becking et al. to chloride interference. At

the same time, in 1960, Johannesson looked for perchlorate occurrence in fresh-seawater samples taken 50 miles apart off the coast of Wellington, New Zealand. He did not find any detectable perchlorate. Two other groups (Loach, 1962 and Iwasaki et al., 1963) have reported non- detectable levels of perchlorate in sea water samples. Based on the above investigations, it appears that perchlorate does not occur naturally in seawater (Schilt, 1979). However, analytical methods to detect low levels of ClO_4^- were not available on the 1960's. Before the development of the IC method by SRLB and Dionex Corporation, the old analytical method was able to detect only concentrations in the mg/L range.

2.1.4 Treatment Technologies

The reference dose (RfD) is typically used to characterize potential health risks of a given contaminant. It also points out the levels to which secure treatment technologies must be developed. Perchlorate shows properties that make the development of treatment technologies difficult. Such properties include the low reactivity as an oxidant due to kinetic barriers and the unreactivity towards most reducing agents when perchlorate is cold and diluted (EPA, 1998). In addition, perchlorate is extremely soluble, even in organic solvents, also it is a non-volatile substance; therefore perchlorate cannot be removed from waters using conventional filtration, sedimentation, or air stripping. Due to the large number of independent variables, it is not likely that one technology by itself will provide an effective solution for every episode of perchlorate contamination in surface and groundwater supplies. An efficient treatment technology for perchlorate removal should be cost effective, have

acceptance to regulatory agencies and the public, cause no other water quality problems and should generate minimal amounts of treatable wastes (EPA,1998).

The industry and the Air Force Research Laboratory Materials and Manufacturing Directorate (AFRL/MLQE) have been developing treatment technologies and processes to recover perchlorate for reuse and to treat residual wastewater containing high concentrations of perchlorate, i.e. 500-10,000 mg/L, from the manufacture and maintenance of rocket motors. Since 1998, several research projects are underway to develop technologies for treating perchlorate contamination in surface and groundwater supplies present at low levels, i.e. 5 to 500 $\mu\text{g/L}$ (EPA, 1998). These research projects are funded by private corporations and by the American Water Works Association Research Foundation (AWWARF). Several technologies are under consideration including biological reduction, ion exchange, conventional ozone/granular activated carbon systems, and reverse osmosis and nanofiltration (AWWARF, 1999).

2.1.4.1 Chemical Processes

Two chemical processes can be used for perchlorate removal: chemical reduction and ozone-peroxide treatment. The latter has been shown to remove perchlorate from groundwater.

2.1.4.1.1 Chemical Reduction

Perchlorate has a very strong affinity for electrons, in other words perchlorate is a highly oxidized compound. Because of those characteristics, one might anticipate that perchlorate could be destroyed by the addition of a chemical reducing agent resulting in

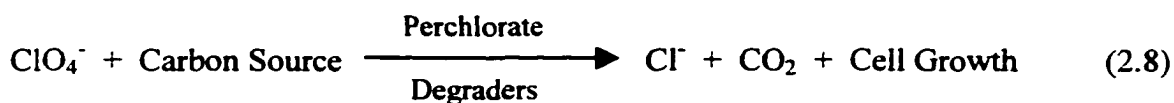
the reduction of perchlorate (Cl (7)) to chloride (Cl (-1)). Unfortunately, the chemical reaction between perchlorate and commonly used reducing agents (e.g. iron, manganese) is too slow to be of efficient use (EPA, 1998). In laboratory experiments, the reaction of perchlorate and exotic reducing agents such as titanium, vanadium, molybdenum, and ruthenium has been shown (Schilt, 1979), but these chemicals are likely to be extremely unstable or too toxic to be used for water treatment approaches. To date, catalysts that could be used to speed up the chemical reduction of perchlorate, when commonly reducing agents are used, have not been identified (EPA, 1998).

2.1.4.1.2 Ozone-Peroxide

The ozone-peroxide treatment by itself appears to have insignificant effect on perchlorate. However, when liquid phase carbon treatment follows ozone-peroxide treatment, perchlorate can be removed from waters. In a water supply well located at the San Gabriel Valley, perchlorate is being removed from groundwater using this coupled technology (EPA, 1998).

2.1.4.2 Biological and Biochemical Processes

Perchlorate is easily biodegradable, as it can be reduced by microorganisms under anaerobic conditions. The biochemical reaction involves the degradation of perchlorate to chloride (reaction 2.8). In this reaction, perchlorate is used as electron acceptor.



In order for biological treatment to occur, in most cases, it is necessary to add nutrients and a carbon source to sustain microbial growth. The energy source compound is the electron donor and could be lactate, acetate, hydrogen gas, methanol, ethanol, etc. When using hydrogen as energy source, the microorganisms need CO_2 as the carbon source and the process is autotrophic. When the energy source and the carbon source is an organic compound, the process is called heterotrophic. The choice of the electron donor added to the reactor is expected to be a critical design factor.

Perchlorate biodegradation has been investigated by several researchers (Hackental et al., 1963; Korenkov et al., 1976; Malmquist et al., 1991; Attaway and Smith, 1993; Rikken, et al., 1996; Wallace et al., 1996; Logan, 1998). Several species of bacteria are capable of reducing perchlorate to chloride and some were described by Hackental et al., in 1963. These researchers focused on the enzymes and mechanisms that governed the reduction of perchlorate and nitrate. In addition, their study clearly identified some bacteria that are able to reduce perchlorate to chloride. Table 2.3 shows the perchlorate degradation rates for several bacteria as well as the electron acceptors utilized by them.

Table 2.3 Perchlorate Biodegradation Rates.

Microorganism	Maximum Rate*	Maximum tolerable ClO_4^- concentration	Electron acceptors	Reference
<i>Vibrio dechloraticans</i> Cuznesove (B-1168)	69 mg/hr g	300 mg/l	ClO_4^- , ClO_3^- , NO_3^-	Korenkov <i>et al</i> (1976) and Malmqvist <i>et al</i> (1991)
<i>Staphylococcus epidermidis</i> (PT-7517)	0.83 mg/hr g	NA	ClO_4^-	Hackenthal <i>et al</i> (1964)
<i>Staphylococcus aureus</i> (SG-511)	0.88 mg/hr g	NA	ClO_4^-	Hackenthal <i>et al</i> (1964)
<i>Bacillus cereus</i> (ATCC-8035)	2.96 mg/hr g	NA	ClO_4^-	Hackenthal <i>et al</i> (1964)
<i>Serratia marcescens</i> (727/61)	2.24 mg/hr g	NA	ClO_4^-	Hackenthal <i>et al</i> (1964)
<i>Escherichia coli</i> (992/51)	3.46 mg/hr g	NA	ClO_4^-	Hackenthal <i>et al</i> (1964)
Mixed Culture	59 mg/l hr	5600 mg/l	ClO_4^-	Korenkov <i>et al</i> (1976)
<i>Acinetobacter thermotoleranticus</i>	NA	NA	ClO_3^- , SO_4^-	Stepanyuk <i>et al</i> (1993)
<i>Ideonella dechloratans</i>	NA	NA	ClO_3^- , O_2 , NO_3^-	Malmqvist <i>et al</i> (1994)
<i>Pseudomonas sp.</i> (various)	NA	NA	BrO_3^-	Hiknen <i>et al</i> (1995)
<i>Wollinella succinogeneses</i> HAP-1	NA	NA	ClO_4^- , ClO_3^- , NO_3^-	Wallace <i>et al</i> (1996)
AB-1	NA	NA	ClO_3^- , NO_3^-	Bliven <i>et al</i> (1996)
GR-1	NA	NA	ClO_4^- , ClO_3^- , O_2 , NO_3^- , Mn(IV)	Rikken <i>et al</i> (1996)
* Specific ClO_4^- degradation rates are expressed as milligrams of ClO_4^- /hr g biomass. Modified from: Shanahan <i>et al</i> (1996) and Logan (1998).				

By utilizing raw domestic sewage as a nutrient source, Korenkov et al. (1974) found that industrial wastewater containing perchlorate and chlorates could be treated biologically.

Attaway and Smith (1993), and Wallace et al. (1996) reported that researchers at the Tydall Air Force Base have developed a perchlorate removal process that uses a suspended-growth reactor and it is able to reduce perchlorate from high concentrations such as 3000 mg/L to 0.5 mg/L (Logan, 1998a). The anaerobic reactor utilizes primarily cultures of *Wollinella succinogenes* HAP-1 and brewers' yeast as a nutrient source. At a detention time of 8 hours, perchlorate could be reduced to concentration lower than 0.5 mg/L.

In laboratory work, acetate (Logan and Kim, 1998), lactate (Liu and Batista, 2000), and hydrogen gas (Rittmann and Nerenberg, 2000) have been used extensively as the electron donors for perchlorate biodegradation. Other likely alternatives are ethanol and methanol. However, methanol and ethanol are alcohol compounds that are federally regulated, and methanol has high health risks (Rittmann and Nerenberg, 2000).

In spite of the fact that bioreactors appear to work efficiently when removing low perchlorate concentrations from drinking water supplies, it is important to point out that the public approval of the biological treatment technology for drinking water has not been well determined (EPA, 1998). Biological treatment of water for potable purpose has never been used in the United States and it could be a significant obstacle when trying to implement the microbiological removal of perchlorate from drinking water.

Shanahan et al. (1996) reported the demonstration of ammonium perchlorate biotreatment in rocket motor wastewater in a bench-scale system. Their system operated

at a dilution rate of 0.054 1/hr and could reduce perchlorate at rates of 148mg/l*hr to concentrations below 10mg/L. Also, in order to reduce dilution requirements for higher-strength wastes, the researchers tested a continuous-flow system that was able to degrade feed solutions containing around 9000mg/L of perchlorate to satisfactory levels.

A test for perchlorate removal from a Minuteman III rocket motor washout wastewater was reported by Wallace *et al.* (1998). It was used an up-flow fixed bed reactor inoculated with HAP-1 (28 to 47% of the microbial consortium population). The feed solution contained 1500 mg/L perchlorate and 3000 mg/L nutrient (brewers' yeast extract). The reactor operated at 1.17 hour detention time and could reduce perchlorate below 300 mg/L during a test over 228 days period, and below 100 mg/L 95% of the time (Logan, 1998a).

A perchlorate removal process that uses an anoxic fluidized-bed methanol-fed reactor using granular activated carbon (GAC) as a support medium for a consortium of microbes obtained from a food-processing wastewater was reported by Catts in 1998. The process was developed by Aerojet and perchlorate concentrations of 20 to 60 $\mu\text{g/L}$ were reduced to $<10 \mu\text{g/L}$.

Logan and Kim (1998) working with fixed-bed sand filters and inoculated with perchlorate-degrading enriched cultures have reported perchlorate removal below detectable levels. In their experiment, the feed solution contained acetate, trace minerals, ammonia and phosphorus and 20 mg/L of perchlorate. At loading rate smaller than 4.48 L/min/m^2 , the perchlorate concentration in the column effluent was below 4 $\mu\text{g/L}$ (i.e. below detectable levels).

A biological perchlorate removal using a membrane-immobilized biofilm was reported by Liu and Batista (2000). In this process, the membrane-immobilized biofilm separates the perchlorate-contaminated water from the microbes, greatly minimizing the presence of microbes in the treated water. This approach has a great advantage over the other types of biological treatment systems such as anoxic fluidized-bed methanol-fed reactor, sand filter bed, and hydrogen gas-phase reactor due to the non-contact between the microbes and the finished water (Liu and Batista, 2000).

Rittmann and Nerenberg (2000) reported the results of the first stage of an experiment designed to reduce perchlorate carried out by hydrogen-oxidizing autotrophic bacteria. In the screening experiment, the removal of perchlorate improved from 40% in the beginning to above 95%, suggesting that the perchlorate-reducing bacteria were selected by the reactor conditions and the reactor became enriched with perchlorate reducers. By varying the hydrogen concentration in the reactor, the researchers concluded that high-hydrogen environments may provide a competitive advantage to perchlorate reducers. Further investigations are necessary and underway to determine other mechanisms affecting perchlorate reduction, to check reduction kinetics, and to design a practical treatment system (Rittmann and Nerenberg, 2000).

It is important to point out that the majority of the studies on biological perchlorate removal to date were performed in conditions of neutral pH (6-8) and low salinity. Regenerant brines from most ion exchange systems have high salinity (6-8%) and biological treatment of these brines may be a challenge. There are no reports on perchlorate biodegradation at high salinity concentrations.

2.1.4.3 Physical Processes

Two physicochemical removal processes are under investigation for their capability to remove perchlorate from waters; they are based on membrane (reverse osmosis and nanofiltration) and on ion exchange processes.

2.1.4.3.1 Reverse Osmosis and Nanofiltration

Membrane-based processes are recognized for their capability to remove several ions such as magnesium and calcium from waters and are now under investigation for perchlorate removal (Yoon and Amy, 2000).

Despite their effectiveness, membrane-based techniques show some disadvantages. For example, the RO process could be impractical for a municipal drinking water treatment for two reasons: (a) the possible fouling of the membranes and (b) the high costs associated with the technique. It is important to note that this may not be always true. Depending on the contaminant concentrations, membrane-based processes can be used at reasonable costs. One possible disadvantage is that RO-treated water has to be remineralized with innocuous salts (e.g. NaHCO_3) in order to prevent corrosion of the distribution system.

The Harvey Mudd College has completed pilot-scale tests for the Metropolitan Water District of Southern California and they have shown that nanofiltration process can reduce perchlorate concentration from 18 $\mu\text{g/L}$ to less than detectable levels, i.e. 4 $\mu\text{g/L}$, (EPA, 1998). The Southern Nevada Water Authority (SNWA) performed reverse osmosis (RO) tests to remove perchlorate from waters and reported satisfactory results (EPA, 1998). Data from this study have not been published.

In 2000, Yoon and Amy reported a study with two nanofiltration (NF) membranes, ESNA and MX07 (Table 2.4). Those membranes have similar chemistry based on material and different relative molecular mass cutoffs (MMCOs). The researchers compared both membranes (ESNA and MX07) in terms of the effects of membrane surface charge, as affected by solution pH and conductivity, on perchlorate rejection. Membranes possessing a negative charge can reject perchlorate and this phenomenon can be explained by basic transport equations based on diffusion and convection (Yoon and Amy, 2000). The Donnan Equilibrium equation can explain the perchlorate exclusion by negatively charged membranes. Based on those equations, the authors concluded that (a) with the increase in pH, the membrane negative charge will increase and it is expected that perchlorate rejection increases; (b) if the ionic strength increases, the perchlorate rejection is expected to decrease and (c) the presence of other ions in solution will influence the perchlorate rejection.

Table 2.4 Membrane physical/chemical properties.

Type	Manufacturer	Material	Molecular Mass Cutoffs (MMCO)	Pure Water Permeation rate (PWP) in L/m ² -day-kPa)	Zeta Potential (ZP) at pH 8 and conductivity 115 mS/m
ESNA	Hydranautics	Polyamide TFC	200	1.05	-43.2 mV
MX07	Osmotics	Polyamide TFC	400	0.47	-41.3 mV

Source: Yoon and Amy, 2000.

With increasing pH, the membranes showed different perchlorate rejections, 70% to 90% for ESNA and 40% to 70% for MX07.

2.1.4.3.2 Ion Exchange Technology

Prior to discussing the research on the use of ion exchange for perchlorate removal, a detailed discussion about ion exchange resins and their properties will follow.

Ion exchange technology is based on the interchange between an innocuous ion, which is attached to the ion exchange resin, with the contaminant ion present in the solution that needs treatment. Ion exchange is perhaps the strongest candidate technology for perchlorate removal from drinking water. In homes and business, ion exchange processes have been used for water softening for many decades (EPA, 1998). This is a very important factor; water utilities are already familiar with ion exchange in their plants and they would probably welcome this technology. The same cannot be said for biological perchlorate degradation that may encounter resistance from water utilities.

Ion exchange resins can be used for several purposes: (a) drinking and industrial water treatment, (b) recovery separation, (c) pollution control, etc. Nevertheless, the water treatment industry uses most of the ion exchange resins produced (Calgon Carbon Corporation, 1998).

There are four basic parameters for the evaluation of the cost-effectiveness of an ion exchange treatment process: (a) treatment ratio or bed volume (BV) run, (b) regeneration waste, (c) regeneration potential, and (d) influence of other ions. Treatment ratio is the volume of feed water treated before breakthrough occurs divided by the volume of resin used in the treatment process. Breakthrough point is defined as the maximum concentration allowed for the effluent water treated and is usually based on drinking water standards. The regeneration waste is the volume of waste, generally brine, generated by the regeneration of the ion exchange resin loaded with the

contaminants. Regeneration potential is related to the resin's capability of being regenerated with economically feasible volumes of regenerant solution. The other ions present in the contaminant solution are an issue because of the ion exchange resin selectivity for these ions compared to that for the contaminant ion to be treated. The selectivity coefficient will determine the resin's preference order of exchange.

2.2 Ion Exchange Materials

Ion exchange materials are non-soluble solids covalently bonded to ionized functional groups that are chemically treated. In consequence, the ionic species attached to the solid bead (negatively or positively charged) can be exchanged stoichiometrically with other species present in solution that have the same charge.

Ion exchange also can be a natural phenomenon that occurs in soil, minerals and tissues of plants and animals. The exchange event occurs with a number of natural solids such as soils, humus, cellulose, wool, protein, activated carbon, coal, lignin, metallic oxides, and living cells, e.g. algae and bacteria (Weber, 1972). Evidences of the use of clay and other natural materials for demineralization of drinking water have been found in the ancient Greek literature (Kunin, 1958). In the modern civilization, J. T. Way and H. S. M. Thompson (1850) were the two first scientists that independently recognized and examined the ion exchange phenomenon in soils. However, the great contribution for the development and advance of ion exchange technology was resulted from the work concluded in 1935 by two English chemists, I. B. A. Adams and E. L. Homes (Samuelson, 1963). These scientists developed the first synthetic ion exchange resin. After their work, notable refinements have been made in the preparation of an ample range of synthetic resins for diverse applications (Weber, 1972). In 1945, D'Alelio developed ion-exchange resins using styrene and divinylbenzene as the monomers. Divinylbenzene (DVB) works as a cross-linker and its presence in ion exchange resins is small, 12% or less. However, DVB is required to form the three-dimensional matrix of the resin (Simon 1991). The amount of cross-linking

(divinylbenzene) will define several properties of the ion exchange resin that will be discussed in the next sections.

2.2.1 Synthetic Ion Exchange Resins

Synthetic ion exchange resins are insoluble polymers formed by a system of hydrocarbon radicals to which ionic functional groups are attached. The toughness and insolubility of the resin is due to its three-dimensional matrix in which the hydrocarbon molecules are cross-linked. Ionic species in aqueous solution, with negative or positive charge, can be exchanged stoichiometrically with those of the same charge attached to the resin's functional group. Figure 2.7 shows a schematic illustration of a cationic exchange resin. Basically, the resin consists of a molecular setting to which functional ionic groups are attached (Weber, 1972).

Ion exchange resins are classified as anionic and cationic based on the charge of the ion bounded to the functional group (counter-ion). An ion exchange resin with a positive charged counter ion is called cationic while an ion exchange resin with a negative charged counter ion is called anionic. In addition, ion exchange resins are classified as strong or weak, and basic or acidic based on their functional groups. Functional groups derived from strong acids (e.g. H_2SO_4) form strong-acid resins. Functional groups derived from weak acids (e.g. HCO_3^-) form weak-acid resins. Ion exchange resins that have amino or substituted amino as functional group are called weak-base resins, and resins with quaternary ammonium as functional group are called strong-base resins. Ion exchange resins can also be classified as styrenic and acrylic

based on the resin structure. Styrenic resins have an aromatic polymer structure while acrylic resins have an aliphatic structure (open carbon chain).

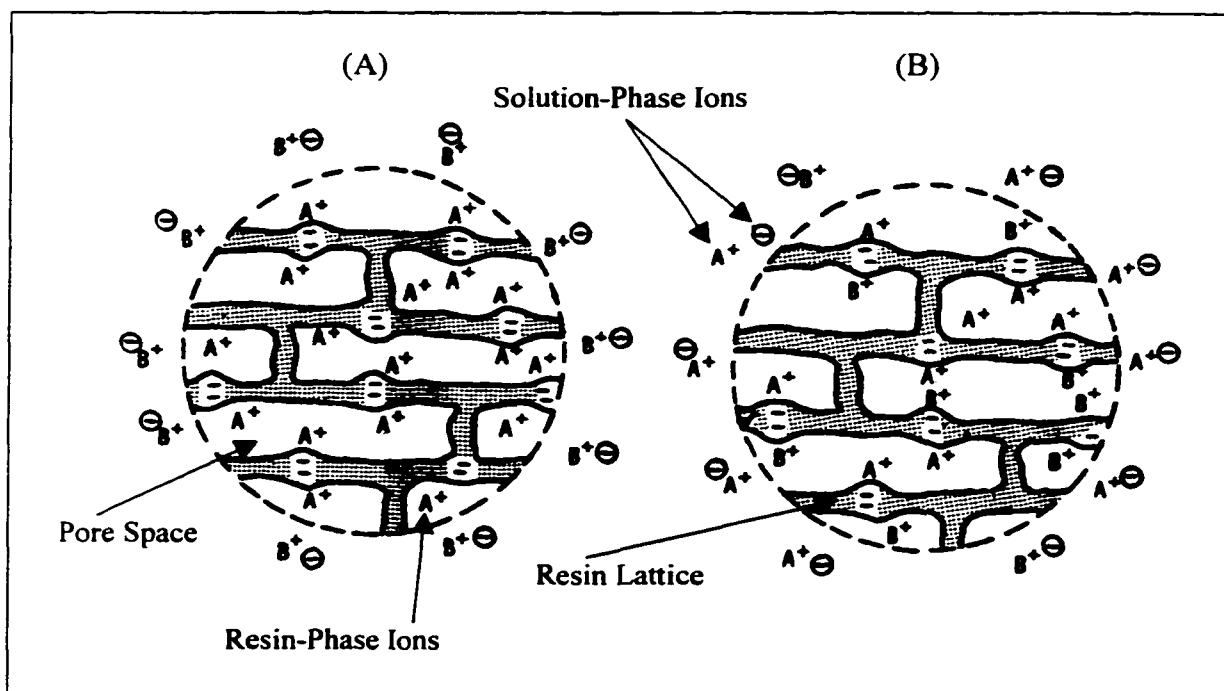


Figure 2.7 Representation of a cationic exchange resin with fixed exchange sites prior to and subsequent to an exchange reaction. (A) Initial condition prior to exchange reaction with cation, B^+ ; (B) Equilibrium condition subsequent to exchange reaction with cation, B^+ (Source: Modified from Weber, 1972).

2.2.1.1 Composition and formation of ion exchangers.

Polymerization controls the synthesis of ion exchange resins, since they are nothing more than polymers containing ionic groups. Figure 2.8 shows the formation of polystyrene by the polymerization of styrene (A). An insoluble copolymer of polystyrene and divinylbenzene is formed (C) when polystyrene chains are cross-linked with divinylbenzene (B). Figure 2.9 also shows the polymerization of styrene and divinylbenzene.

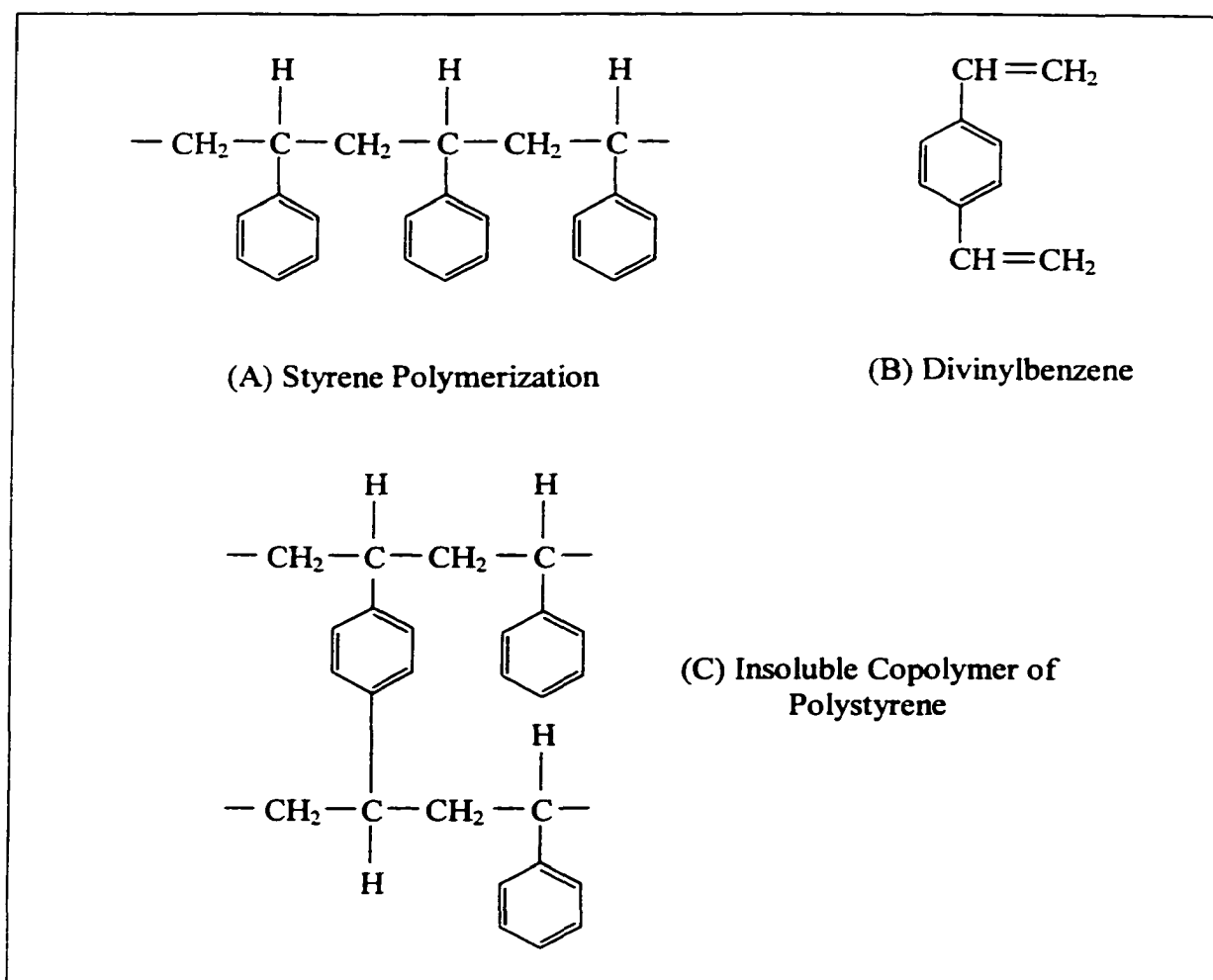


Figure 2.8 Styrene polymerization cross-linked with divinylbenzene to form an insoluble copolymer of polystyrene and divinylbenzene (Source: Modified from Kunin, 1958).

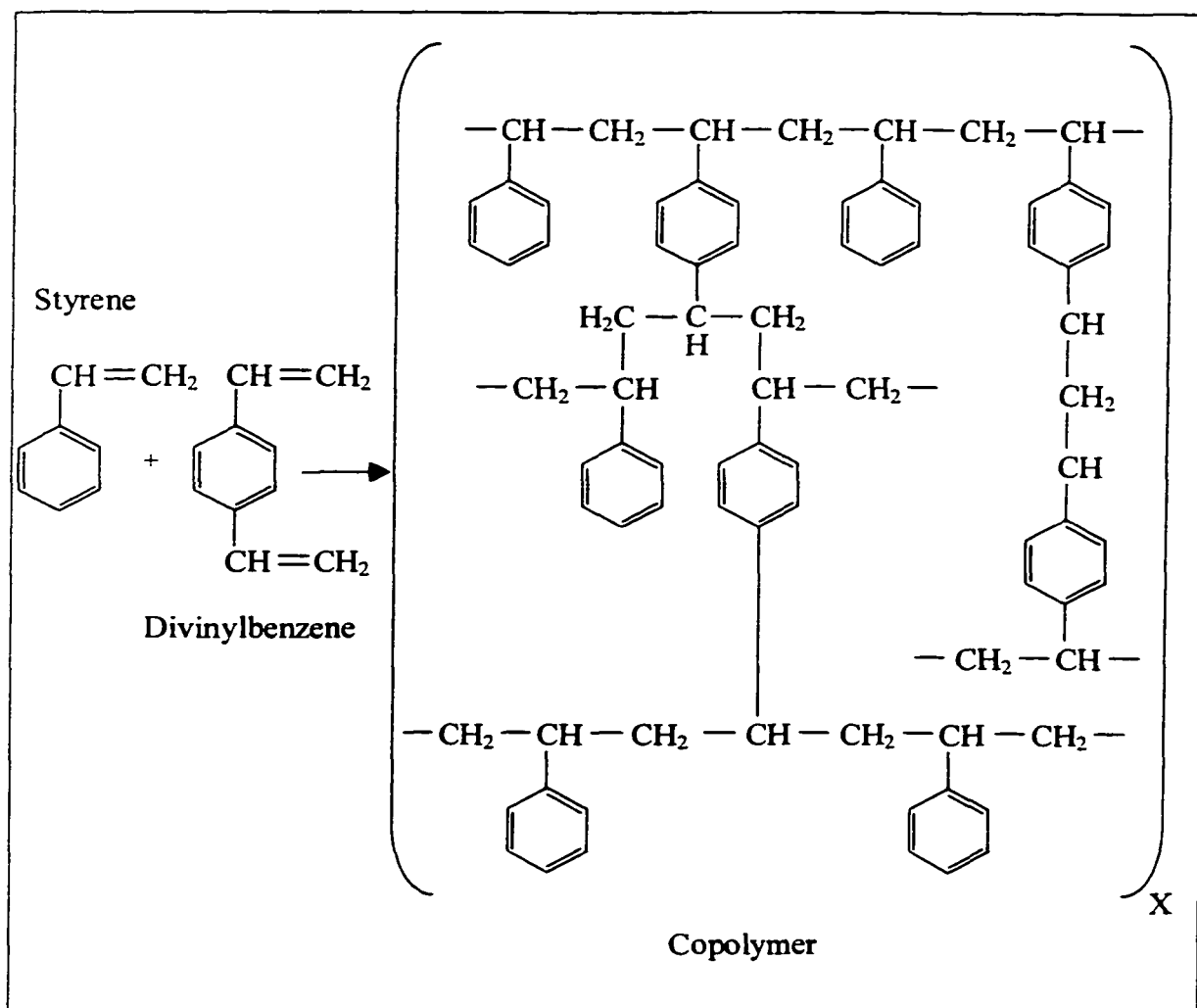


Figure 2.9 Polymerization of styrene and divinylbenzene (Source: Simon, 1991).

The preparation of a type-I and type-II strong-base anionic exchange resin is shown in Figures 2.10 and 2.11 respectively. Figure 2.12 shows an example of preparation of weak-base anionic exchange resin.

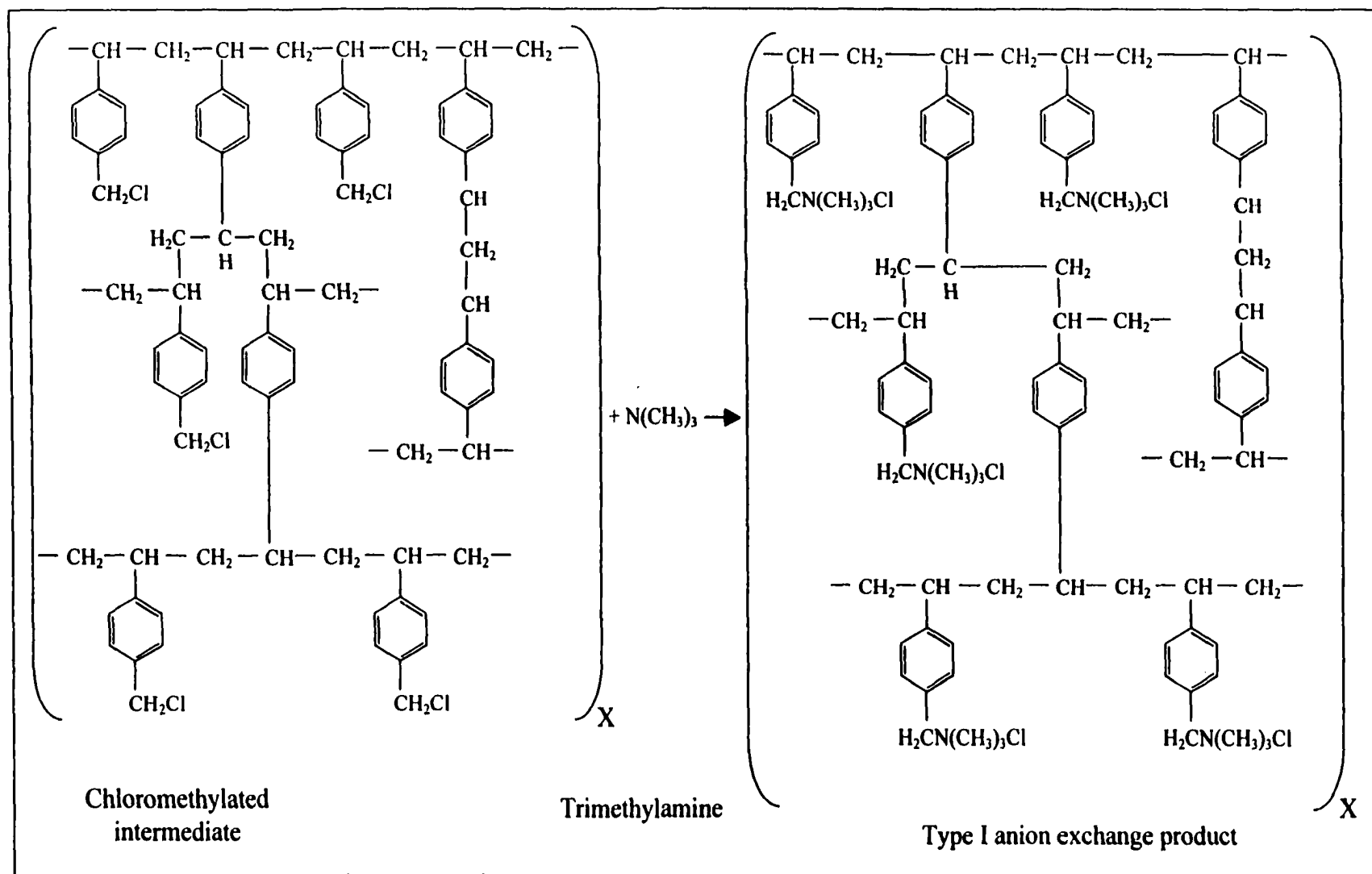


Figure 2.10 Preparation of type-I strong base anionic exchange resin from the chloromethylated intermediate (Source: Simmon, 1991)

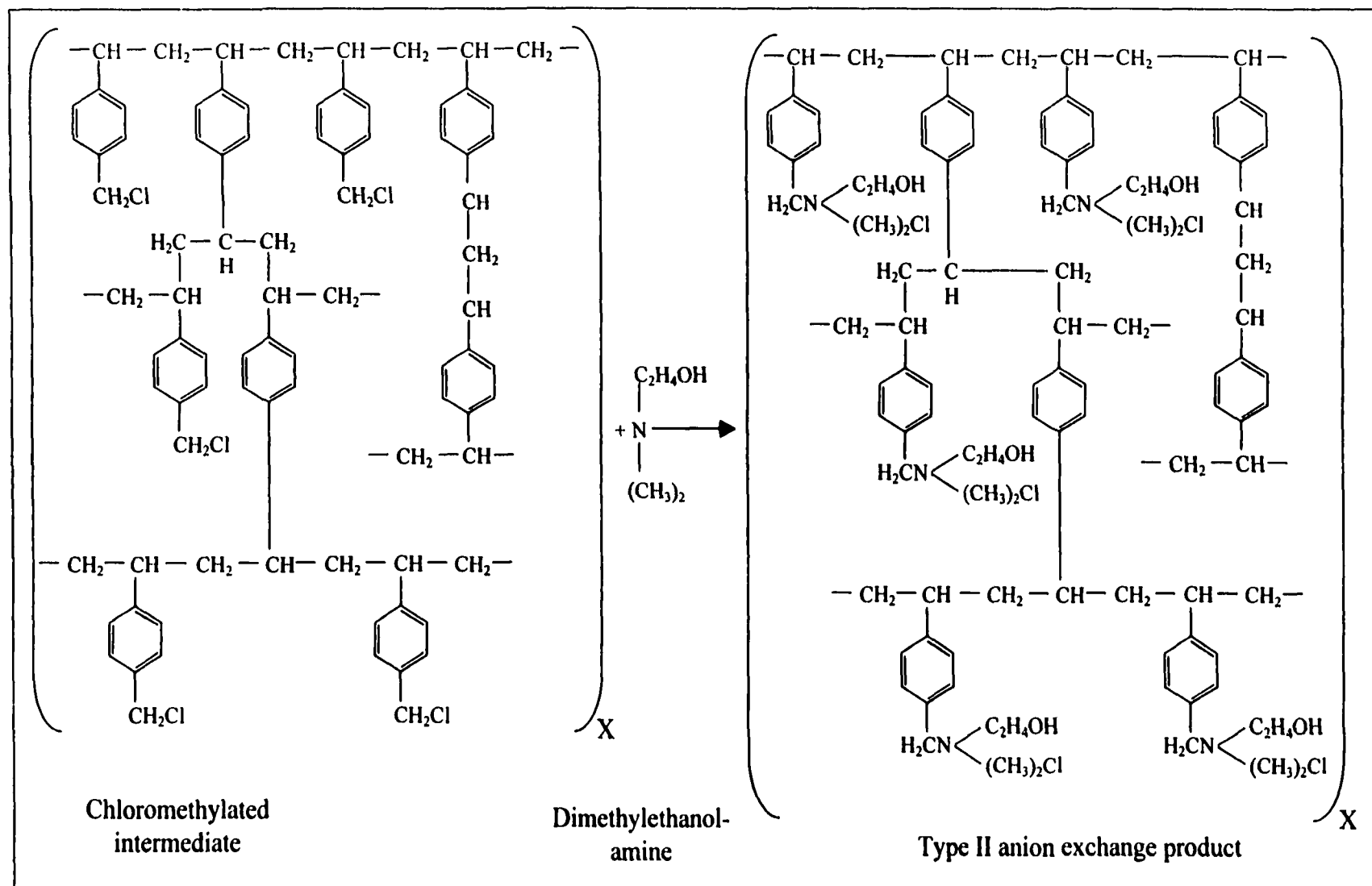


Figure 2.11 Preparation of type-II strong-base anionic exchange resin from the chloromethylated intermediate (Source: Simmon, 1991)

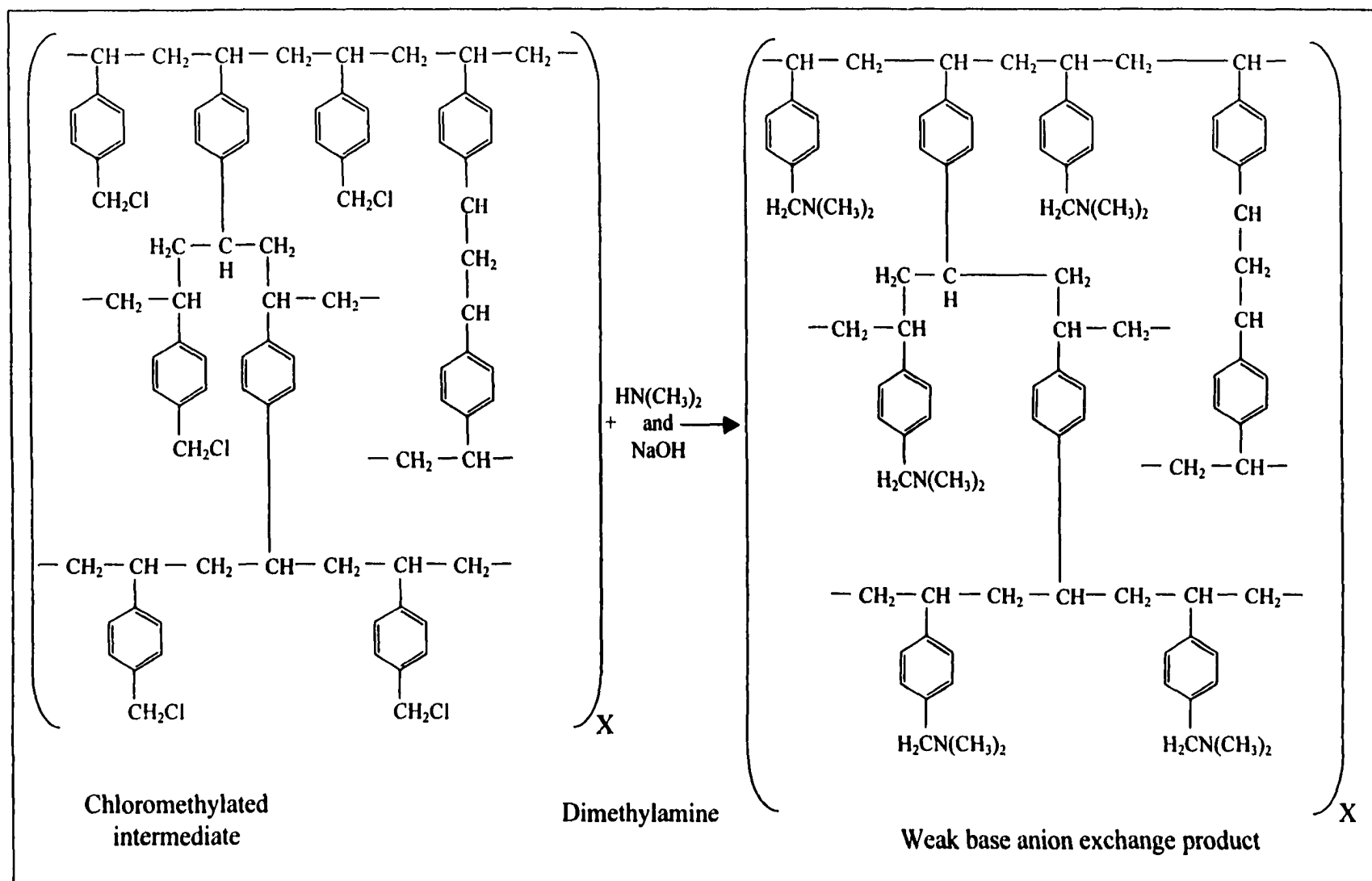


Figure 2.12 Preparation of weak base anionic exchange resin from the chloromethylated intermediate (Source: Simmon, 1991)

2.2.1.2 Physical properties

The physical properties directly related to the resin structure are (a) density, (b) hydration and swelling, (c) resistance to osmotic shock, (d) diffusion, and (e) relative porosity.

The insoluble property of ion exchange resins is due to the use of the divinylbenzene cross-linking. The amount used varies over an order of magnitude: 2-16 weight percent (wt%). The volume changes that occur during normal ion exchange operation can damage the resins if they have less than 2 wt% of divinylbenzene (Simon 1991). On the other hand, above 16 wt%, ion exchange resin production becomes difficult and costly. In addition, the resin density is directly related to the degree of cross-linking. Table 2.5 shows the relation between resin density and the amount of divinylbenzene.

Table 2.5 Relationship between cross-linking and resin density on a strong acid cationic exchange resin.		
Cross-linking (wt%)	Density (g/L)	
	Sodium Form	Hydrogen Form
2	120	90
4	260	220
6	360	320
8	420	385
10	460	430
12	490	460
14	510	480
16	520	500
Source: Simon, 1991		

The resin swelling is also related to the amount of cross-linking. The higher the amount of cross-linking, the smaller the amount of water the ion exchange resins will

retain. Other factors that will influence the amount of water incorporated into the resins are (a) the nature of the functional group and (b) the ion exchanged on the group. When immersed in water, the active groups attached to the resin hydrate causing swelling (Simon 1991).

Osmotic shock is the phenomenon that occurs with the resin when submitted to different salt concentrations due to the usual application and regeneration cycles. In the regeneration process, when the salt concentration is high, the salt will desorb water from the resin phase making it shrink. At low salt concentration solutions, the opposite will occur and the resin will swell. In order for the resin to be resistant to these shocks, it should be flexible enough to support several operating cycles involving swelling and shrinking without developing internal stresses that would fracture the beads (Simon 1991).

The resin bead size and the degree of cross-linking are factors that affect the diffusion of the counter-ion and the ion in solution. For exchange to occur, an ion must diffuse through the frontier layer and the solid resin phase to a position where it can react with the counter-ion. As a consequence, the counter ion must diffuse in the opposite direction to complete the reaction (Simon, 1991). Table 2.6 shows the relationship between diffusion rate of bromide, cross-linking and temperature when a type II strong base anionic resin is used. Notice that the diffusion rate decreases with the increase in the percent of cross-linking.

Table 2.6 Cross-linking effect on bromide diffusion at two temperatures when type II strong base anionic resin (gel type) is used.		
Cross-linking (wt%)	Solid diffusion rate (cm/sec)	
	0.3 °C	25 °C
1	4.4×10^{-7}	9.1×10^{-7}
2	3.0×10^{-7}	6.4×10^{-7}
3	2.0×10^{-7}	4.5×10^{-7}
6	1.5×10^{-7}	3.9×10^{-7}
8	6.1×10^{-8}	2.0×10^{-7}
16	6.0×10^{-8}	2.6×10^{-7}
Source: Simon, 1991		

Resin porosity relates to the hydrated sizes of the ions involved on the exchange process. The common ions found in waters have relatively small size ($<10 \text{ \AA}$). Sometimes, natural organic acids (fulvic and humic) also can be found in surface waters. These acids have very high molecular weight and they can be larger than 100 \AA (Simon, 1991). Some of these porous resins can have pore diameters of over $100,000 \text{ \AA}$. As expected, the amount of divinylbenzene used in the resins controls its porosity (Tooper and Wirth, 1956)

In general, the higher the cross-linking, higher the density, higher the resistance to deformation, the smaller the swelling, the lower the diffusion rate, and the lower the porosity.

2.2.1.3 Chemical properties

An ion exchange process is regularly referred as a heterogeneous system, because it involves two different media: (a) a solid phase (ion exchange resin) and (b) a liquid phase (usually water). Therefore, the chemical properties of an ion exchange resin are

based on heterogeneous system and they are (a) hydration, (b) ionization, and (c) equilibria and selectivity. The matrix structure and the chemical nature of the active group attached to the resin have great influence on its chemical properties (Simon, 1991).

The presence of water in the resin will influence the ionization of the functional groups and the amount of water imbibed in the resin is dependent on the cross-linking (i.e. rigidity).

Strong base anionic and strong acid cationic exchange resins are entirely hydrated when in solution and for this reason the counter ions associated with the functional group are always free to exchange with ions of like charge in solution. The pK value is the point at which ionization becomes effective. Table 2.7 shows the pK's values for different resins.

Table 2.7 Ionization and pK values of ion exchange resins.		
Ion exchange type	Active group	Approximate pK value
Strong acid cationic	R-SO ₃	<1
Weak acid cationic	R-COH	4-6
Strong base anionic – Type I	R-N(CH ₃) ₃	>13
Strong base anionic – Type II	R-N(CH ₃) ₂ (C ₂ H ₄ OH)	>13
Weak base anionic	R-N(CH ₃) ₂	7-9
Source: Simon, 1991		

At any pH greater than 1, the strong-acid cationic exchange resin will be effectively ionized and can then be capable of exchanging ions. At any pH lower than 13, the strong-base anionic exchange resin will also be effectively ionized. Thus, these resins will work well at any pH value. The weak-acid cationic exchange resin is effectively ionized when the pH is above 4-6. The weak-base anionic exchange resin is

effectively ionized when the pH is below 7-9. Therefore, weak (acid cationic and base anionic) type resins have an optimum pH range at which they work well.

2.2.1.4 General Structure

Acids are the active groups of cationic exchange resins. Sulfonic acid groups ($\text{R-SO}_3\text{H}$) are present in the majority of the strong-acid cationic exchange resins. Other acid groups include (a) phenolic, R-OH , (b) carboxylic, R-COOH , and phosphoric $\text{R-PO}_3\text{H}_2$. These sulfonic acid groups can dissociate in basic media as well as acid media. In the sodium form, the sulfonic strong acid cationic resins can be represented as (Samuelson, 1963):



The weak acid cationic resins containing carboxyl groups are usually used for analytical purposes and in the sodium form they can be represented as:



The functional groups (e.g. SO_3^- and COO^-) are fixed to the resin matrix. The counter ions, i.e. the ions with opposite charge, can be exchanged for other ions with the same charge. Therefore, cationic exchange resins can be considered as polyvalent anions (depending on the functional group) with positively charged counter ions, and anionic exchange resins can be considered as polyvalent cations with negatively charged counter ions (Samuelson, 1963). It is clear that the counter ions are the ions replaced in the ion exchange process and the functional groups remain fixed to the resin matrix.

The properties of the anionic exchange resins are usually due to the presence of three groups: (a) amino, (b) substituted amino, and (c) quaternary ammonium (Samuelson, 1963). The amino groups are divided into (a) primary amine, $R-NH_2$; (b) secondary amine, $R-R'NH$; and (c) tertiary amine, $R-R'_2N$. The quaternary ammonium group is represented by $R-R'_3N^+OH^-$ and the R' represents organic radicals, e.g. methyl group, CH_3 . The strong base anionic resins contain quaternary ammonium as a functional group while the weak base anionic resins contain functional groups derived from weak base amines. Figure 2.13 displays a schematic illustration of the structures of (A) weak-base tertiary amine and (B) strong-base quaternary amine functional groups.

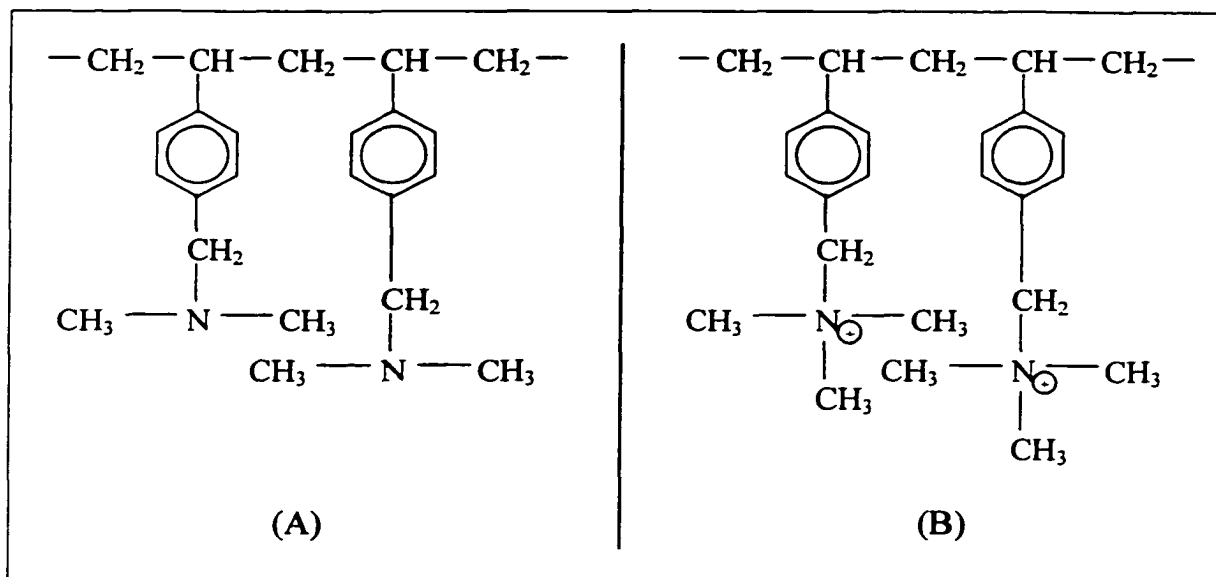


Figure 2.13 Schematic illustration of (A) weak-base dimethyl tertiary amine functional group and (B) strong-base trimethyl quaternary amine functional group (Source: Modified from Sengupta and Roy, 1988).

From Figure 2.13, it can be seen that strong-base anionic resins have at least one additional methyl ($-CH_3$) group as opposed to weak-base anionic resins. In consequence, the strong-base trimethyl quaternary amine functional group will more strongly hinder

the exchange of a large hydrated counter-ion than weak-base dimethyl tertiary amine functional group will (Sengupta and Roy, 1988).

The structure difference between polystyrene and polyacrylic resins is shown in Figure 2.14. Both resins have the same functional group (trimethyl quaternary amine). Notice that the polystyrene resin (Figure 2.14 – A) is formed by aromatic polymer structures while the polyacrylic resin (Figure 2.14 – B) has an open chain (aliphatic structure).

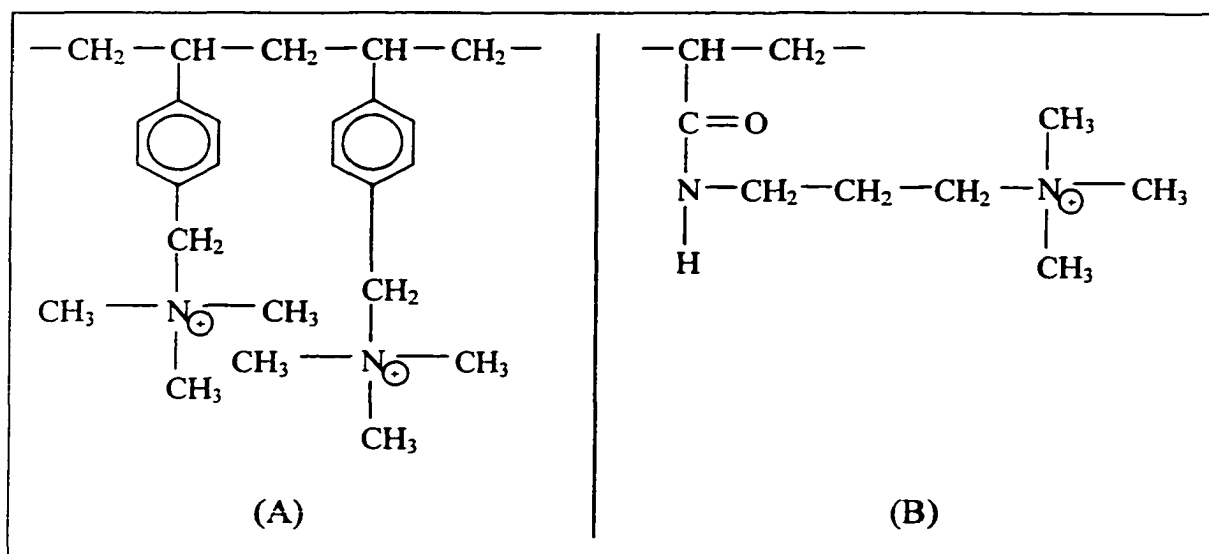


Figure 2.14 Schematic illustration of (A) polystyrene strong-base resin with trimethyl quaternary amine functional group (B) polyacrylic strong-base resin with trimethyl quaternary amine functional group (Source: Modified from Sengupta and Roy, 1988).

Due to irreversible fouling problems, observed when common anion exchange resins (gel-type) were used to treat water supplies containing low concentrations of organic substances, a new type of ion exchange resin was developed; the porous ion exchange resins. These resins facilitate the diffusion of the high molecular weight humic acids molecule in and out of the ion exchange beads (Simon, 1991). Those resins are

commonly named macroporous, macro-reticular or fixed-porous ion exchangers, depending on the manufacturer. Figure 2.15 shows a schematic illustration of (A) the gel-type cationic exchange resin and (B) the porous ion exchange resin.

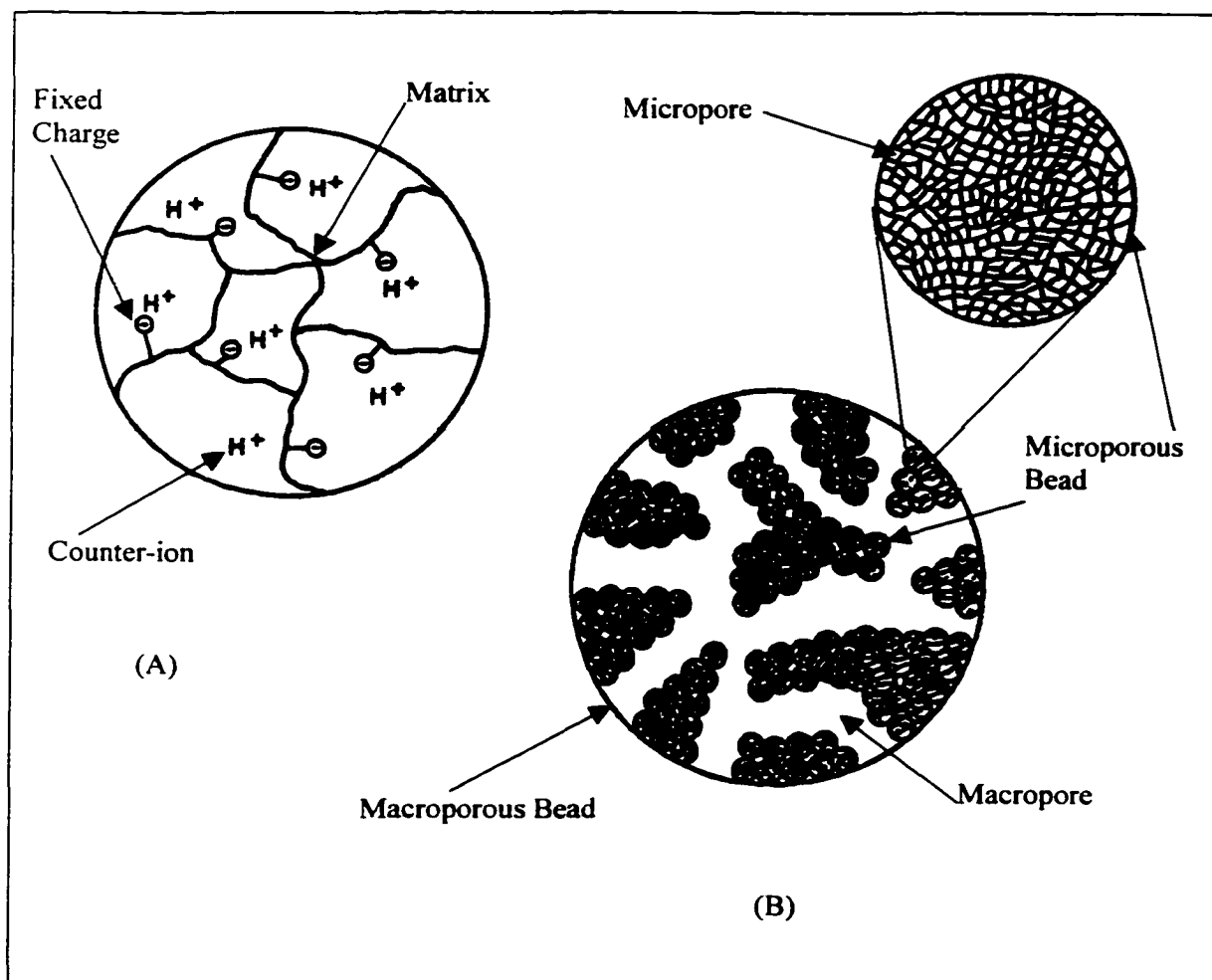


Figure 2.15 Schematic illustration of (A) gel-type cationic exchange resin containing mobile H^+ counter-ions and (B) macroporous ion exchange resin (Source: Modified from Helfferich and Hwang, 1988).

2.2.1.5 Functional Groups of Some Strong- And Weak-Base Anionic Exchange Resins.

Figure 2.16 shows the structure of styrenic type I resin. It is a strong-base anionic exchange resin in the chloride form with a trimethyl quaternary amine functional

group. In contrast, Figure 2.17 shows a structure of a polyacrylic resin, Macro T, with trimethyl quaternary amine as functional group. Macro T is a strong-base anionic exchange resin and it is in the chloride form.

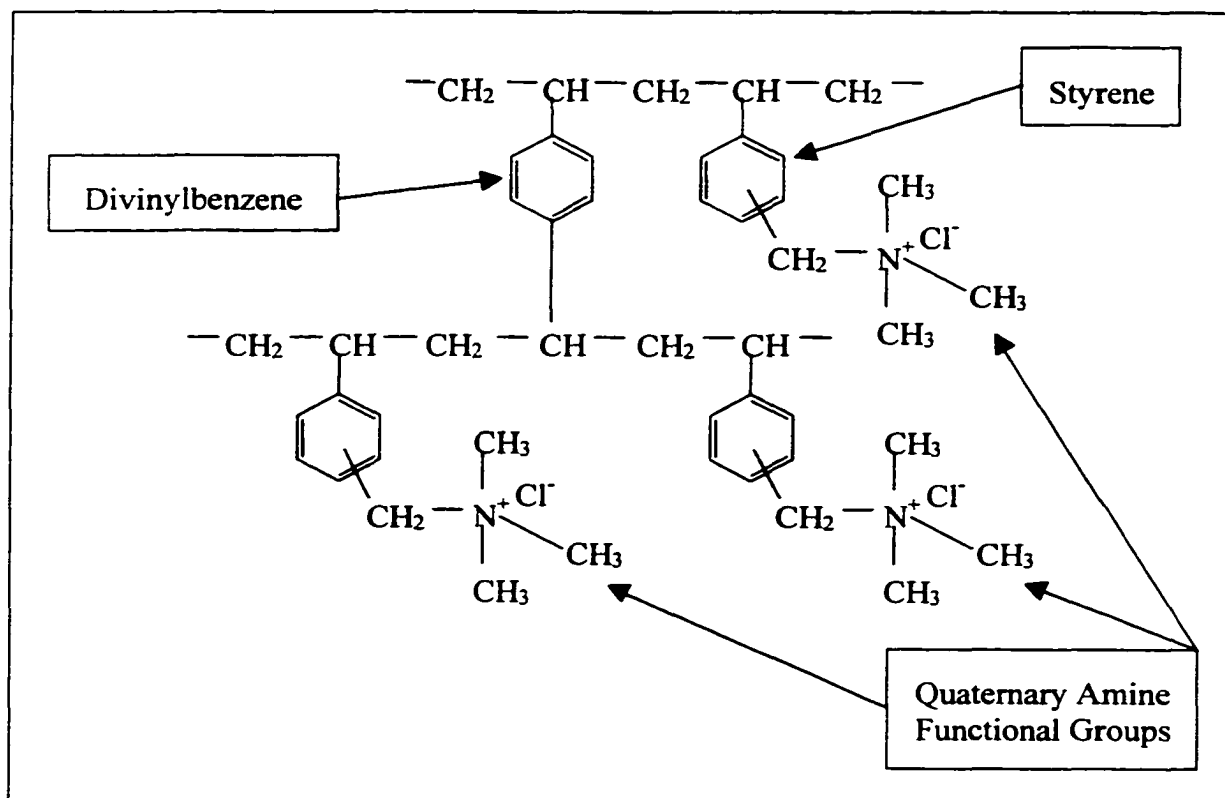


Figure 2.16 ASB1 – strong-base anionic exchange resin, polystyrene, trimethyl quaternary amine in the chloride form (Source: Modified from Tripp and Clifford, 2000).

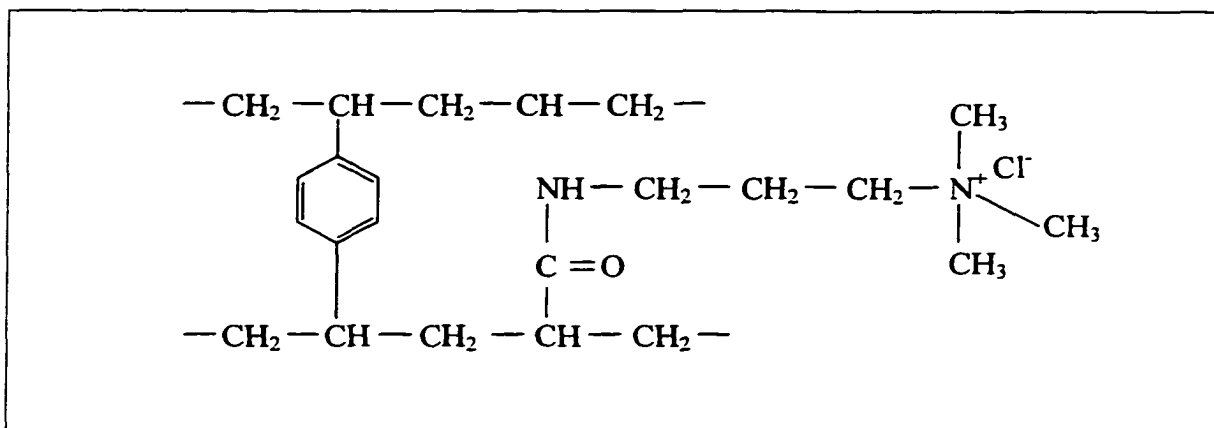


Figure 2.17 Macro T – strong base anionic exchange resin, polyacrylic, trimethyl quaternary amine in the chloride form (Source: Modified from Tripp and Clifford, 2000).

Figure 2.18 shows the different quaternary amine functional groups used to form strong-base anionic exchange resins: (A) trimethyl, used in ASB1, ASB1 PC, and Macro T, (B) dimethylethanol, used in ASB2 and (C) tripropyl, used in SR-7.

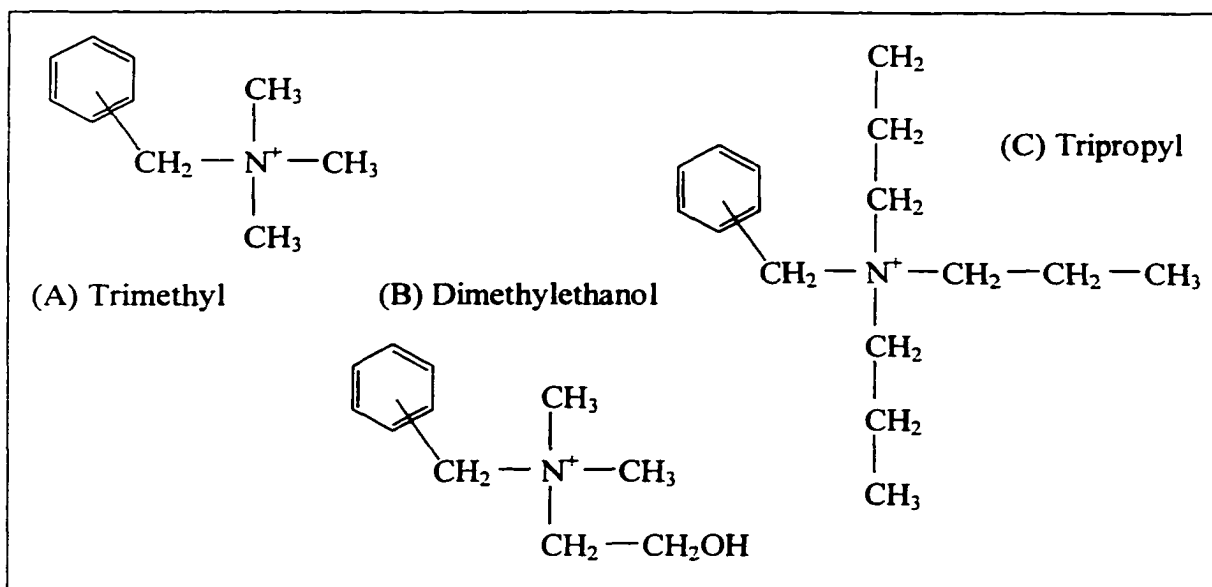


Figure 2.18 Structure of three different quaternary amine functional group of interest. (A) Trimethyl used in ASB1, ASB1 PC, and Macro T, (B) Dimethylethanol, used in ASB2 and (C) Tripropyl, used in SR-7 (Source: Modified from Tripp and Clifford, 2000).

2.2.1.6 Regeneration of Weak- And Strong-Base Anionic Exchange Resins.

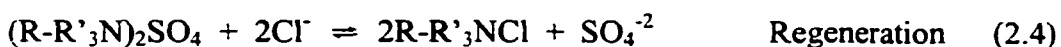
The exchangeable counter-ions for a basic anion resin may be chloride, hydroxide, or other monovalent anion. When these counter-ions have been exchanged to a certain degree that is usually denominated breakthrough, the regeneration of the ion exchange material is required to reestablish its exchange capacity. It is important to note that regeneration is an operational factor. Theoretically all resins could be 100% regenerated, but high amounts of the regenerant solution would be required. Therefore, a cost effectiveness balance for the regeneration process should be determined for each situation. The regeneration process is performed with a strong (approximately 2-12% by weight) solution of the exchangeable counter-ion. Reactions 2.1 to 2.8 show the regenerant equations for strong- and weak-base anionic exchange resins (Weber, 1972).

(A) Strong-base anionic exchange resin

(a) Resin in the hydroxide form is regenerated with NaOH as follow:

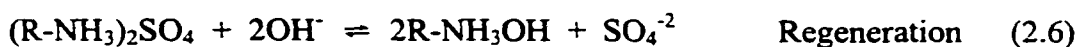
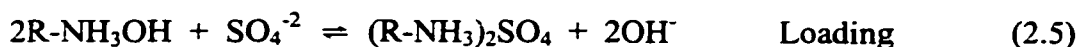


(b) Resin in the chloride form is regenerated with NaCl or HCl as follow:

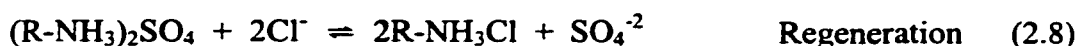
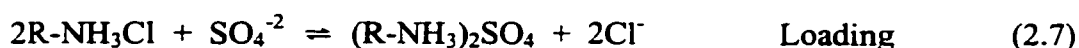


(B) Weak-base anionic exchange resin

(a) Resin in the free base or in the hydroxide form is regenerated with NaOH, NH₄OH or Na₂CO₃ as follow:



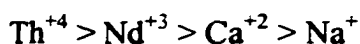
(b) Resin in the chloride form is regenerated with NaCl or HCl as follow:



2.2.1.7 Ion Selectivity

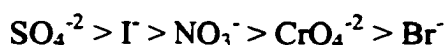
It is important for water treatment purposes to determine the preference of an ion exchange for specific ions within classes of similar charge. The selectivity of the resin has great influence in the determination of equilibrium conditions for a specific ion. Kunin in 1958 predicted that it may be possible to synthesize a resin incorporating particularly high selectivity for certain ions and nowadays this is a common practice. Generally speaking, the ionic charge and the ionic size are the factors influencing the selectivity of a functional group resin for the exchange of ions. Basically, counter ions of high valence are preferred by an exchange resin. Therefore, an order of preference is expected for ions of interest to water treatment as follows:





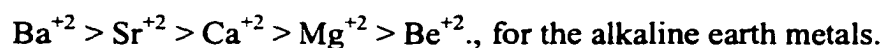
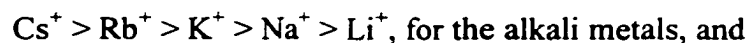
Therefore, phosphate is preferred over sulfate, and sulfate is preferred over chloride. In the second series, the ions on the left are preferred over the ones on the right.

This is not a completely definitive rule. When the solution to be treated has high concentrations (usually more than 3 moles/L) of a specific ion, it is possible that an exchange resin will have a greater affinity for ions of lower charge but of higher exchange potential and the following exchange order can occur (Weber, 1972):

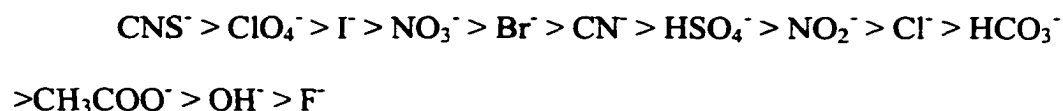


The left-most ion is preferred over the ones to its right. Thus, sulfate is preferred over iodine that is preferred over nitrate and so on.

A second factor that influences the selectivity of an exchange reaction is the hydrated radius of the ion. In a solution, the resin holds more tightly the ion with the smallest radius in a group of ions of equal charge. In general, the hydrated radius is inversely proportional to the unhydrated ionic radius. Therefore, with the increase in atomic number and ionic radius and with the decrease in hydrated radius the preference for the ion will increase in the following order (Weber, 1972):



In the above sequence, the most left ion is preferred over the ones on its right. For anions, the preference is as follows:



Thus, perchlorate would be more preferred over nitrate and chloride by the same resin (Weber, 1972).

2.2.1.8 Perchlorate Removal by Ion Exchange

An optimum performance of an ion exchange resin for perchlorate removal, includes finding an ion exchange resin that can selectively remove perchlorate and at the same time limit the unnecessary removal of other ions that are typically present in higher concentrations than perchlorate (e.g. chloride, sulfate, nitrate, bicarbonate). Further treatment of the brine may be needed to attenuate its toxicity or decrease its volume before disposal, since ion exchange process produces perchlorate-rich waste brines (EPA, 1998).

Resin exchange equilibrium kinetics is a very important factor to be considered. It does not matter how high the selectivity of the resin is for perchlorate, if the rate of exchange is too slow, the resin will not be effective. This can be illustrated based on the experiment performed by Tripp and Clifford (2000). They found a very high separation

factor ($>1,500$) for the polystyrene tripropyl quaternary amine resin (Sybron SR-7) but this resin did not reach equilibrium even after seven days of mixing in batch test.

In August 1998, the Environmental Engineering Laboratory (EEL) of the University of Nevada Las Vegas (UNLV) started investigations on the use of ion exchange resins to remove perchlorate from waters. Three months earlier, the EEL-UNLV already implemented an analytical method to measure perchlorate concentrations at low levels (i.e. $4\text{ }\mu\text{g/L}$) using ion chromatograph. The work performed by the EEL-UNLV is the subject of this thesis and will be discussed in detail in the next chapters.

At the end of 1998, Calgon Carbon Corporation announced the successful finalization of field trials for perchlorate removal in the groundwater of San Gabriel Valley, California, utilizing a system denominated ISEP® that is a continuous ion exchange system. The groundwater at this site was treated by ion exchange process on an ongoing continuous basis and the perchlorate concentration was reduced from $75\text{ }\mu\text{g/L}$ to below the action level of $18\text{ }\mu\text{g/L}$. The field trial lasted for an entire month (Calgon Carbon Announces, 1998). These results were demonstrated by bench- and pilot-scale studies. In addition, the studies have provided useful information on (a) resin selection and regeneration, (b) brine production, and (c) cost (EPA, 1999). This information is vital to the design and operation and, to the determination of the cost-effectiveness of full scale ion exchange treatment processes.

In 1999, the first commercial ISEP® system to remove perchlorate was installed to treat water from three wells in La Puente Valley Water District, located in Southern California. At this site, perchlorate is being reduced from $200\text{ }\mu\text{g/L}$ to less than $5\text{ }\mu\text{g/L}$. The system is capable of treating approximately 2,500 gpm (gallons of water per

minute). This system is the first commercial application of a technology to remove perchlorate from drinking water in the world. (Calgon Carbon Announces, 1999). At the beginning of 2000, the California Department of Health Services gave the approval for the use of the ISEP[®] ion exchange system and it became the first system for perchlorate removal that has received this ratification (Calgon Carbon Announces, 2000). On January 7, 2000, Calgon Corporation installed a 350 gpm ion exchange resin system in Las Vegas to treat perchlorate-contaminated water from the Kerr McGee site. The plant influent averages 90 mg/L and effluent discharge averages 1-5 mg/L. Unfortunately, a complete review and evaluation of Calgon Carbon's data is not possible, since their publications omitted important design parameters due to corporate confidentiality.

Tripp and Clifford (2000) have calculated separation factors for various strong base resins at three different temperatures. They believe the successful application of ion exchange processes requires basic information associated with the selectivity of perchlorate relative to the common anions found in natural waters. The resins tested by Tripp and Clifford include polystyrene, polyacrylic, and polyvinylpyridine with several functional groups (e.g. trimethylamine, dimethylethanolamine, methylpyridine, and trialkylamine). Table 2.8 shows the perchlorate-chloride separation factor considering the effects of different resin characteristics. Separation factor is the most appropriate quantity to characterize resin selectivity. Selectivity is defined as the preference of one counterion over another. Mathematically, separation factor is defined as the concentration ration of the exchanging counterions 'X' and 'Y' in the ion exchanger divided by that ratio in solution.

$$\alpha_{XY} = (CR_X/CR_Y) / (C_X/C_Y), \text{ where:}$$

CR_X : concentration of ion 'X' in the ion exchanger;

CR_Y : concentration of ion 'Y' in the ion exchanger;

C_X : concentration of ion 'X' in solution;

C_Y : concentration of ion 'Y' in solution;

For $\alpha_{XY} > 1$, ion 'X' is preferred over ion 'Y'; in the other hand for $\alpha_{XY} < 1$, ion 'Y' is preferred over ion 'X'.

Table 2.8 The result of diverse resin characteristics on perchlorate (ClO_4^-) separation factor, in relation to chloride (Cl^-)		
Characteristic	Resin	Separation Factor
Cross-Linking	IRA-400	125
Cross-Linking	IRA-402	100
Matrix	Polyvinylpyridine	275
Matrix	Polystyrene	125
Matrix	Polyacrylic	6
Functional Group	Trimethyl	125
Functional Group	Triethyl	>1000
Functional Group	Tripropyl	>1500
Source: Tripp and Clifford, 2000.		

The data in Table 2.8 show the percent cross-linking did not affect selectivity of perchlorate significantly. It also shows that the highest separation factor for perchlorate, when observing the resin's matrix is achieved for polyvinylpyridine. Other observation

that can be made from the table is that the separation coefficient increased with increasing length of the functional group carbon chains.

In addition, Tripp and Clifford investigated the effect of temperature on the equilibrium constant (separation factor). Tests were performed at temperatures of 20°, 40° and 60°C. Approximate 30% decreases in separation factors were observed for the 20°-40°C and the 40°-60°C temperature changes. These results indicate that the ion exchange reaction is exothermic and as temperature increases, the separation factor decreases. In consequence, the warmer the temperature, the lower the separation factor, the shorter the run length before saturation and the smaller volume of solution needed for regeneration. In order to maximize the efficiency of the process, the loading phase should be at cool temperatures and the regeneration process at warmer temperatures (Tripp and Clifford, 2000).

In another study using a polystyrene divinylbenzene type II, strong base anion-exchange resin with dimethylethanolamine quaternary nitrogen functional groups, Tripp and Clifford were able to demonstrate repeatable run lengths of almost 1000 bed volumes (BV). The regeneration for this type of resin required large amounts of NaCl, and it generated high operating costs for chemicals and regenerant disposal (Tripp and Clifford, 1999). Focusing on the amount of salt used for regeneration, the researchers tried to regenerate the spent resins at elevated (60°C) temperature. The amount of salt required during regeneration was significantly decreased by the increase in temperature. As result, the regeneration was more efficient using smaller amounts of salt and generating smaller volumes of regenerant for disposal (Tripp and Clifford, 1999). It is

important to notice that for the second resin exhaustion, the number of bed volumes run before breakthrough was far smaller than in the first exhaustion.

The use of high selective anion exchange resins for the treatment of perchlorate-contaminated groundwater was investigated by Gu *et. al.* (1999). The resin in question is a bi-functional high selective anion exchange resin and was developed by the Oak Ridge National Laboratory (ORNL). The resin is technically called RO-02-119 and the bi-functional group is trihexylamine/triethylamine. It has selective exchange for large poorly hydrated anions such as perchlorate. The choice of this functional group was based on results of experiments for K_d values (i.e. measures the selectivity of resins) for perchlorate sorption as a function of the length of the hydrocarbon chain (size of the alkyl groups). In a 24-h experiment, the results indicated that the K_d values increased in the series of methyl < ethyl < propyl and the bi-functional group trihexylamine/triethylamine would be the most selective for perchlorate (Brown *et. al.*, 1999). In the bi-functional resin, the triethylamine group has the objective of improving the exchange kinetics while the trihexylamine is required for selectivity purposes. Table 2.9 shows the results of the distribution coefficients (K_d) for two bi-functional resins (RO-02-119 and Purolite D-3696) and two commercial resins (Purolite A-520E and Sybron SR-6). The Purolite D-3696 is a commercial scale-up version of the laboratory synthesized bi-functional resin RO-02-119.

Table 2.9 Distribution coefficients (K_d) as a functional of time and different resins.			
Resin	1 h K_d (mL/g)	24 h K_d (mL/g)	168 h K_d (mL/g)
RO-02-119	285,000	> 3,300,000	> 3,300,000
Purolite D-3696	164,800	1,877,000	1,842,000
Purolite A-520E	97,000	203,000	217,000
Sybron SR-6	65,400	250,000	282,000
Source: Brown et. al., 1999			

Laboratory and in-situ field experiments completed with the bi-functional resin Purolite D-3696 and the commercial resin Purolite A-520E showed that the former performed approximately five times better when treating simulated and actual groundwater (Brown *et. al.*, 1999). In addition, the researchers stated that when the high selective bi-functional resin was used, no pretreatment or removal of undesired organic or inorganic components in the groundwater were needed. The laboratory experiments were performed in glass columns (10x40 mm) with a flow rate of 30 ml/min (approximately 10 bed volumes per minute). The perchlorate initial concentration was 1.1 mg/L and the background anion concentration (composed of HCO_3^- , NO_3^- , Cl^- and SO_4^{2-}) was about 3 to 4 times higher than the perchlorate concentration. After about 5000 bed volumes, an 8% breakthrough ($C/C_0 = 0.08$) was observed for the commercial resins (Purolite A-520E and Sybron SR-6) and only a 0.5% breakthrough was observed for the laboratory bi-functional resin (RO-02-119). The small-scale field trials were performed with two glass columns (25x102 mm) in series with an average flow rate of 200 mL/min (about 2 bed volumes per minute). The groundwater contained about 50 $\mu\text{g/L}$ perchlorate. At 10% breakthrough (effluent concentration equals to 5 $\mu\text{g/L}$ perchlorate), the bi-functional resin Purolite D-3696 could treat up to 110,000 bed

volumes while the commercial Purolite A-520E resin could treat only about 24,000 bed volumes of the groundwater under the same circumstances (Brown *et. al.*, 1999).

CHAPTER 3

EXPERIMENTAL METHODS AND MATERIALS

3.1 Types of Ion Exchange Resins Used

In this investigation, several types of strong- and weak-base anionic exchange resins were tested for their potential to remove perchlorate from synthetic perchlorate solutions and from natural waters contaminated with perchlorate. Sybron Chemicals and Purolite provided the resin samples used in all experiments. Table 3.1 shows the characteristics of the resins used.

3.2 Resin Preservation

All resins were stored in deionized water to avoid drying and breakage of the resin beads.

3.3 Reagents And Solutions

Reagents used included:

- Sodium perchlorate (NaClO_4) 99% purity, A.C.S. reagent, Aldrich Chemical Company, Inc.
- Sodium chloride (NaCl), crystals, reagent, A.C.S., 99% purity, VWR Scientific.

Table 3.1: Resins used in the research.

Commercial name	Type	Matrix	Functional Group	Total exchange capacity eq/L (minimum)	Anion Form.	Manufacturer
AFP 329	Weak-base anionic	Styrene-DVB macroporous	Tertiary amine	1.6 eq/L 1.35 eq/L (weak-base capacity)	Free Base	Sybron Chemicals
A 830	Weak-base anionic	Polyacrylic	Tertiary amine	2.7 eq/L	Free Base	Purolite
A-365	Weak-base anionic	Acrylic gel	Tertiary amine	3.5 eq/L	Free Base	Sybron Chemicals
XR 405	Weak-base anionic	Styrene-DVB	Tertiary amine	2.0 eq/L	Free Base	Sybron Chemicals
ASB1	Type 1 – strong-base anionic	Styrene-DVB gel	Quaternary trimethyl amine	1.4 eq/L	Cl ⁻	Sybron Chemicals
ASB2	Type 2 – strong-base anionic	Styrene-DVB gel	Dimethylethanol amine	1.4 eq/L	Cl ⁻	Sybron Chemicals
SR-7	Strong-base anionic	Styrene-DVB	Quaternary tripropyl amine	0.8 eq/L	Cl ⁻	Sybron Chemicals
Macro-T	Strong-base anionic	Polyacrylic macro porous	Quaternary trimethyl amine	1.1 eq/L	Cl ⁻	Sybron Chemicals
A 850	Strong-base anionic	Polyacrylic	Quaternary amine	1.25 eq/L	Cl ⁻	Purolite
ASB1 PC	Type 1 – strong-base anionic	Styrene-DVB gel	Quaternary trimethyl amine	1.2 eq/L	Cl ⁻	Sybron Chemicals

- Ammonium hydroxide ($\text{NH}_4(\text{OH})$), 27% solution, Mallinckrodt N.F
- Organic Carbon Standard, 1000 mg/L, Ricca Chemical Company
- Sodium hydroxide ($\text{Na}(\text{OH})$), pellets, reagent, assay minimum 97%, VWR Scientific
- Compressed carbon dioxide, Praxair
- 50% sodium hydroxide solution ($\text{Na}(\text{OH})$ 50% w/w), Fisher Scientific
- Potassium sulfate (K_2SO_4), 99% purity, EM Science
- Sodium nitrate ($\text{Na}(\text{NO}_3)$), A.C.S. grade VWR Scientific
- IC nitrate standard, Ricca Chemical Company
- IC sulfate standard, Ricca Chemical Company
- Perchlorate contaminated water from the Las Vegas Valley
- Buffer solution pH 7.00 ± 0.01 , Fisher Scientific
- Buffer solution pH 10.00 ± 0.02 , Fisher Scientific
- Sodium bicarbonate, NaHCO_3 , 99.7% purity, EM Science

Sodium perchlorate stock solution (1000 mg/L) was prepared monthly and kept refrigerated. This solution was used to prepare standards for the ion chromatograph (IC). IC standards were prepared weekly and kept refrigerated. The synthetic perchlorate solution to feed the columns was prepared from an 80 g/L stock solution. This solution was prepared bi-monthly and kept refrigerated. Regenerant solutions (NaCl , NaOH , NH_4OH) were prepared on the same day they were used. All chemicals used to prepare solutions were weighed using a calibrated analytical balance (Sargent Welch, TLA 100).

3.4 Empty Bed Contact Time for Loading and Regeneration of The Resins

Empty bed contact time (EBCT) is defined as the volume of the resin bed (volume occupied by the resin including the voids) divided by the flow rate of the feed solution.

$$EBCT = V/Q \quad (1)$$

Where Q is the flow rate in mL/min, V is the volume of the resin bed in mL, and EBCT in minutes.

The EBCT's for resin loading varied from 4.5 to 7 minutes. Regeneration was performed at longer EBCT's varying from 8 to 10 minutes.

3.5 Column Utilization

Column utilization to breakthrough is defined as the amount of contaminant that exchanged with the resins from time zero to the time immediately before breakthrough divided by the theoretical amount of contaminant that would exchange with the resin and given by the resin exchange capacity (Manufacturer information). This value is given as a percentage. Total column utilization is the total amount of contaminant that exchanged with the resin divided by the theoretical amount of contaminant that would exchange with the resin and given by the resin exchange capacity (Manufacturer information). This value is also given as a percentage.

3.6 Experimental Set Up for Column Testing of The Resins

The tests were performed using fixed-bed column experiments. Fixed-bed glass columns (15 to 25.4 mm ID) with bed height of approximately one foot were used. The resins were supported by sequential layers (from bottom to top) of coarse ceramic chips, glass beads, and cotton. Synthetic and natural perchlorate-containing feed solutions were placed in 20 L polyethylene bottles. Peristaltic pumps (Cole Parmer Instrument Company, model number 7553-80) equipped with flow rate controllers were used to feed and regenerate the columns. Masterflex® Tygon tubing (#6409-16) was used to feed the solutions to the columns. Synthetic sodium perchlorate and natural perchlorate-containing solutions were fed to the columns in a downflow mode. The pH of the synthetic solution used ranged from 5.8 to 7.0 while the pH of the natural perchlorate-containing solutions ranged from 7.44 to 8.28 (Please see Table 4.4.1). The effluents from the columns were collected, at pre-determined time intervals and analyzed for perchlorate, other anions of interest, and pH. Perchlorate analyses were performed using a Dionex-120 ion chromatograph. Regeneration of spent columns was performed in an upflow mode. Bed expansion during regeneration varied from 10-30%. After regeneration, columns were rinsed with 5-10 bed volumes of deionized water prior to reloading of the resin beds. Figure 3.1 and 3.2 show the experimental set-up for perchlorate removal testing by ion exchange.

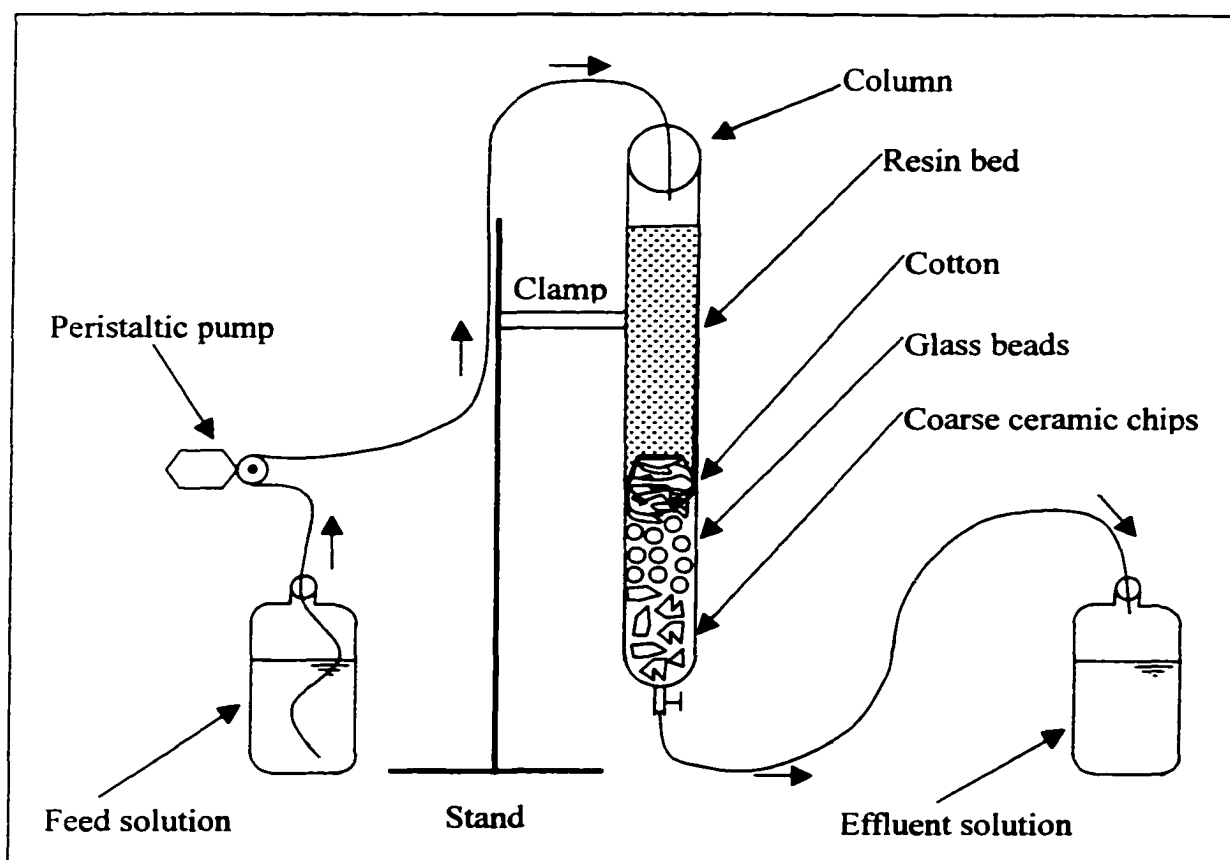


Figure 3.1 Schematic set-up used for testing perchlorate removal by ion-exchange.

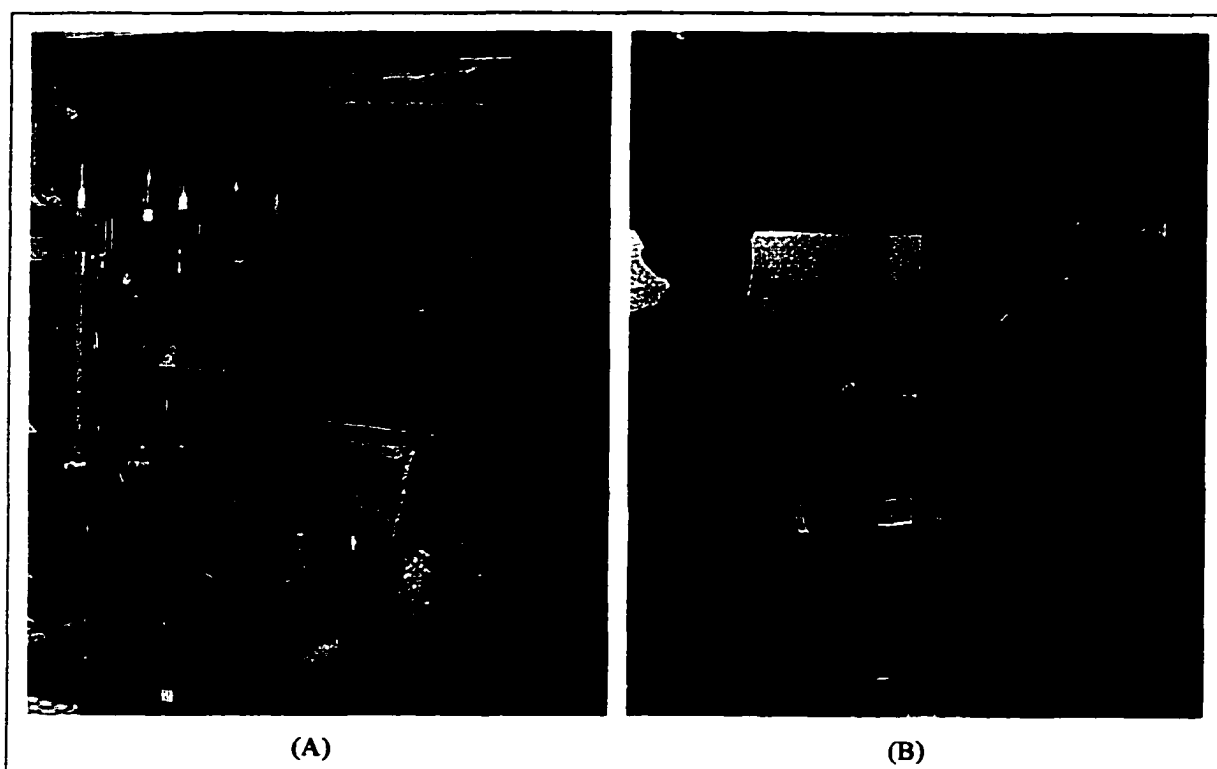


Figure 3.2 Experimental set-up for perchlorate removal testing by ion exchange. (A) Resin loading and (B) upflow resin regeneration.

3.7 Resin Regeneration

Regeneration was performed either with 12% (120 g/L) sodium chloride (NaCl) solution or with caustic solutions (1% ammonium hydroxide $\text{NH}_4(\text{OH})$ or 1% sodium hydroxide (NaOH)).

Regeneration efficiency was calculated by dividing the total amount of perchlorate recovered in the regeneration process by the total perchlorate exchanged with the resins in the loading process. This value was multiplied by 100 to give a result as a percentage. The amount of perchlorate recovered during regeneration was calculated by measuring the perchlorate concentrations in samples collected during regeneration and

multiplying that amount by the volume of the samples. In addition, the concentration of perchlorate in the combined volume of the spent regeneration solution was measured. The total mass of perchlorate recovered was obtained by adding the mass of perchlorate in the samples with the mass of perchlorate in the spent regeneration solution. The total amount of perchlorate exchanged with the resins in the loading process was calculated by multiplying the volume of solution used until half resin exhaustion was reached by the perchlorate concentration in the feed solution. Illustrations of such calculations are shown on Appendix C.

3.8 Major Pieces of Equipment Used

- Dionex 120 ion chromatograph with AS40 automated sampler
- Shimadzu TOC-5000A Total Organic Carbon Analyzer with ASI-5000A autosampler
- Fisher Scientific AR10 pH meter
- Sargent Welch TLA 100 (0.1 mg resolution), analytical balance

3.9 Ion Chromatograph Analytical Procedure and Calibration for Perchlorate and Anion Analyses

The analytical procedure used for perchlorate analysis follows the procedure developed by the California Department of Health Services (CDHS) and the Dionex Company (California Department of Health Services, 1997; Dionex, 1997). A copy of the CDHS procedure is shown in Appendix A. A slight modification was made to accommodate the use of the Dionex 120 machine instead of the Dionex 500 machine, for

which the procedure was developed. The modification consists of using 49 mM sodium hydroxide (NaOH) as the eluent instead of using the 100 mM eluent as originally recommended in the procedure. The separation and guard columns used were Dionex AS11-4mm and AG11-4mm with 1000 μ L injection loop.

A calibration procedure for perchlorate analysis was developed. The procedure consists of two deionized water samples; calibration standards of 5, 10, 15, 30, 60, 80, and 100 μ g/L; two deionized water samples before measurements begin. After the calibration is completed a R^2 (from least square analysis) of at least 0.997 is required. A quality control (QC) standard is run after every twenty samples. A QC is a sample prepared by a member of the research team, different from the person who prepared the calibration standards. A similar procedure was used for sulfate and nitrate analysis, except that the eluent solution was 5 mM NaOH, the injection loop was 25 μ L, and the standards for the calibration curve were 15, 30, 50, 100, 300, 500, and 1000 μ L.

3.10 Total Organic Carbon (TOC) Analyzer Procedure and Calibration Standards

The TOC analyzer was calibrated every time before use. Calibration was performed using standards containing 1, 5, 30 and 100 mg/L of carbon. The low sensitivity-high range catalyst was used and ultra-pure air (Praxair, compressed air, hydrogen free HCF) was the carrier and sparging gas.

3.11 Quality Assurance(QA) and Quality Control (QC)

The majority of the column tests were performed in duplicate. The analytical balance was calibrated by independent contractor every six months. Pipettes were calibrated gravimetrically monthly.

The ion chromatograph was calibrated daily as per procedure described in section 3.8. When the established R^2 was not met, new standards were prepared and calibration was repeated.

TOC analyses were performed in triplicate and the maximum acceptable coefficient of variance among sample readings was 2%.

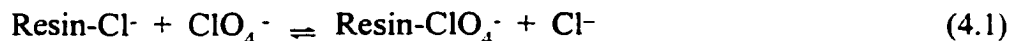
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Potential Perchlorate Removal Systems Combining Ion Exchange Resins and Biodegradation

When the perchlorate anion (ClO_4^-) was discovered in groundwater, an instantaneous connection was made to using strong-base anionic exchange resins for its removal, since these resins have been extensively investigated for the removal of other anions (e.g. nitrate (NO_3^-), arsenate (HAsO_4^{2-}), etc) from waters. Strong-base anionic exchange resins have proven to be very effective in removing perchlorate from waters to very low levels (Batista *et al.*, 1999; Clifford and Tripp, 1999; Montgomery and Watson, 1999; Calgon Carbon Corporation, 1999). While strong-base anionic resins have been intensively studied for their capacity to remove perchlorate from waters, there are no reports of the use of weak-base anionic resins for this purpose. In this thesis, both weak- and strong-base anionic exchange resins have been investigated for their potential to remove perchlorate from contaminated waters.

The removal of perchlorate from waters by strong-base anionic exchange resins (in the chloride form) can be described by the following reactions:



When the breakthrough point, the point at which a specific amount of the influent is detected in the effluent (in this thesis, the breakthrough point equals 20 µg/L) is reached the resin can potentially be regenerated with sodium chloride (NaCl) according to the reaction below.



In the regeneration process, NaCl is used in excess; thus the regenerant solution is very saline and contains high concentrations of perchlorate. It is important to note that ion exchange is only a separation process and does not eliminate perchlorate from the environment. Any potential technology to remove perchlorate, based on separation, will have to address the final disposal of highly concentrated perchlorate solutions. Biodegradation has been thought as a strong candidate technology to treat regenerant brines from ion-exchange systems that remove perchlorate from waters. Perchlorate is readily biodegradable as it can be reduced by microorganisms under anaerobic conditions to chloride, an innocuous anion.

Figure 4.1.1 shows a schematic representation of a potential system that would use strong-base anionic exchange resins as the separation technology and biodegradation as the choice to treat the regenerant brine. In this case, the challenge is to isolate microorganisms that are capable of tolerating high concentrations of salt (halophiles). Regenerant solutions from such systems would have sodium chloride (NaCl) concentrations varying from 6-12%. Most microorganisms cannot tolerate salt

concentrations greater than 3%. However, it may be possible to isolate and acclimate perchlorate degraders that are tolerant of such conditions.

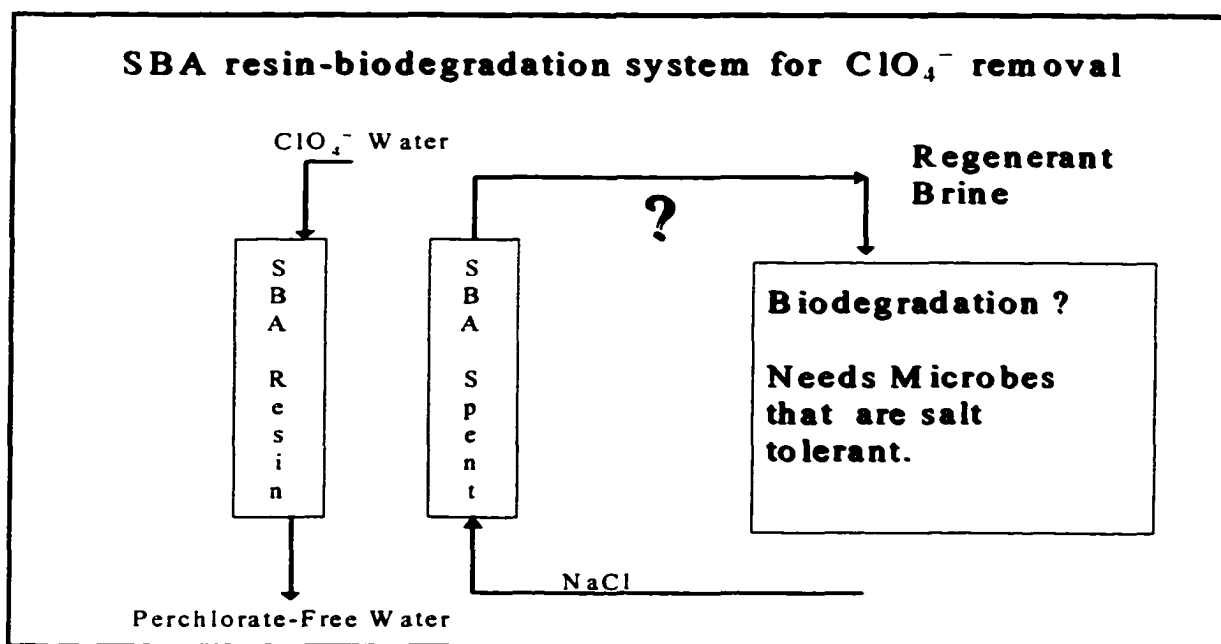
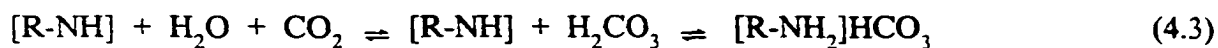


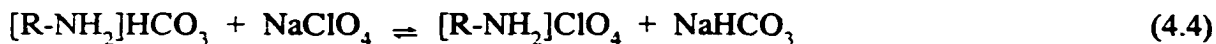
Figure 4.1.1 Potential combination of strong-base anionic exchange resin and biodegradation to remove perchlorate from waters. The regenerant brine is very saline and biodegradation may not be possible, unless salt tolerant microbes capable of perchlorate biodegradation are isolated.

Instigated by the work performed by McGarvey (1964) and Kunin et al. (1964) on deionization of waters, this thesis explored the feasibility of using weak-base anionic exchange resins to remove perchlorate from waters. The process involves converting the resin to the bicarbonate form, by passing a carbon dioxide containing solution through the resin, prior to the loading of perchlorate. It is hypothesized that the following steps are needed to remove perchlorate from waters using a weak-base anion-exchange resin:

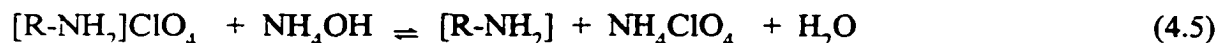
Carbonation step:



Perchlorate Exchange step:



Regeneration step:



Carbonation can be performed in two ways: (a) by directly adding compressed carbon dioxide (CO_2) to the perchlorate-containing water before passing it through the resin bed, (b) by generating CO_2 from the reaction of sodium bicarbonate (NaHCO_3) solution with strong-acid cationic exchange resin (SACX). In this case, a bed of SACX resin is added before the weak-base resin bed.

Figure 4.1.2 schematically shows a potential perchlorate removal system using weak-base anionic exchange resins. The major advantage associated with using weak-base anionic resins (WBAX) for perchlorate removal is that the perchlorate-laden WBAX resin can be regenerated using caustic solutions (ammonium hydroxide (NH_4OH) or sodium hydroxide (NaOH)) or NaCl . Contrary to NaCl , ammonium hydroxide can be used by microbes as a nutrient and biodegradation of the regenerant brine would then be feasible and facilitated. The high pH of the ammonium hydroxide regenerant solution can be easily adjusted to values acceptable to biodegradation by acid addition.

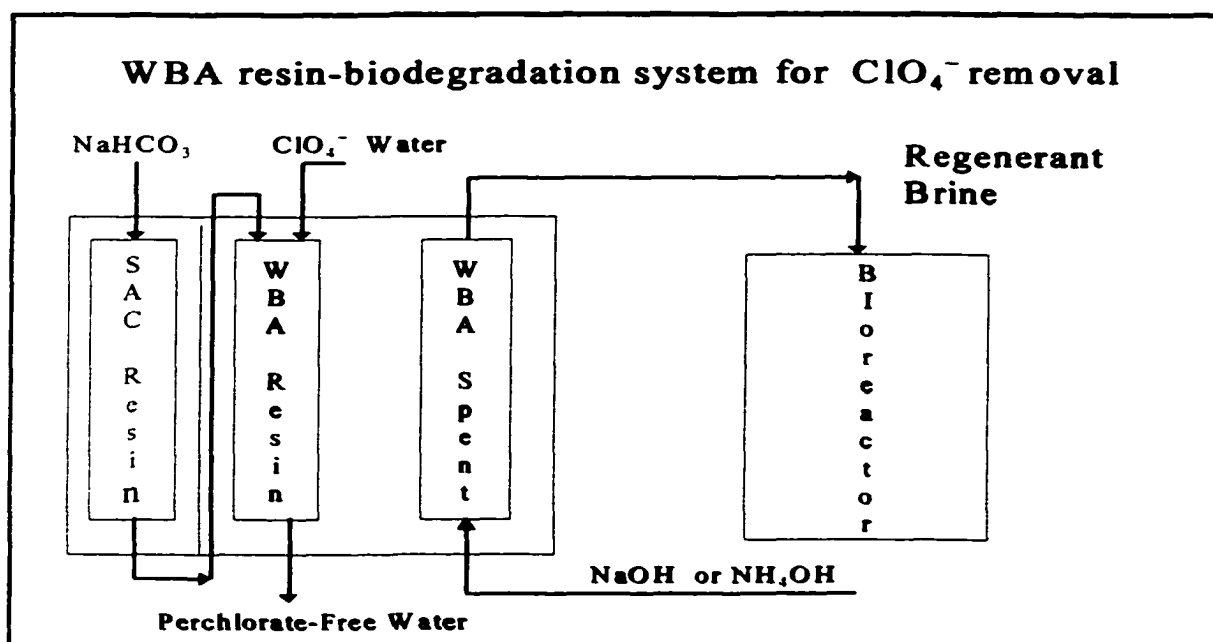


Figure 4.1.2 Potential combination of weak-anion exchange resin and biodegradation to remove perchlorate from waters. When caustic solutions such as NH_4OH or NaOH are used, the regenerant solution is not a brine and biodegradation is potentially more favorable.

The results obtained from the testing of weak and strong-base anionic exchange resins are presented in the next section. Notice that all experimental points were connected by a continuous line. However, these continuous lines are not intended to be an exact representation of the breakthrough and regeneration curves for the resins in question. To exactly represent the regeneration and breakthrough curves, experimental data would have to be collected at very short sampling intervals. The curves presented here are meant to give an idea of the behavior of the resin when perchlorate removal takes place.

4.2 Strong Base Anionic Exchange Resins.

4.2.1 ASB1 resin (Styrenic DVB – Quaternary amine, Sybron Chemicals)

Figure 4.2.1 shows the breakthrough curve for a strong base anionic styrenic type I resin (ASB1 – Styrenic DVB) loaded with 40 mg/L perchlorate synthetic solution. The resin was in the chloride form and had a minimum total exchange capacity of 1.4 eq/L. The empty bed contact time (EBCT) for this test averaged 4.9 minutes. The bed volume (BV) was 117.84 cm³. Notice that the column utilization for the synthetic solution was 100% showing that this strong-base styrenic type resins are very efficient for perchlorate removal and about 3500 BV of 40 mg/L perchlorate synthetic solution were processed before breakthrough.

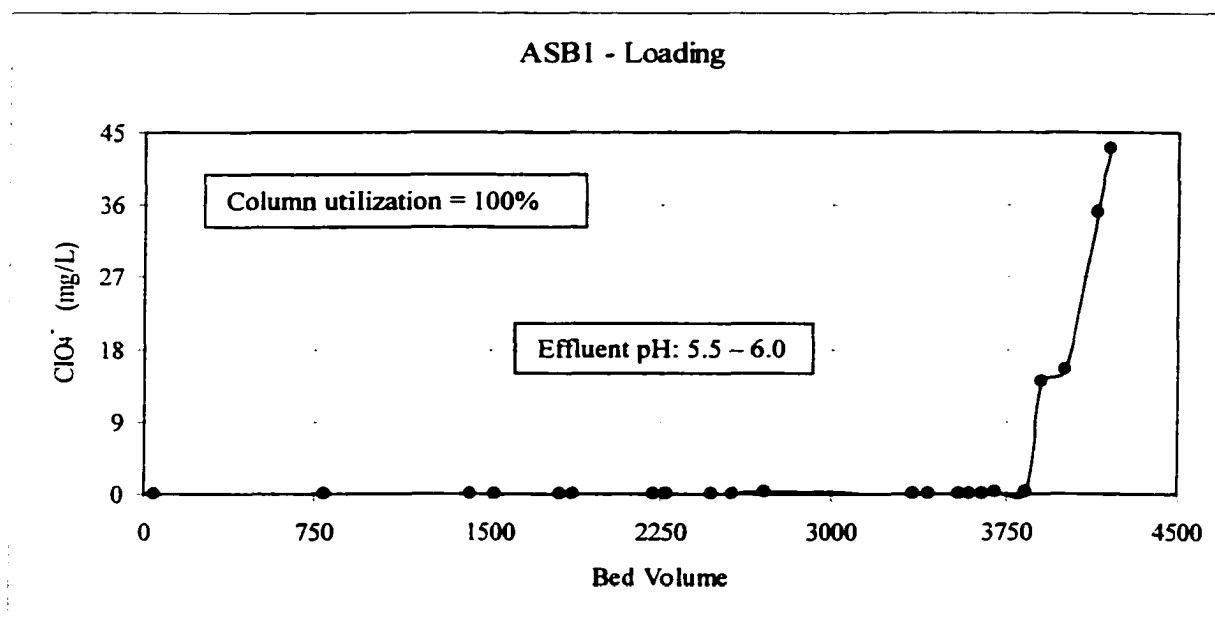


Figure 4.2.1 Exhaustion of ASB1 resin (styrenic DVB – quaternary amine); fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.9 minutes and BV = 117.84 cm³.

The result of the regeneration of the resin bed using 12% NaCl is shown in Figure 4.2.2. Only approximately 37% of the loaded perchlorate was removed during regeneration. This indicates that perchlorate attaches very strongly to this resin.

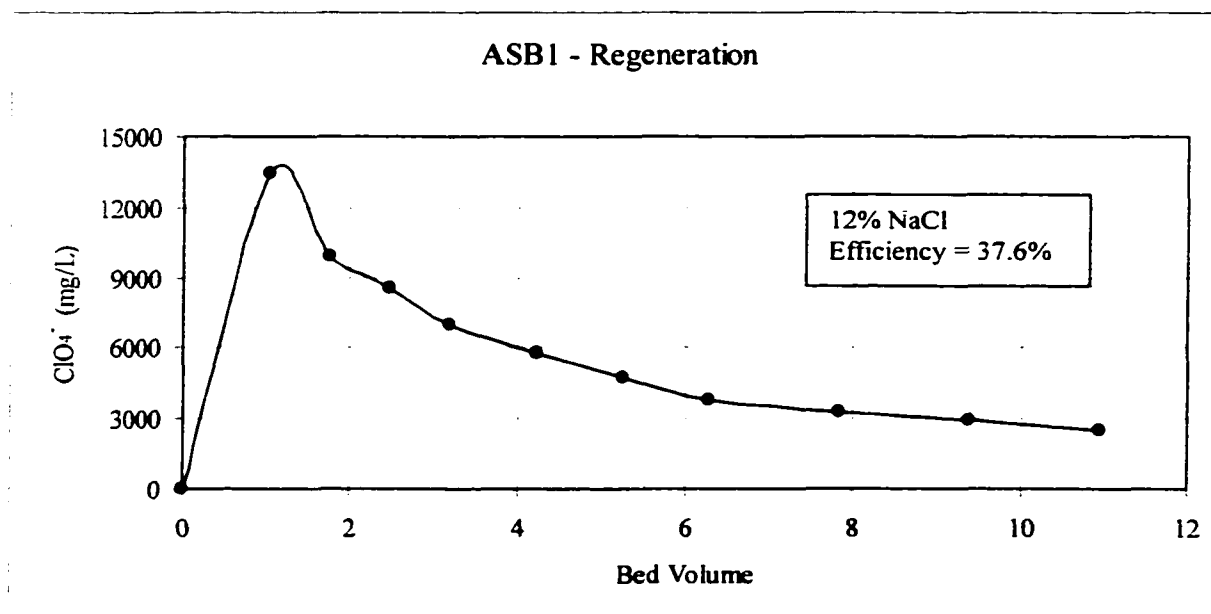


Figure 4.2.2 Regeneration of ASB1 resin (styrenic DVB – quaternary amine) with 12% NaCl, EBCT = 7.8 minutes, and BV = 96.94 cm^3 .

4.2.2 ASB2 resin (Styrenic DVB – Dimethylethanolamine, Sybron Chemicals)

The exhaustion of a strong base styrenic type II resin (ASB2 - Styrenic DVB) with 40 mg/L synthetic perchlorate solution is shown in Figure 4.2.3. The resin bed for this experiment had a volume of 123.54 cm^3 . The EBCT averaged 4.5 minutes. The minimum total exchange capacity for the ASB2 resin as given by its manufacture is 1.4 eq/L. Similar to ASB1, this resin has shown 100% column utilization. The regeneration efficiency of ASB2 resins was found to be slightly higher than for ASB1 type resin. As shown in Figure 4.2.4, the regeneration efficiency for ASB2 was about 43%.

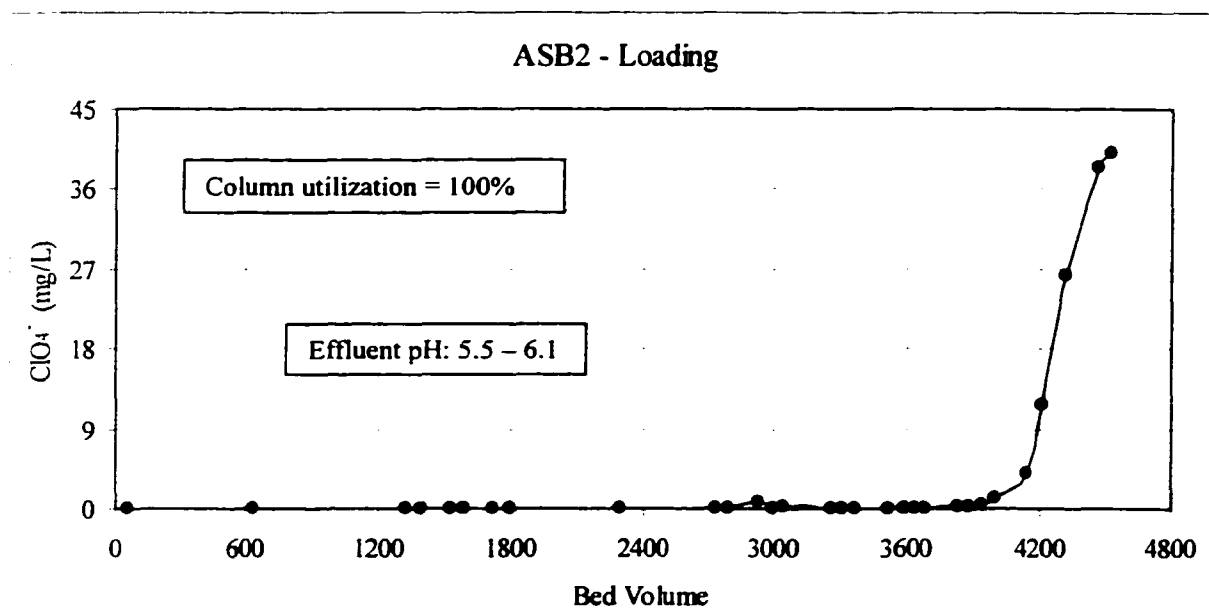


Figure 4.2.3 Exhaustion of ASB2 resin (styrenic DVB – dimethylethanolamine); fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.5 minutes and BV = 123.54 cm³.

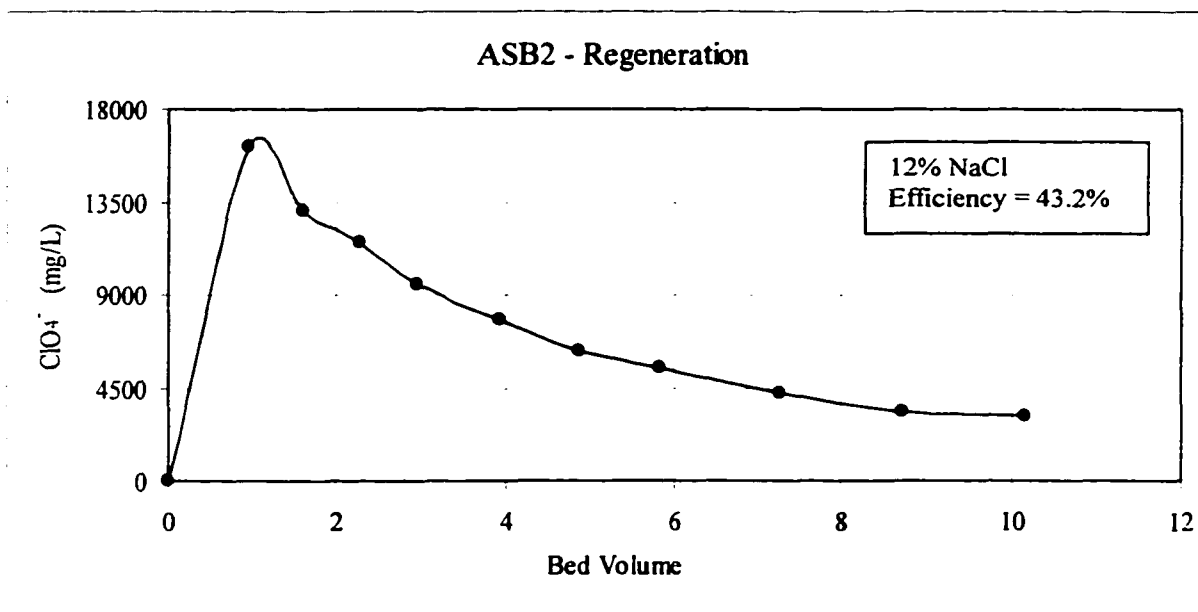


Figure 4.2.4 Regeneration of ASB2 resin (styrenic DVB – dimethylethanolamine) with 12% NaCl, EBCT = 7.6 minutes, and BV = 104.54 cm³.

4.2.3 SR-7 resin (Styrenic – Tripropyl, Sybron Chemicals)

Figures 4.2.5 and 4.2.6 show the exhaustion and regeneration data for another styrenic strong-base resin (SR-7 - Styrenic). In this case, the functional group is tripropyl. SR-7 has exchange capacity equals to 0.8 eq/L. For this resin, column utilization was satisfactory (59% in average) and more than 1165 BV were processed before breakthrough was reached. This test was run in duplicate and both breakthrough curves are plotted in Figure 4.2.5. The column utilizations were practically the same even though the EBCT's were slightly different (4.1 minutes for column 1 and 4.4 minutes for column 2). Regeneration with 12% NaCl was ineffective and only 19.9 % of the loaded perchlorate could be stripped out of the resin.

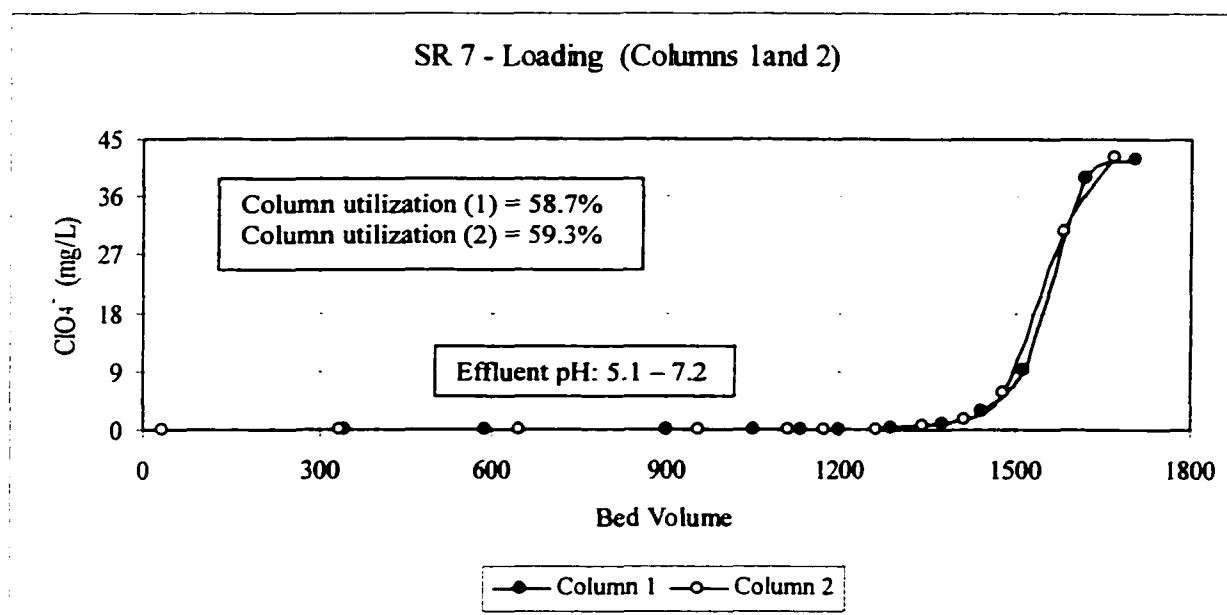


Figure 4.2.5 Exhaustion of SR-7 resin (styrenic – Tripropyl); fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.1 minutes, BV = 57.43 cm³ (column 1), EBCT = 4.4 minutes, and BV = 55.67 cm³ (column 2).

After regeneration, an attempt was made to reload the resin bed, but the column broke through very quickly. This may be attributed to poor stripping of perchlorate from

this resin. In addition, it is suspected that the rinsing cycle after regeneration was not sufficiently long to remove all the excess of NaCl from regeneration. Testing with longer rinsing cycles would be needed to confirm this hypothesis.

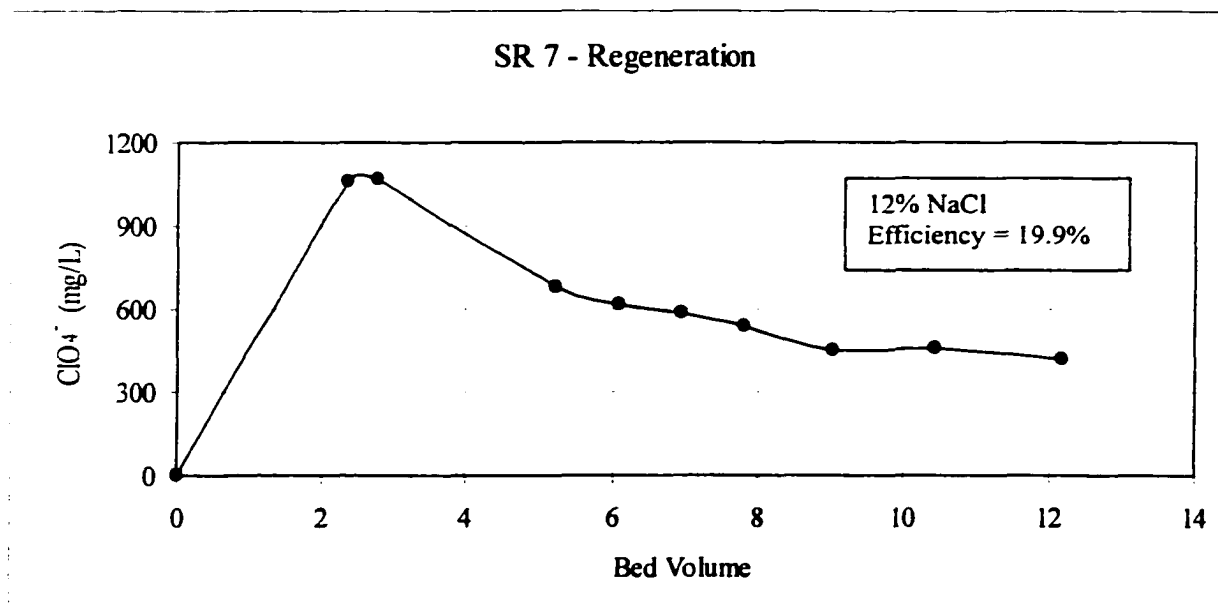


Figure 4.2.6 Regeneration of SR-7 resin (styrenic – Tripropyl) column 1, with 12% NaCl, EBCT = 4.5, and BV = 57.43 cm³.

4.2.4 Macro-T resin (Polyacrylic – Quaternary amine, Sybron Chemicals)

The exhaustion and regeneration data for an acrylic strong base anionic exchange resin with a quaternary amine group (Macro-T - Polyacrylic) are shown in Figures 4.2.7 and 4.2.8, respectively. The Macro-T resin have a total anion exchange capacity given by the manufacturer of 1.1 eq/L. The exhaustion test was run in duplicate. In average, 52.6% of the resin bed was utilized and regeneration with 12% NaCl was able to remove 100% of the loaded perchlorate. More than 1400 BV, in both columns, could be processed before the breakthrough was reached. For column 1, the test was performed

with an EBCT equal to 4.2 minutes and the BV was 54.78 cm³. For column 2 the EBCT was 4.4 minutes and the BV was 53.01 cm³.

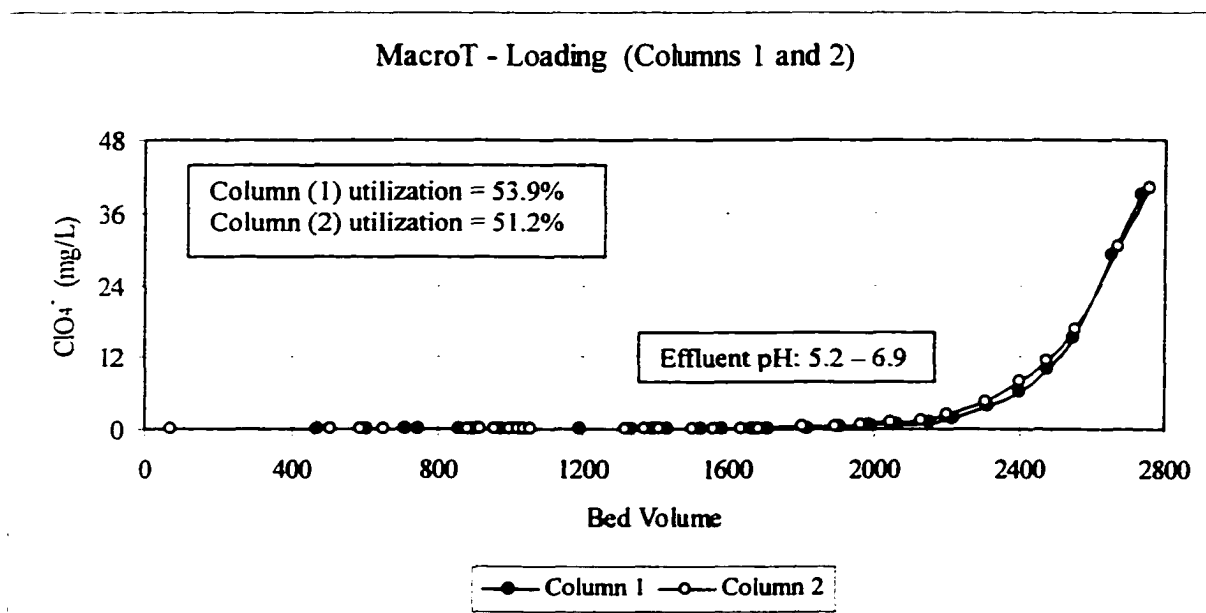


Figure 4.2.7 Exhaustion of Macro-T resin (polyacrylic – quaternary amine); fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.2 minutes, BV = 54.78 cm³ (column 1), EBCT = 4.4 minutes, and BV = 53.01 cm³ (column 2).

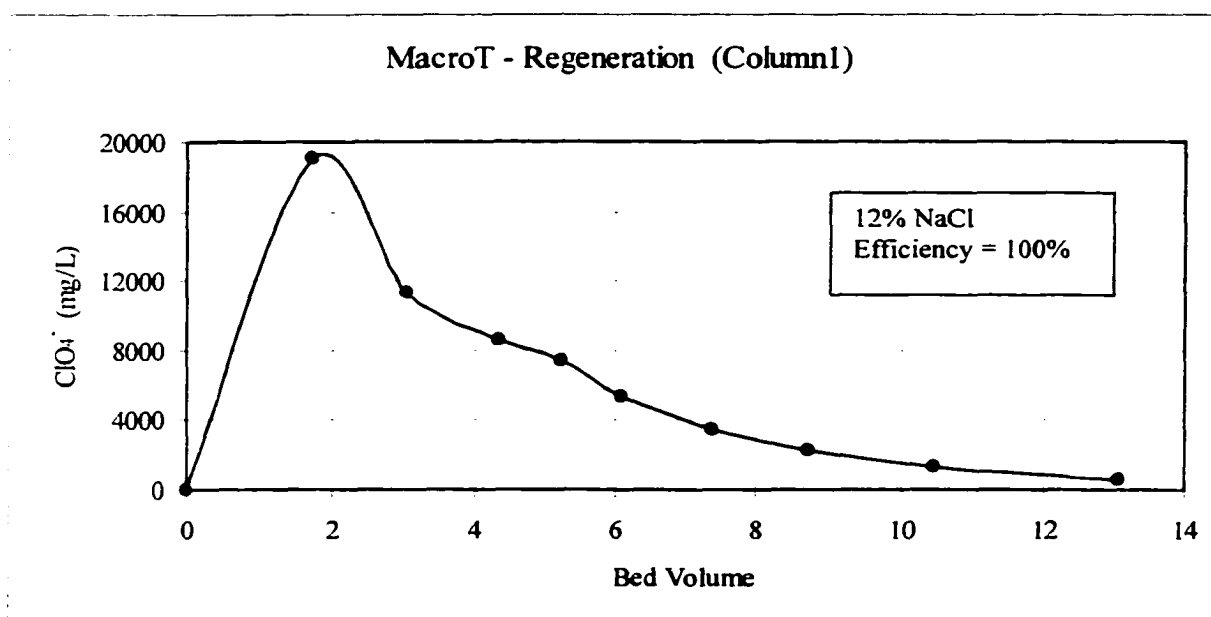


Figure 4.2.8 Regeneration of Macro-T resin (polyacrylic – quaternary amine) with 12% NaCl, EBCT = 4.4 minutes, and BV = 54.78 cm^3 .

Similar to the SR-7 resin, the second exhaustion of the Macro-T resin was not successful. Here again, it is believed that the rinsing cycle was not long enough to remove the excess regenerant.

In a separate experiment, a bed of Macro-T resin was exhausted and regenerated again. After regeneration the resin was rinsed thoroughly before attempting the second exhaustion. To assure that no excess regenerant was present when reloading, the conductivity of the rinse solution was measured. The first rinsate had conductivity higher than 50,000 μmhos . After 11.5 BV of rinsing, the conductivity decreased drastically to 30 μmhos , showing that the excess brine had been removed. The breakthrough curves showing the first and second exhaustion of the resin are shown in Figure 4.2.9. This time, the column was fed with 190 mg/L perchlorate synthetic solution to accelerate the resin exhaustion.

Notice that column utilization to breakthrough for the first exhaustion was 67.7% while it was 36.2% for the second exhaustion (Figure 4.2.9). On the other hand, when the total column utilization was calculated, the results for the first and second exhaustion were approximately the same and about 92%. It seems that in the second exhaustion the resin lost the capability of removing perchlorate to very low concentrations (i.e. below 20 $\mu\text{g/L}$) and the exchange kinetics appeared to be slower. This is detailed in the four sub-plots of Figure 4.2.9. Similar to the first regeneration (Figure 4.2.8) regeneration (Figure 4.2.10) with 12% NaCl was 100% efficient.

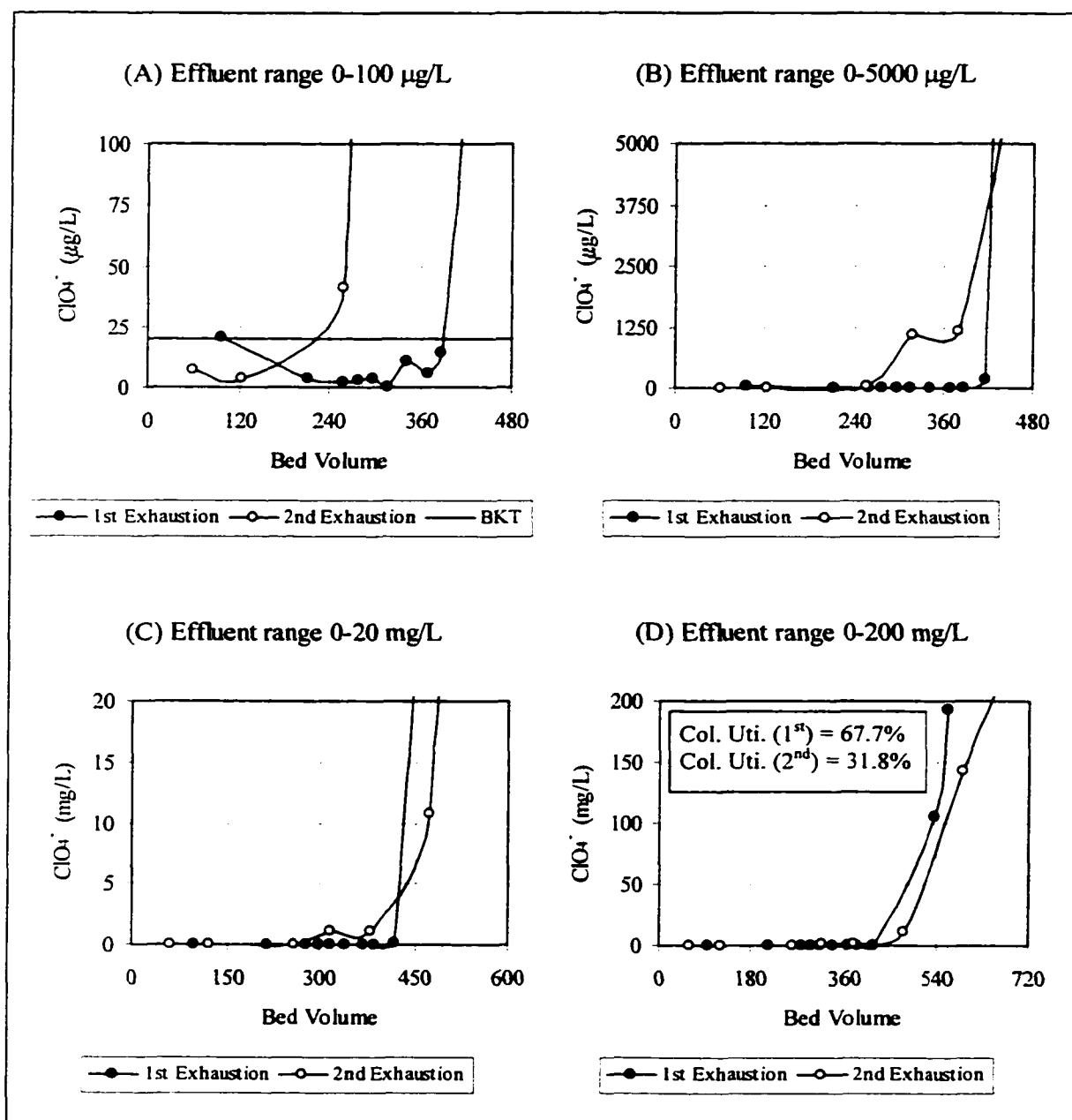


Figure 4.2.9 First and second exhaustion of Macro-T resin (polyacrylic – quaternary amine); fed with 190 mg/L (Test 2) synthetic perchlorate solution, EBCT = 4.7 minutes, BV = 55.7 cm^3 , and column utilization to breakthrough = 67.7% (First exhaustion); EBCT = 4.5 minutes, BV = 53.01 cm^3 , and column utilization to breakthrough = 31.8%. (Second exhaustion). Total column utilization averaged for both columns = 92.0%. The graph has been broken into different ranges of effluent concentration to better show the behavior of the different exhaustion.

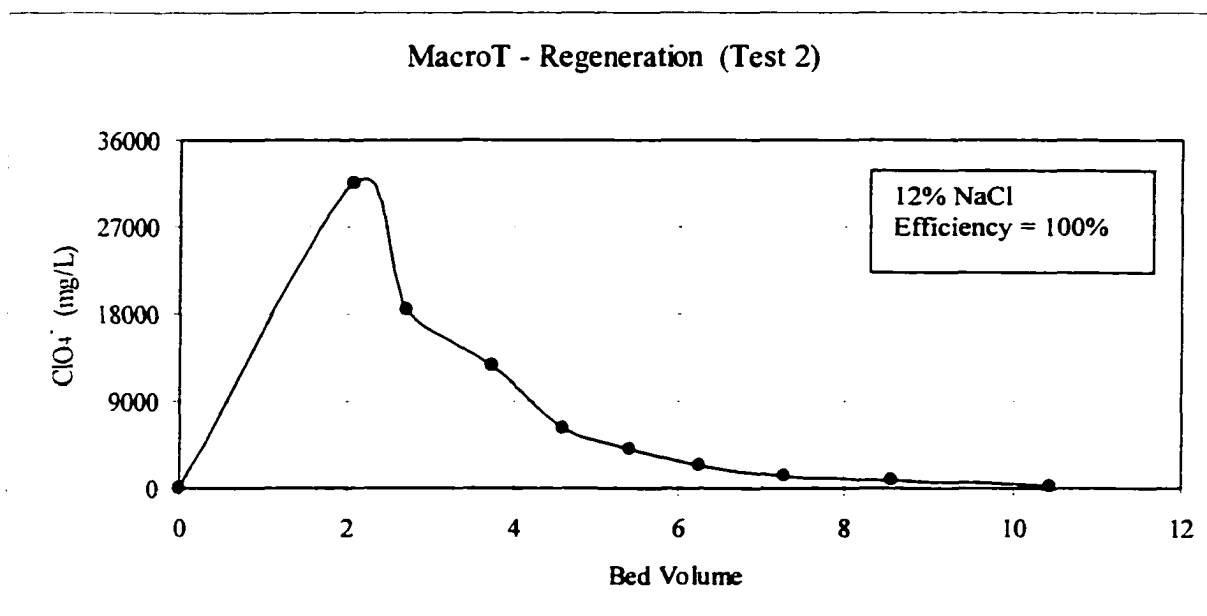


Figure 4.2.10 Regeneration of Macro-T resin (polyacrylic – quaternary amine) with 12% NaCl, EBCT = 9.6 minutes, and BV = 47.89 cm³ (Test 2).

4.2.5 A-850 resin (Polyacrylic – quaternary amine, Purolite Ion Exchange Resins)

Figure 4.2.11 displays the duplicate exhaustion data for a polyacrylic strong base resin with a quaternary amine functional group (A-850 - Polyacrylic). The manufacturer gives the total volume capacity for this resin as 1.25 eq/L. More than 1975 BV were processed before breakthrough was reached, representing an average column utilization of 64.5% for both columns. Regeneration of the column 2 with 12% NaCl had impressive results and 100% of the loaded perchlorate could be stripped out of the resin. On the other hand, the regeneration of column 1 with 1% NaOH was able to remove only 38% of the loaded perchlorate (Figure 4.2.12). It seems that strong base polyacrylic type resins can be completely regenerated with NaCl for the same regeneration results were achieved with the Macro T resins.

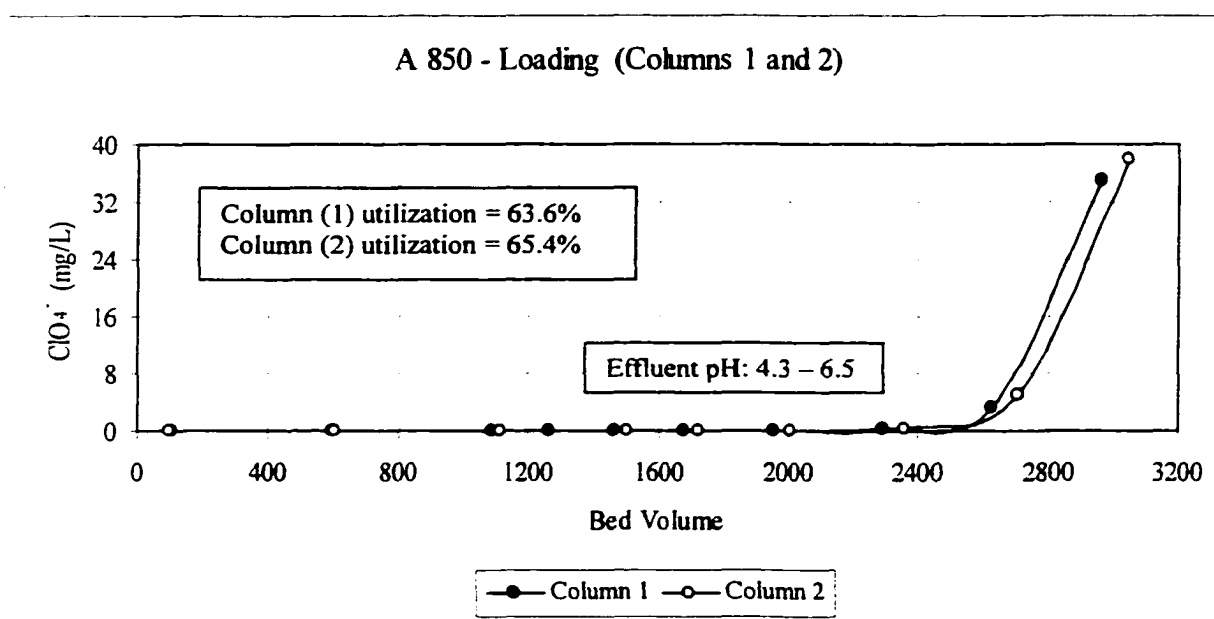


Figure 4.2.11 Exhaustion of A-850 resin (polyacrylic – quaternary amine); fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.4 minutes, BV = 53.90 cm³ (column 1), EBCT = 4.3 minutes, and BV = 54.80 cm³ (column 2).

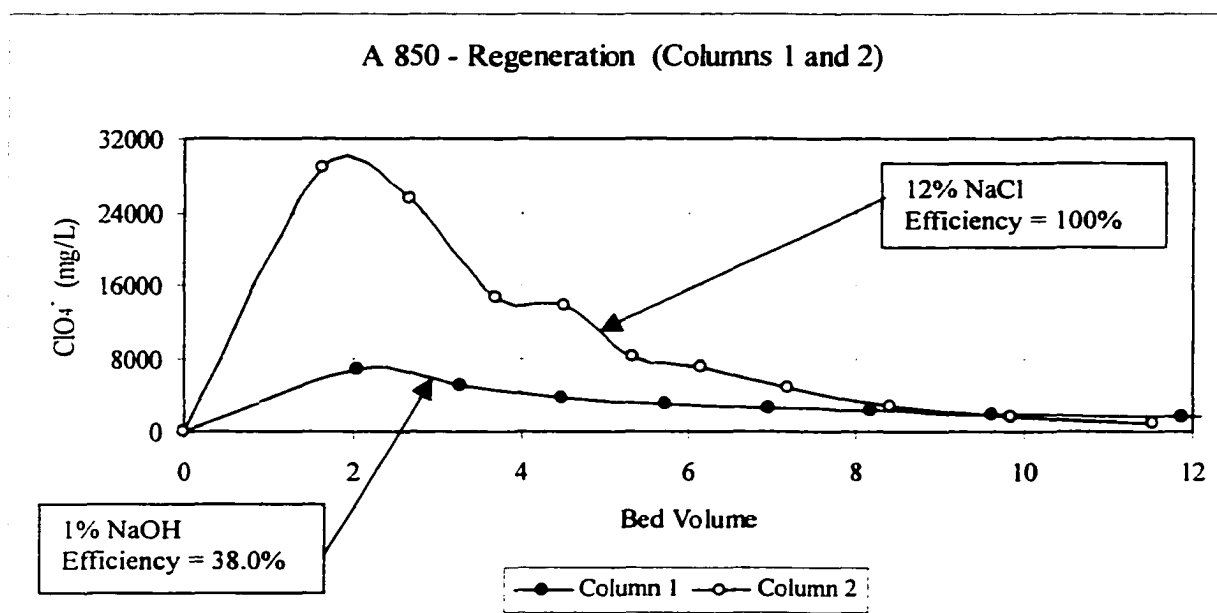


Figure 4.2.12 Regeneration of A-850 resin (polyacrylic – quaternary amine) with 1% NaOH, EBCT = 4.8 minutes, and BV = 48.9 cm³ (Column 1) and 12% NaCl, EBCT = 6.9 minutes, and BV = 48.69 (Column 2)

Because of the excellent regeneration achieved with this resin when using 12% sodium chloride (NaCl), a second test was performed. The resin bed was exhausted with 190 mg/L perchlorate synthetic solution. During rinsing (after regeneration), samples were taken at the beginning and after 11 BV of rinsing and analyzed for their conductivity. The first sample had conductivity higher than 50,000 μmhos , while after 11 BV the conductivity drastically decreased to 15 μmhos , showing that excess brine had been removed. The results of this experiment (Test 2) are shown in Figures 4.2.13 and 4.2.14. The breakthrough curve in Figure 4.2.13 has been broken into different ranges of effluent concentrations to better show the behavior of the first and second exhaustion.

The column utilization to breakthrough for the first exhaustion (Figure 4.2.13) was about 3 times larger than for the second exhaustion. On the other hand, when the total column utilization was calculated, the results for the first and second exhaustion were approximately the same and about 86%. Again, it appears that in the second exhaustion the resin lost its capability of removing perchlorate to very low concentrations (i.e. below 20 $\mu\text{g/L}$), but it continues removing perchlorate to relatively low levels (i.e. 1,000 $\mu\text{g/L}$), compared with the influent concentration (190,000 $\mu\text{g/L}$). The result of the resin regeneration with 12% NaCl is shown in Figure 4.3.14. Regeneration was 100% efficient, repeating the result obtained in test 1.

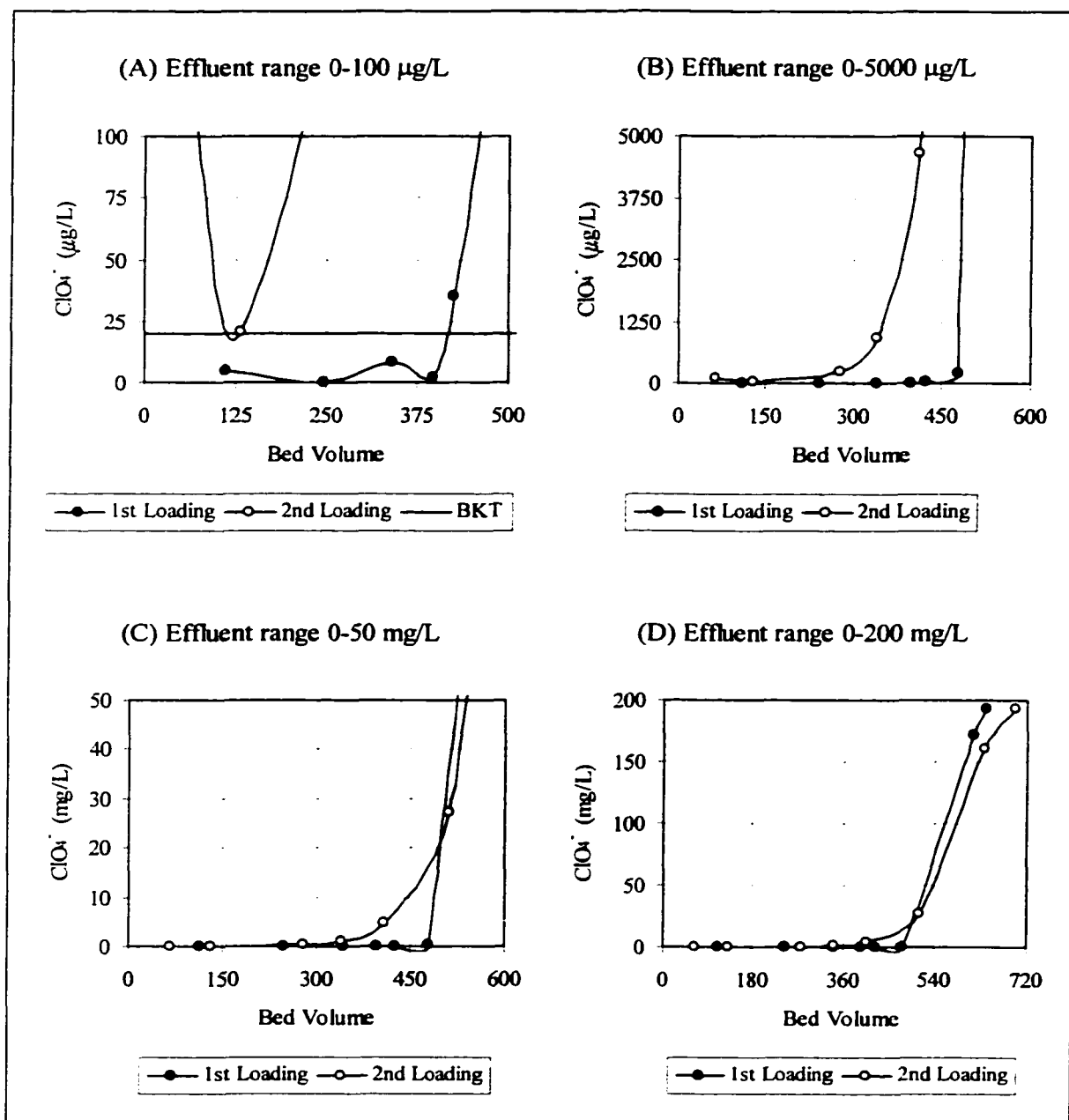


Figure 4.2.13 First and second exhaustion of A-850 resin (polyacrylic – quaternary amine); fed with 190 mg/L (Test 2) synthetic perchlorate solution, EBCT = 4.1 minutes, BV = 54.8 cm^3 , and column utilization to breakthrough = 63.2% (First exhaustion); EBCT = 4.2 minutes, BV = 55.7 cm^3 , and column utilization to breakthrough = 20.4% (Second exhaustion). Total column utilization averaged for both columns = 86.0%. The graph has been broken into different ranges of effluent concentration to better show the behavior of the different exhaustion.

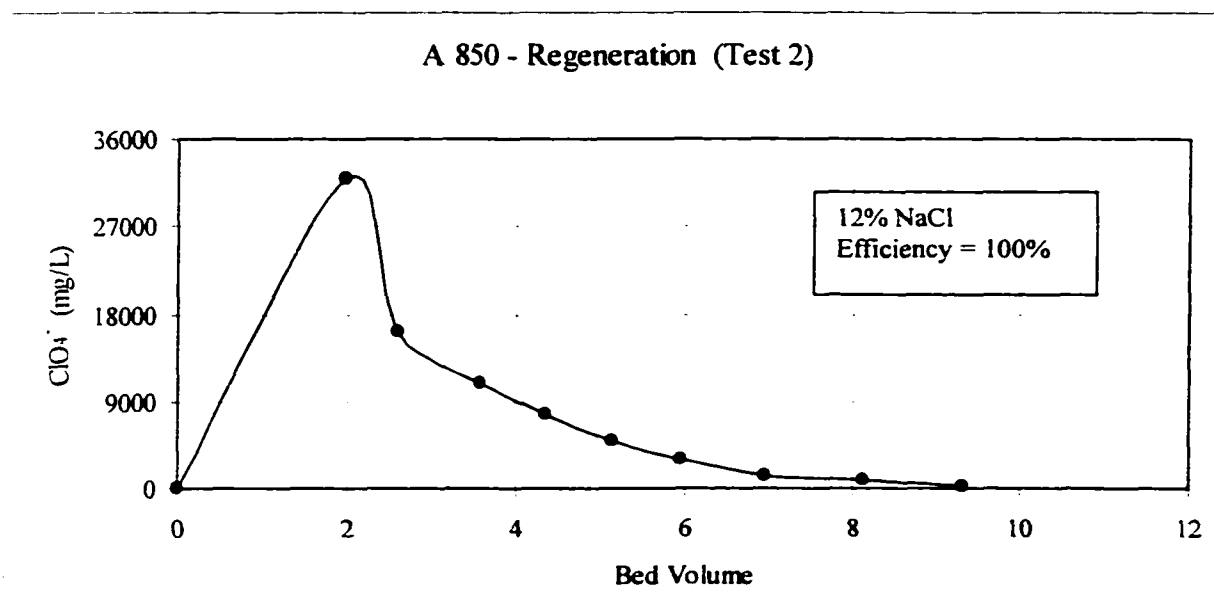


Figure 4.2.14 Regeneration of A-850 resin (polyacrylic – quaternary amine) with 12% NaCl, EBCT = 9.5 minutes, and BV = 50.4 cm³ (Test 2).

4.2.6 Discussion of the Results of the Strong-Base Anionic Resin Testing

Table 4.2.1 summarizes the results for the strong-base anionic exchange resins exhausted with 40 mg/L perchlorate synthetic solution. The table includes the resin type, feed solution, column utilization to breakthrough and total column utilization, regeneration efficiency, and the type of regenerant solution.

Table 4.2.1 Summary of the results of the strong-base anionic resins testing.

Strong-base anionic exchange resin type	Feed solution (a)	BV to BKT (b)	Column Utilization to BKT (%) (c)	Total column Utilization (%) (d)	Regeneration efficiency (%) (e)	Regenerant type (f)
ASB1 Styrenic – Trimethyl	40 mg/L ClO_4^-	3486	100	>100	37.6	12% NaCl
ASB2 Styrenic Dimethylethanol	40 mg/L ClO_4^-	3520	100	>100	43.2	12% NaCl
SR-7 Styrenic – Tripropyl	40 mg/L ClO_4^-	1174	59.0	77.2	19.9	12% NaCl
Macro T Polyacrylic Trimethyl	40 mg/L ClO_4^-	1438	52.6	93.1	100	12% NaCl
Macro T – 1 st EXH** Polyacrylic Trimethyl	190 mg/L ClO_4^-	389	67.7	90.9	100	12% NaCl
Macro T – 2 nd EXH Polyacrylic Trimethyl	190 mg/L ClO_4^-	208	36.2	97.4	Not performed	-
A 850 Polyacrylic Trimethyl	40 mg/L ClO_4^-	1976	63.6	88.5	38.0	1% NaOH
A 850 Polyacrylic Trimethyl	40 mg/L ClO_4^-	2033	65.4	92.0	100	12% NaCl
A 850 – 1 st EXH Polyacrylic Trimethyl	190 mg/L ClO_4^-	413	63.2	85.8	100	12% NaCl
A 850 – 2 nd EXH Polyacrylic Trimethyl	190 mg/L ClO_4^-	133	20.4	87.51	Not performed	-
Note: pH of influent solutions was 6.8. Effluent pH varied from 5-7, except for A-850 where pH varied from 4-7.						
** EXH = Exhaustion.						

Notice that all strong-base resins (styrenic and acrylic) show high total column utilization (Table 4.2.1, column d) for perchlorate, with ASB1 and ASB2 being totally exhausted and SR-7 as the resin that shows the lower total column utilization (about 77%). The column utilization to breakthrough for two styrenic resins (ASB1 and ASB2) is much larger than the utilization for all other resins. Therefore, for the same bed volumes of perchlorate contaminated water processed, these resins would produce an effluent with lower perchlorate concentrations (columns b and c) than the other resins.

From the three styrenic resins, SR-7 presents the lowest total column utilization and utilization to breakthrough. The functional group of this resin is tripropyl and apparently it is the cause of its poor performance as compared to ASB1 and ASB2 (column c). The SR-7 resin is a nitrate selective resin. Guter (U.S. Patent 4,479,877) demonstrated that increasing the size of the carbon chain of the functional group in a strong base resin resulted in a greater affinity of the resin for nitrate. Apparently, the long carbon chain (Tripropyl) in SR-7 also contributes to poor exchange for perchlorate. Tripp and Clifford (2000) reported separation factors for perchlorate of 1500 and 125 for SR-7 and ASB1 resins, respectively. However, they also reported that the SR-7 resin did not reach equilibrium with the perchlorate solution even after 7 days. They suggested the hydrophobic nature of the SR-7 resin may cause water transport to the resin to become the limiting step in achieving equilibrium. The experimental results for the SR-7 resin confirms Tripp and Clifford's belief that this resin has some equilibrium limitations despite its high separation factor.

Except for ASB1 and ASB2 resins, all other resins have had early breakthrough. The breakthrough curves for ASB1 and ASB2 (Figures 4.2.1 and 4.2.3)

were very sharp, reflecting a sharp, small mass transfer zone (MTZ), while the curves for the other resins (Figures 4.2.5 and 4.2.7) were sloped, reflecting larger MTZ's. This can be attributed to the kinetics of exchange in the resin beads; all experiments were performed at approximately the same empty bed contact times and the total column utilization (column d) was very high as compared to the column utilization to breakthrough. For future research it would be useful to perform exchange tests with these resins at different empty bed contact times.

Regeneration of the resins with 12% NaCl, show that acrylic resins (Macro T and A850) regenerated much better than styrenic ones. Both Macro T and A850 (column e) could be completely regenerated. All styrenic resins regenerated poorly and SR-7 had the smallest regeneration efficiency (less than 20%). Although the mechanisms for perchlorate loading and detachment to ion exchange resins are not yet well understood, it is suspected that the hydrophilic character of acrylic resins (due to aliphatic groups in its composition) plays a major role in the regeneration ability of these resins.

4.3. Weak Base Anionic Exchange Resins.

4.3.1. AFP 329 resin (Styrenic DVB macroporous – Tertiary amine, Sybron Chemicals)

Figure 4.3.1 shows the result of duplicate exhaustion testing for a styrenic weak-anion exchange resin (AFP 329, Sybron Chemicals). Notice that column utilization to breakthrough for this resin was very poor (12% in average). About 480 BV of 40 mg/L perchlorate synthetic solution could be processed before breakthrough. This resin has total exchange capacity of 1.6 eq/L which 0.25 eq/L is due to the presence of strong base groups. Regeneration with 12% NaCl, at low EBCT (about 4 minutes) was able to remove only 17.7% of the loaded perchlorate. The reason for this low regeneration efficiency could be the low EBCT used in the regeneration process.

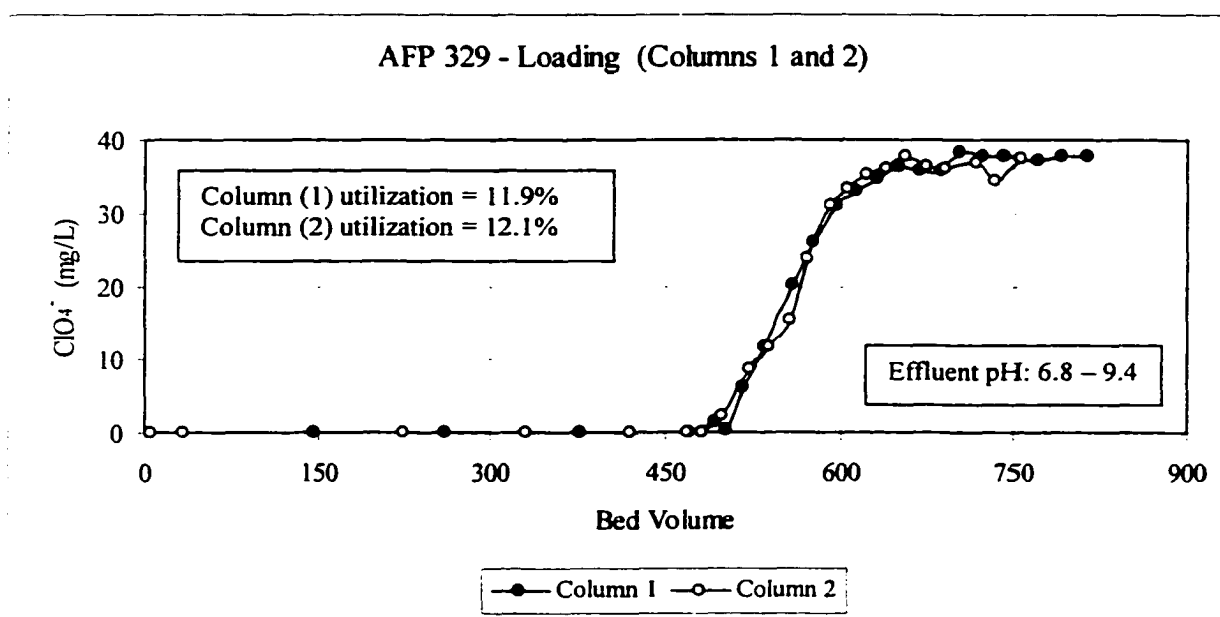


Figure 4.3.1 Exhaustion of AFP 329 resin (Styrenic DVB macroporous – Tertiary amine), fed with 40 mg/L synthetic perchlorate solution, EBCT = 7.0 minutes, BV = 209.49 cm³ (column 1), EBCT = 7.3 minutes, and BV = 209.49 cm³ (column 2). Without carbonation.

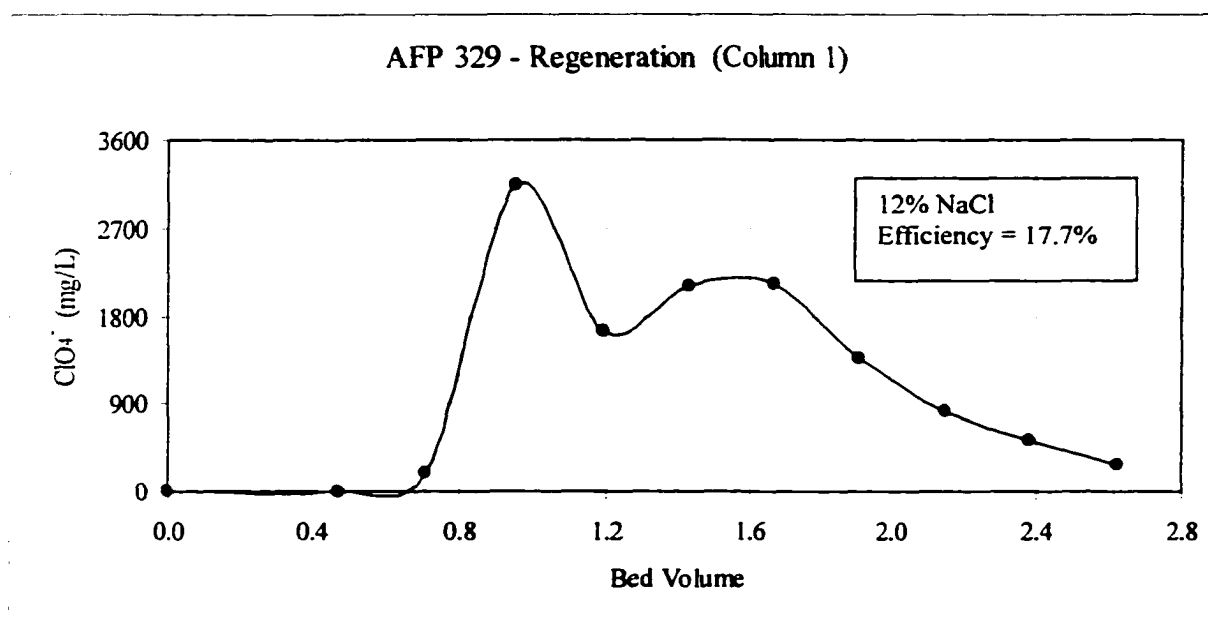


Figure 4.3.2 Regeneration of AFP 329 resin (Styrenic DVB macroporous – Tertiary amine) with 12% NaCl, EBCT about 4 minutes, and BV = 209.49 cm³.

Figure 4.3.3 shows the results of exhaustion duplicate column testing using the styrenic AFP-329 resin after carbonation (Equations 4.3 – 4.5). Carbonation was performed by passing a NaHCO₃ solution through a bed of strong acid cationic exchange resin (C-267 Sybron Chemicals). Notice that column utilization for this resin was very poor (12.0% in average). About 500 BV of solution could be processed before breakthrough. Thus, carbonation did not improve the exhaustion capacity of this resin. Exhaustion data for this resin without carbonation (Figure 4.3.1) and with carbonation (Figure 4.3.3) show the same number of bed volumes being processed before breakthrough was reached. Regeneration of one of the columns (Figure 4.3.4) using 1% NaOH was able to remove only 12.4 % of the loaded perchlorate. However, regeneration with 12% NaCl was able to remove 61.6% of the loaded perchlorate. These results were unexpected, since the perchlorate loaded to the weak base anionic exchange

resin should be removed by NaOH. Further investigation of the issue revealed that the weak anionic resin used in this test contains about 16% strong-base groups (Sybron Chemicals, 1999). Calculations of the perchlorate exhaustion indicated that the amount of perchlorate removed by the resin is roughly equivalent to the capacity of the strong-base groups present. This explains the greater efficiency of NaCl as compared to NaOH as regenerant for this resin. Therefore, strong-base groups, present in weak base anionic exchange resins, play a role in perchlorate removal by weak base resins. Further investigation is needed to evaluate the influence of these strong-base groups on perchlorate removal and regeneration by weak base anionic exchange resins.

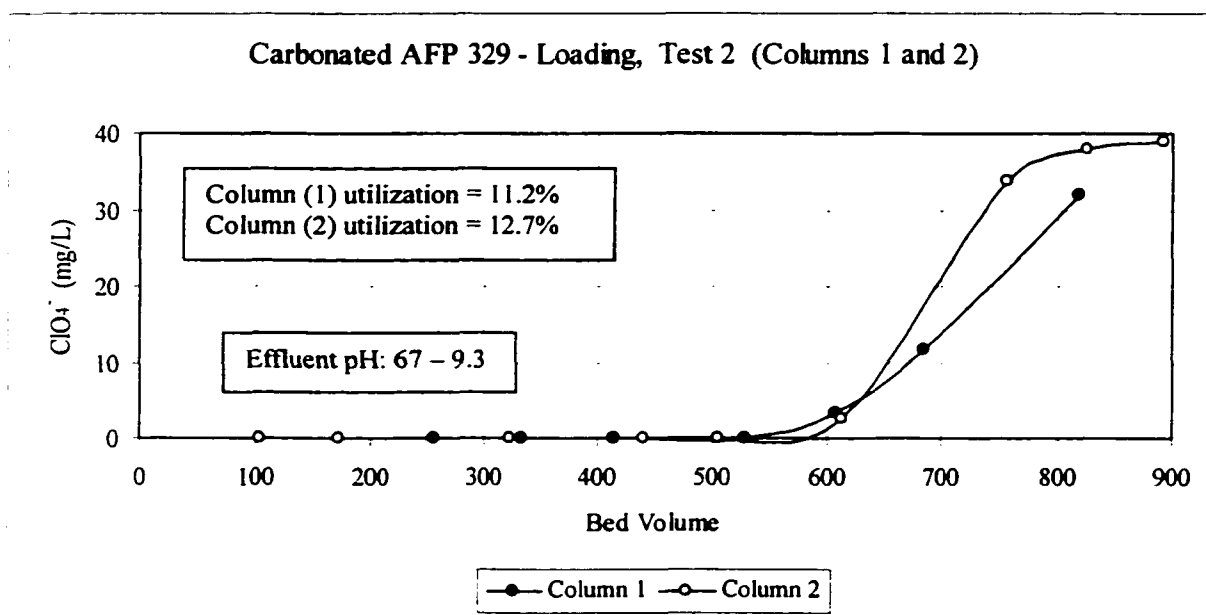


Figure 4.3.3 Exhaustion of Carbonated AFP 329 resin (Styrenic DVB macroporous – Tertiary amine), Test 2, fed with 40 mg/L synthetic perchlorate solution, EBCT = 5.5 minutes, BV = 53.01 cm³, and total column utilization = 18.2% (column 1), EBCT = 4.5 minutes, BV = 54.78 cm³, and total column utilization = 17.4% (column 2). The influent feed solution was carbonated.

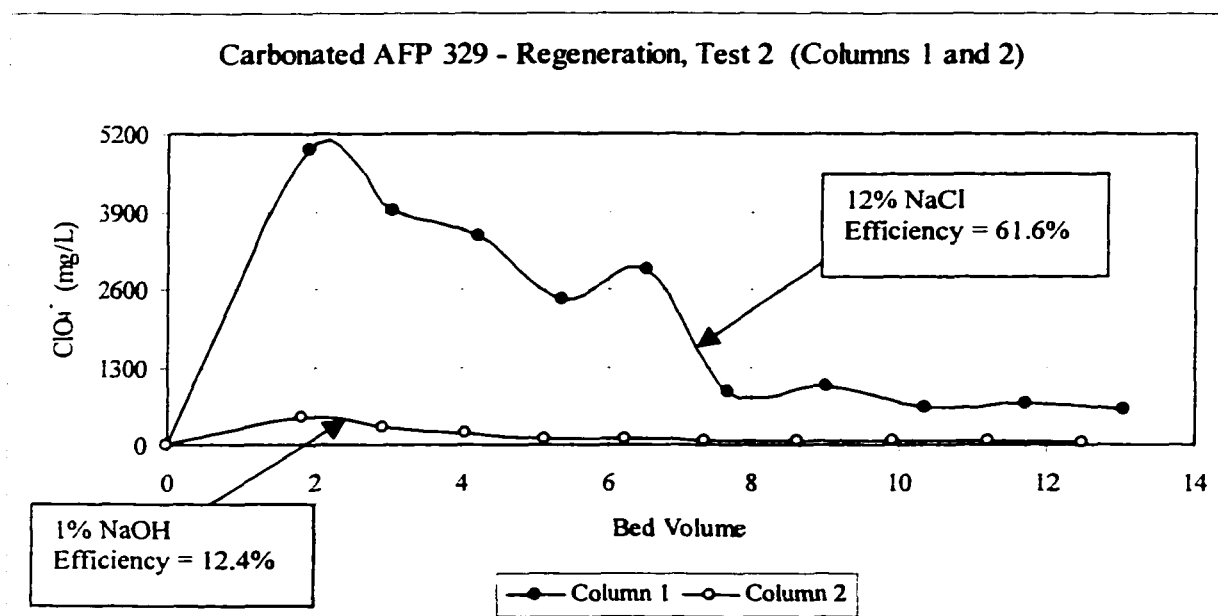


Figure 4.3.4 Regeneration of carbonated AFP 329 resin, Test 2 (Styrenic DVB macroporous Tertiary amine) with 12% NaCl, EBCT = 18.9 minutes, and BV = 52.14 cm³ for column 1; 1% NaOH, EBCT = 8.7 minutes, and 54.43 cm³ for column 2.

The exhaustion and regeneration of AFP 329 resin with 10 mg/L perchlorate and 50 mg/L nitrate are shown in Figures 4.3.5, 4.3.6, and 4.3.7. Notice in Figures 4.3.5 and 4.3.7 that more than 1760 BV of solution were processed before perchlorate broke through. Nitrate broke through at about 200 BV. Even though this resin shows low column utilization for perchlorate, it is interesting to note that the column utilization did not decrease when nitrate was present when compared with the individual exhaustion of perchlorate on the resin (Figures 4.3.1 and 4.3.3). The regeneration with 1% NaOH was able to remove only 10.1% and 19.8% of the loaded perchlorate and nitrate, respectively (Figure 4.3.6).

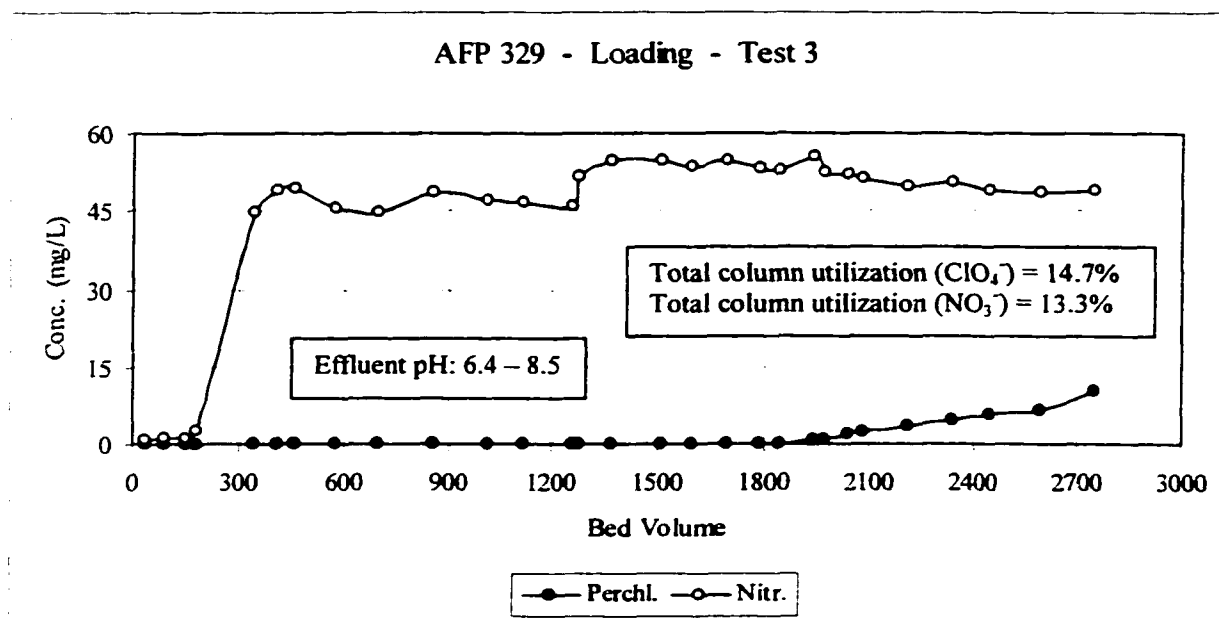


Figure 4.3.5 Exhaustion of AFP 329 resin (Styrenic DVB macroporous - Tertiary amine), Test 3, fed with synthetic solution containing 10 mg/L perchlorate and 50 mg/L nitrate. EBCT = 4.4 minutes, BV = 50.9 cm³.

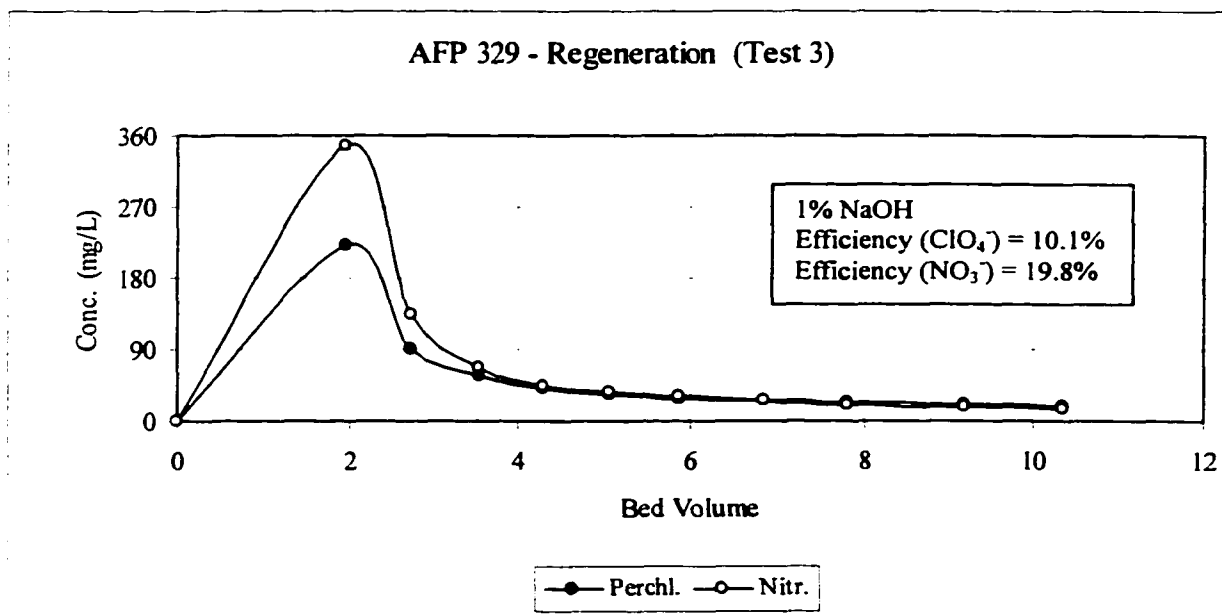


Figure 4.3.6 Regeneration of AFP 329 resin, Test 3 (Styrenic DVB macroporous Tertiary amine) with 1% NaOH, EBCT = 9.8 minutes, and 51.25 cm³.

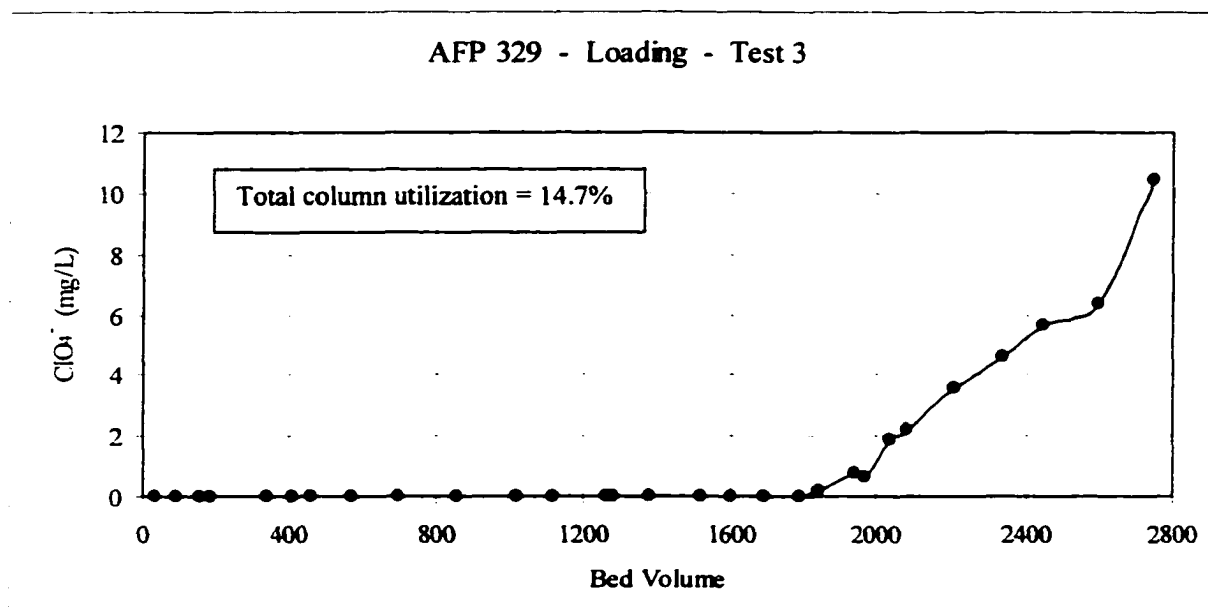


Figure 4.3.7 Exhaustion of AFP 329 resin (Styrenic DVB macroporous – Tertiary amine), Test 3, fed with synthetic solution containing 10 mg/L perchlorate and 50 mg/L nitrate. EBCT = 4.4 minutes, BV = 50.9 cm³, total column utilization = 14.7% and column utilization to breakthrough = 11.1%

4.3.2. A 830 resin (Acrylic – Tertiary amine)

Figure 4.3.8 shows the removal of perchlorate in duplicate columns by an acrylic weak base anionic exchange resin (A-830, Purolite), with tertiary amine functional groups. On average, more than 2330 BV of 40 mg/L synthetic perchlorate solution were processed before breakthrough was reached and column utilization was 35.1%. Regeneration with 1% NaOH was able to remove about 76% of the loaded perchlorate. Conversely, when the regeneration was performed with 12% NaCl, the efficiency increased to 100% (Figure 4.3.9). These results show that acrylic weak base resins have high column capacity and regenerate easily with caustic solution or sodium chloride. These types of resin can be used to give regenerant solutions that are amenable to biodegradation.

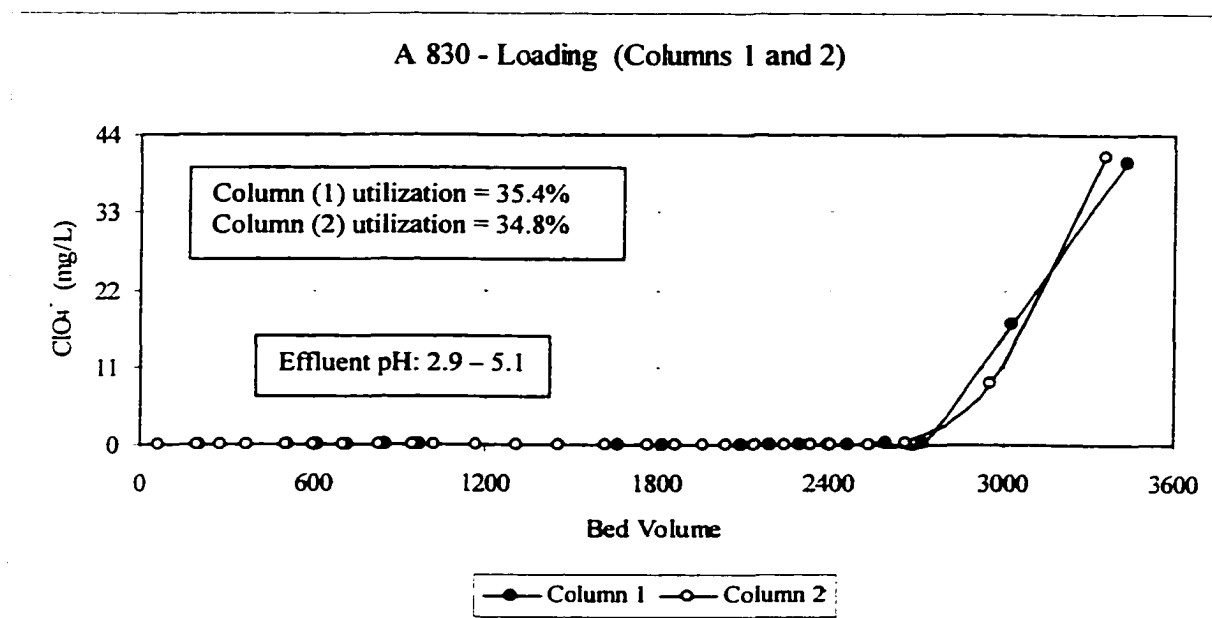


Figure 4.3.8 Exhaustion of A-830 resin (Acrylic – Tertiary amine), fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.6 minutes, BV = 56.55 cm³ (column 1), EBCT = 4.7 minutes, and BV = 54.78 cm³ (column 2).

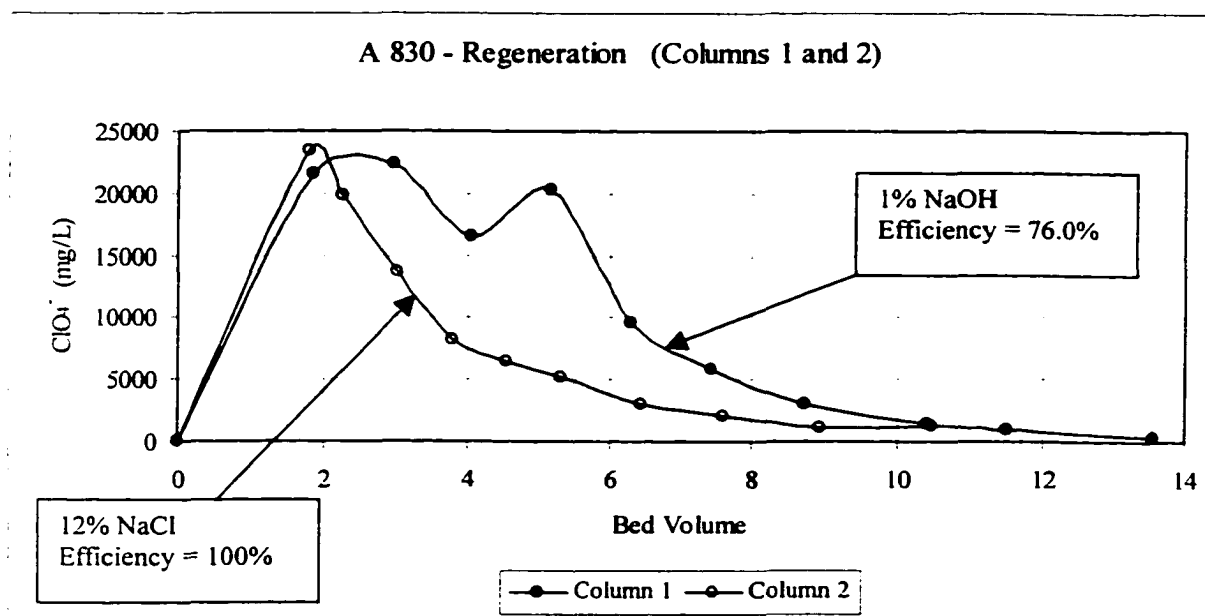


Figure 4.3.9 Regeneration of A 830 resin (Acrylic – Tertiary amine) with 1% NaOH, EBCT = 6.7 minutes, and BV = 53.9 cm³ (column 1); 12% NaCl, EBCT = 7.7 minutes, and BV = 52.58 cm³ (column 2).

The removal of 10 mg/L perchlorate by the A-830 acrylic resin in the presence of 100 mg/L sulfate, 100 mg/L nitrate, and 100 mg/L chloride is shown in Figures 4.3.10 and 4.3.11. The exhaustion and regeneration of perchlorate for the same column in question is shown in Figures 4.3.12 and 4.3.13. Notice in Figures 4.3.10 and 4.3.12 that more than 765 BV were processed before breakthrough. Sulfate breakthrough occurred after about 450 BV followed by nitrate breakthrough at 760 BV. Figure 4.3.11 and 4.3.13 display the regeneration results. Observe that 100% of the perchlorate loaded could be removed by regenerating with 1% NaOH.

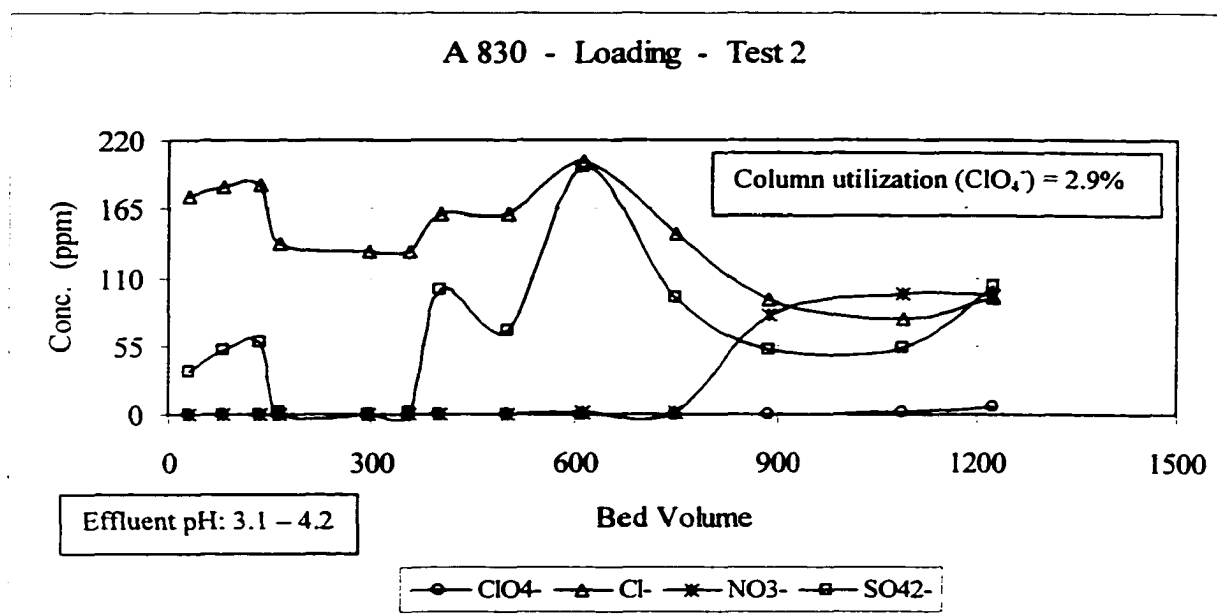


Figure 4.3.10 Exhaustion of A 830 resin (Acrylic – Tertiary amine), Test 2, fed with synthetic solution containing 10 mg/L perchlorate, 100 mg/L sulfate, 100 mg/L nitrate, and 100 mg/L chloride. EBCT = 4.5 minutes, BV = 55.67 cm³.

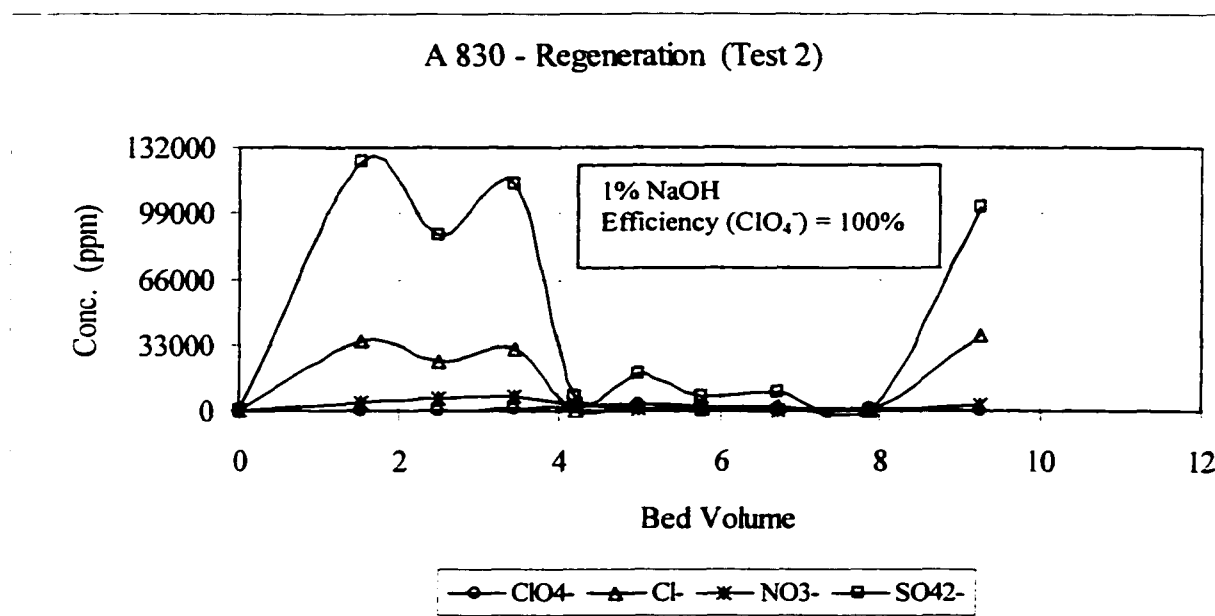


Figure 4.3.11 Regeneration of A 830 resin, Test 2 (Acrylic – Tertiary amine) with 1% NaOH.

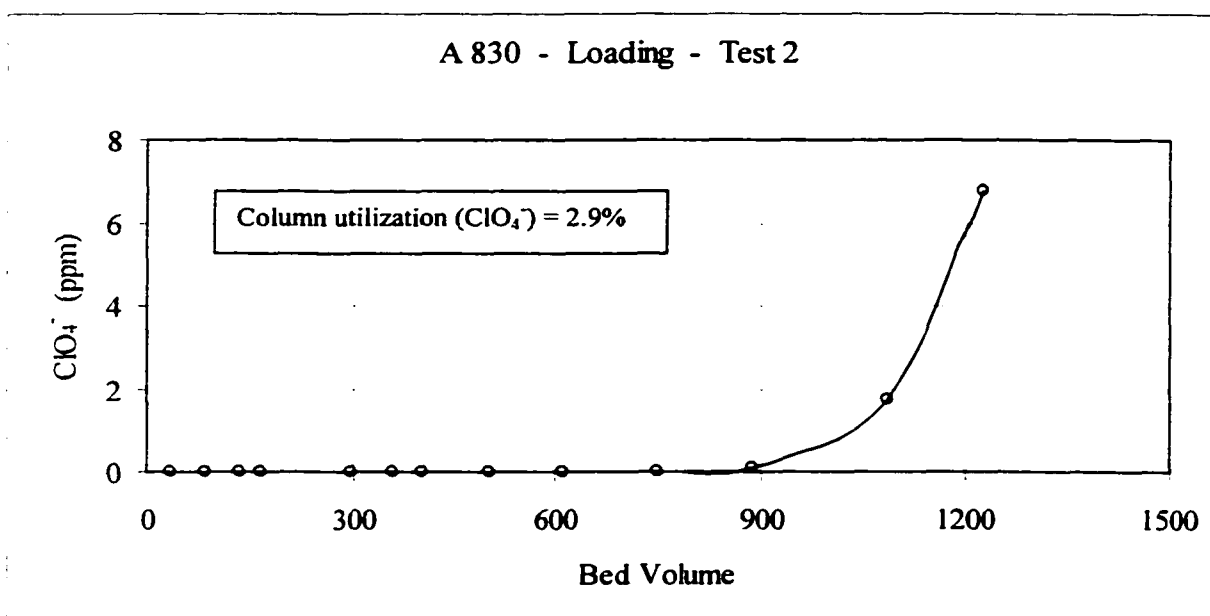


Figure 4.3.12 Exhaustion of A 830 resin (Acrylic – Tertiary amine), Test 2, fed with synthetic solution containing 10 mg/L perchlorate, 100 mg/L sulfate, 100 mg/L nitrate, and 100 mg/L chloride. EBCT = 4.5 minutes, BV = 55.67 cm³.

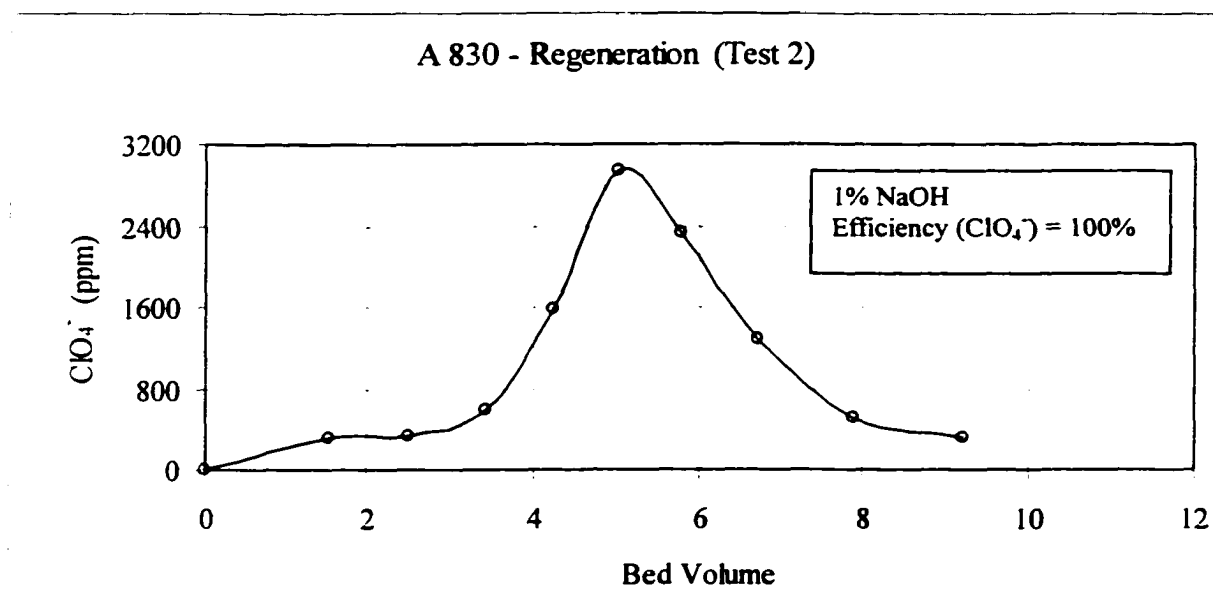


Figure 4.3.13 Regeneration of A 830 resin, Test 2 (Acrylic – Tertiary amine) with 1% NaOH.

4.3.3. A 365 resin (Polyacrylic DVB – Tertiary amine)

The duplicate exhaustion data for a polyacrylic weak base anionic exchange resin with a tertiary amine groups (A 365, Sybron Chemicals) is shown in Figure 4.3.14. The BV for the column 1 was 52.13 cm^3 and the EBCT used for the exhaustion equals to 4.1 minutes, while column 2 had BV equal to 53.01 cm^3 and EBCT equal to 4.5 minutes. For both columns the resin utilization to breakthrough was equal 0%. This type of resin was not able to remove perchlorate from the 40 mg/L synthetic feed solution. The total exchange capacity for this resin was given as 3.5 eq/L. Even in the first sample, the perchlorate concentration in the effluent was almost equal to the influent feed solution.

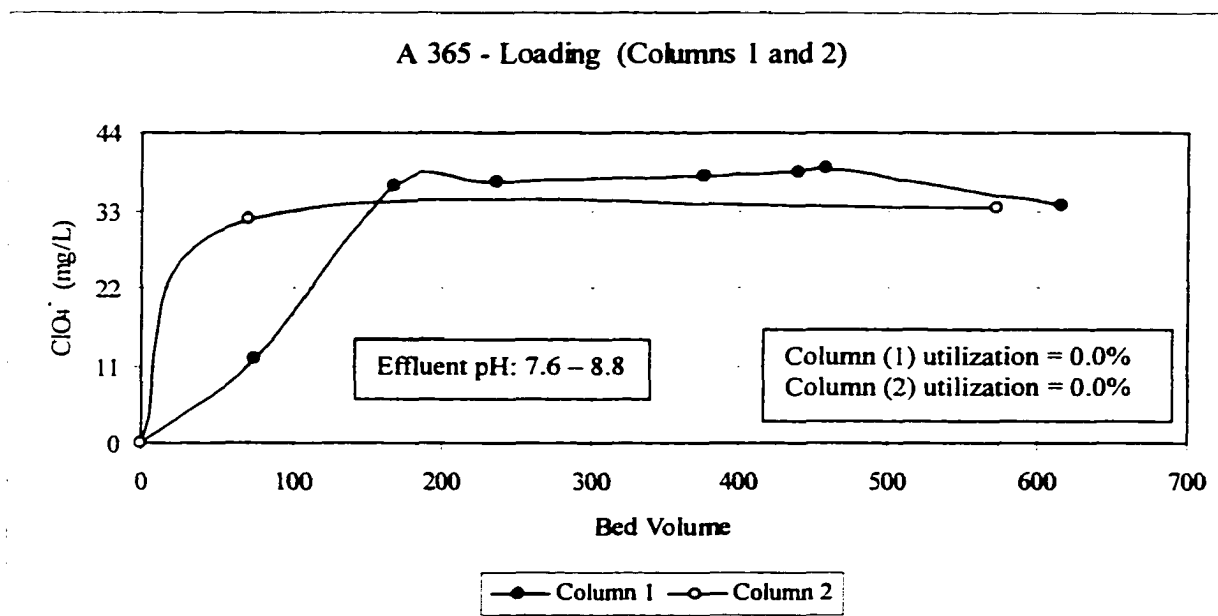


Figure 4.3.14 Exhaustion of A-365 resin (Polyacrylic DVB – Tertiary amine), fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.1 minutes, BV = 52.13 cm^3 (column 1), EBCT = 4.5 minutes, and BV = 53.01 cm^3 (column 2).

4.3.4. XR 404 resin

Figure 4.3.15 displays the regular exhaustion result and the exhaustion after carbonation for a special-made weak base anionic exchange resins (XR 404, Sybron Chemicals). Similar to A 365-type resin, this one also was not able to remove perchlorate from the 40 mg/L synthetic solution. Again, the first collected effluent sample contained perchlorate concentration close to the concentration for the feed solution in both tests. The BV for the test 1 was 54.79 cm^3 and the EBCT used for the exhaustion was equal to 4.0 minutes, while test 2 had BV equals to 54.79 cm^3 and EBCT equals to 4.6 minutes. For both tests the resin utilization to breakthrough was equal 0%.

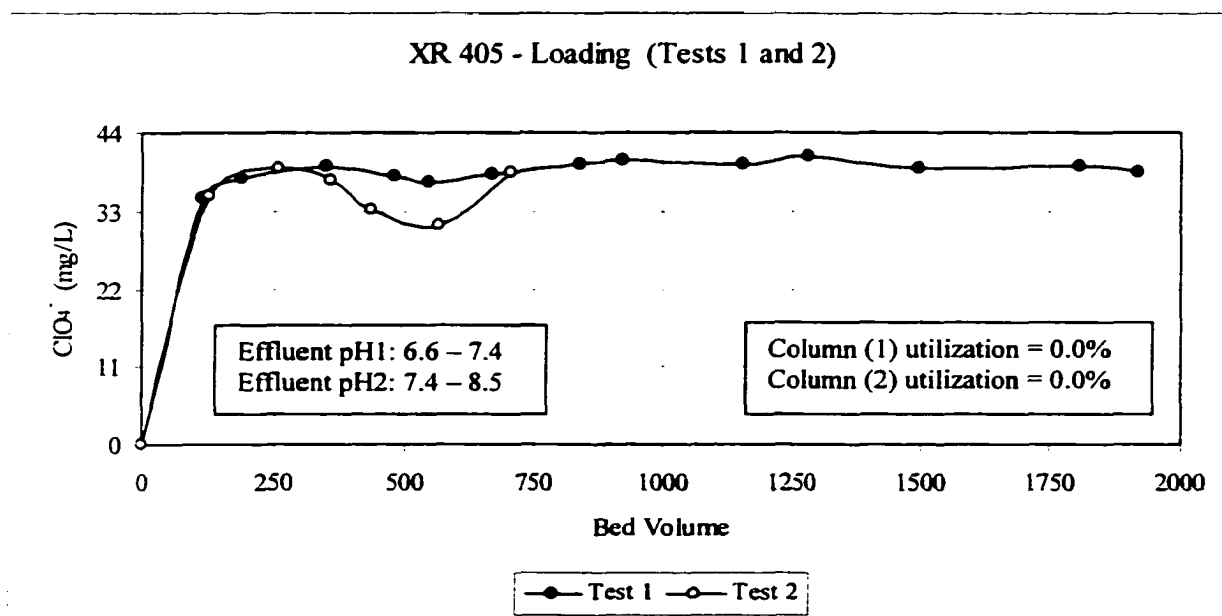


Figure 4.3.15 Exhaustion of XR-405 resin (Styrenic DVB – Tertiary amine), fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.0 minutes, BV = 54.79 cm³ (Test 1), EBCT = 4.6 minutes, and BV = 554.79 cm³ (Test 2 – exhaustion after carbonation step).

4.3.5 Discussion of the Results of the Weak-Base Anionic Resin Testing

Table 4.3.1 summarizes the results for the weak-base anionic exchange resins testing using synthetic solution of perchlorate and other anions. The table includes the resin type, feed solution, bed volumes run to breakthrough, column utilization to breakthrough and total column utilization, regeneration efficiency, and type of regenerant solution.

Table 4.3.1 Summary of the results for the weak-base anionic exchange resins tested.

Weak-base anionic exchange resin type	Feed solution (a)	BV to BKT (b)	Column Utilization to BKT (%) (c)	Total column Utilization (%) (d)	Regeneration efficiency (%) (e)	Regenerant typ(f)
AFP 329 - Tertiary amine styrenic	40 mg/L ClO_4^-	476	12.0	14.5	17.7**	12% NaCl
AFP 329 – Tertiary amine styrenic, with carbonation	40 mg/L ClO_4^-	447	11.2	18.2	61.6	12% NaCl
AFP 329 – Tertiary amine styrenic, with carbonation	40 mg/L ClO_4^-	506	12.7	17.4	12.4	1% NaOH
AFP 329 – Tertiary amine styrenic	10 mg/L ClO_4^- + 50 mg/L NO_3^-	1768	11.1	14.7	10.1	1% NaOH
A 830 Tertiary amine Polyacrylic	40 mg/L ClO_4^-	2376	35.4	45.0	76.0	1% NaOH
A 830 Tertiary amine Polyacrylic	40 mg/L ClO_4^-	2334	34.8	45.6	100	12% NaCl
A 830 Tertiary amine Polyacrylic	10 mg/L ClO_4^- + anions	768	2.9	4.28	100	1% NaOH
A 365 Tertiary amine Polyacrylic	40 mg/L ClO_4^-	0	0	0	Not performed	Not performed
XR 405 – Tertiary amine styrenic	40 mg/L ClO_4^-	0	0	0	Not performed	Not performed
** Performed at low EBCT (about 4 minutes) Note: Influent pH was about 6.8. Effluent pH for AFP 329 varied from 7-9 and for A-830 varied from 2.6-5.						

Four types of weak-base anionic exchange resins were tested. Two of the weak base resins exchanged perchlorate (AFP-329 and A-830). A-365 and XR 405 did not exchange perchlorate. A-365 is a polyacrylic tertiary amine and XR-405 is a styrenic tertiary amine that was specially made by Sybron Chemicals for this research. Carbonation of the weak-base resins, as described by Equations (4.3 to 4.5), using both compressed carbon dioxide and strong-acid cationic exchange resin did not seem to significantly affect the performance of these resin. It was noticed that, with and without carbonation, the weak resin performed similarly. The mechanisms for this exchange are subject of further research.

The total column utilization for AFP-329 with and without carbonation was very low. Carbonation improved the column utilization only slightly. However the column utilization to breakthrough was not affected by carbonation. The manufacturer of this resin reports that the composition of AFP-329 contains about 16% strong base groups (Sybron Chemicals, 1999). Thus, the column utilization measured reflects the capacity of the strong-base groups, rather than the total capacity of the resin per se. This is further confirmed by the better regeneration of the resin with 12% sodium chloride than with 1% sodium hydroxide (Table 4.3.1, columns (e) and (f)). The A-830 polyacrylic resin worked the best. About 50% of the capacity was utilized and column utilization to breakthrough was about 35% (columns (c) and (d)). Regeneration of the resin with both sodium chloride (12%) and sodium hydroxide (1%) was very effective. It is likely that a higher concentration of NaOH would promote very similar removal efficiency to that of sodium chloride.

In conclusion, weak-base styrenic resins cannot effectively remove perchlorate from waters. However, weak and strong polyacrylic resins can effectively remove perchlorate from waters. Weak-base resin, however, can be efficiently regenerated with either sodium chloride or sodium hydroxide. Thus, the weak polyacrylic resin would be good candidate for the system described in Figure 4.1.2. These resins would produce regenerant solutions that are potentially treated biologically.

An issue that deserves consideration when using weak- and strong-base anionic resin for perchlorate removal is the pH of the treated water and the pH of the regenerant solution. Weak-base anionic resins will generate finished water with low pH and a regenerant solution with high pH, when regenerated with caustic solutions. Thus, the process would require increasing the pH of the finished water and decreasing the pH of the regenerant if the regenerant were to be treated biologically. Strong-base anionic exchange resins produce finished water with pH in desirable ranges, but the regenerant brine is very saline and would require isolation of halophile microorganisms capable of perchlorate biodegradation. Table 4.3.2 summarizes the pros and cons of using weak- and strong-base resins when perchlorate is to be removed and the regenerant solution is to be treated biologically.

Table 4.3.2 Advantages and Disadvantages of using weak- and strong-base ion exchange resins for perchlorate removal

	pH of treated water	Regenerant Solution	Finished water treatment required	Requirements and regenerant solution adjustment for biodegradation.
Strong-Base	range (5-7)	High salinity	None	Need to isolate halophiles
Weak-Base	Low pH (3-5)	High pH	Base addition to increase pH.	Acid addition to decrease pH to desired levels for optimum microbial growth.

4.4 Use Of Ion Exchange Resins To Remove Perchlorate From Las Vegas Valley Contaminated Groundwater.

This section evaluates the removal of perchlorate by several anion exchange resins from a contaminated groundwater in the Las Vegas Valley. The resins tested include 4 strong bases (ASB1, ASB2, ASB1 PC, and Macro T) and 1 weak base (AFP 329). In this thesis, the term “real” water will refer to the contaminated groundwater from the Las Vegas Valley. In this experiment, over 118 gallons of contaminated groundwater were used. The groundwater in question was collected from an impoundment of the contaminated groundwater located by the Las Vegas Wash (in the intersection of Pabco Road and the Las Vegas Wash, with Global Position System (GPS) of N 36°05'14.29'' – W 114°59'23.65''). It is important to point out that the contaminated groundwater used in the tests was collected in 20-L bottles in three trips to the impoundment on different dates. The water composition varied somewhat from trip to trip. The impoundment is located in a marsh area where the main vegetation is salt cedar (*Tamarix ramosissima*). Tamarix has very deep, thick roots in the marsh and it is assumed that the high TOC levels in the water is the result of Tamarix decay. Table 4.4.1 shows the concentration of major anions for several water samples used in the resin testing. Observe that perchlorate (ClO_4^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and total organic carbon (TOC) concentrations averaged 80, 1970, 49, and 45 mg/L, respectively. In addition, note that the concentration of ClO_4^- , SO_4^{2-} , and NO_3^- varied slightly from bottle to bottle and TOC concentration variations were sometimes significant.

Table 4.4.1 pH and Concentration of Major Anions in the "Real" Water.

	Resin used	Concentrations (mg/L)					pH	Bottle #
		ClO ₄ ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	TOC		
First sample set 10/29/99	ASB1	79.95	2114	57.84	2094	32.13	8.25	1
		78.15	2098	50.10	2083	53.16	8.20	2
		80.27	2085	50.88	2052	55.16	8.11	3
		78.84	2100	50.68	2088	51.86	8.18	4
	ASB2	80.67	2085	50.88	2059	40.08	8.28	5
		78.87	2100	50.18	2091	53.13	8.17	6
		82.45	2095	51.68	2077	57.87	8.08	7
		84.36	2094	51.30	2080	50.75	8.14	8
Second sample set 11/01/99	ASB1	77.71	2044	48.90	2059	36.11	7.47	1
		77.94	2077	52.90	2067	30.95	7.63	2
		78.36	2083	51.30	2070	41.26	7.53	3
		76.44	2017	51.00	2035	40.61	7.46	4
	ASB2	75.39	2053	48.40	2055	43.44	7.50	5
		77.31	2031	48.92	2033	30.47	7.52	6
		76.54	2023	52.00	2022	35.13	7.54	7
		76.48	2041	50.68	2047	26.68	7.52	8
Average	ASB1	78.46	2077	51.70	2069	42.66	7.85	Average
	ASB2	79.01	2066	50.51	2058	42.19	7.84	

Table 4.4.1 Continued							
	Resin used	Concentrations (mg/L)					Bottle #
		ClO ₄ ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	TOC	
Third sample set 11/06/99	AFP 329	81.07	1957	50.82	1914	52.28	1
		79.81	1988	46.00	1932	56.78	4
		83.21	1971	49.60	1880	41.91	7
		81.36	1972	48.81	1909	50.32	Average
	Macro T	80.80	1961	48.10	1896	50.09	2
		80.91	1943	48.00	1895	45.67	5
		82.26	1970	44.80	1921	42.61	8
		81.32	1958	46.97	1904	46.12	Average
	ASB1-PC	80.82	1977	46.00	1871	57.25	3
		80.38	1989	45.86	1933	46.9	6
		82.58	1946	45.52	1892	31.79	9
		81.26	1971	45.79	1899	45.31	Average

4.4.1 ASB1 resin (Strong base - Styrenic DVB - Quaternary amine)

Figure 4.4.1 shows the breakthrough curve for a strong-base styrenic type I resin (ASB1, Sybron Chemicals) loaded with the “real” water. Notice that the total column utilization was only 48% when loaded with the “real” water and it was 100% (Figure 4.1.1) when loaded with the 40 ppm perchlorate synthetic solution. This indicates that approximately 50% of the resin capacity was occupied by anions other than perchlorate. However, observe that the sulfate concentration is about 20 times that of perchlorate and nitrate. At a first glance, it seems that sulfate and nitrate did not exchange much. However, for the test performed it would take only about 30 to 40 BV of the contaminated water to saturate the resins with sulfate. Because sulfate is a divalent anion and it is present in the “real” water in high concentrations, this anion will very strongly attach to the resin. The fact that perchlorate is still removed from the water despite the high sulfate concentration can be explained by the capability of perchlorate to replace sulfate in the resin. Thus, sulfate is first attached to the resins and it is then pushed out by perchlorate. Theoretically, a resin could be preloaded with sulfate for perchlorate removal purposes, just like chloride is currently used.

It was noticed that the resin bed through which the “real” water was run became very dark, suggesting the presence of humic substances (Figure 4.4.2). This was confirmed by measuring the total organic carbon (TOC) in the “real” water. TOC in the “real” water averages 45 mg/L. In addition, a later analysis of the “real” water has shown that it contains about 65 mg/L chlorate (ClO_3^-), but this anion was not monitored during testing. Figure 4.4.3 shows the influent and the effluent concentrations of total organic carbon (TOC) when the “real” water was loaded to ASB1 resins. It was

necessary to show the influent concentration of TOC because it varied from bottle to bottle. Notice that the decrease in TOC effluent between 330-500 BV is the consequence of decreasing TOC influent concentration (Figure 4.4.3). After 500 BV, despite decreasing influent TOC concentration, the TOC levels in the effluent increased. These results show that considerable portion of TOC is exchanged with the resins. After about 500 BV the TOC started to detach from the resins. This is about the same point at which perchlorate concentration in the effluent started increasing. It appears that perchlorate is pushing the TOC out of the resin. However, further investigations, using binary synthetic solutions of humic acids and different anions, are needed to quantify the effects of humic acids on perchlorate removal by ion exchange resins. Such testing is currently underway in the UNLV Environmental Engineering Laboratory.

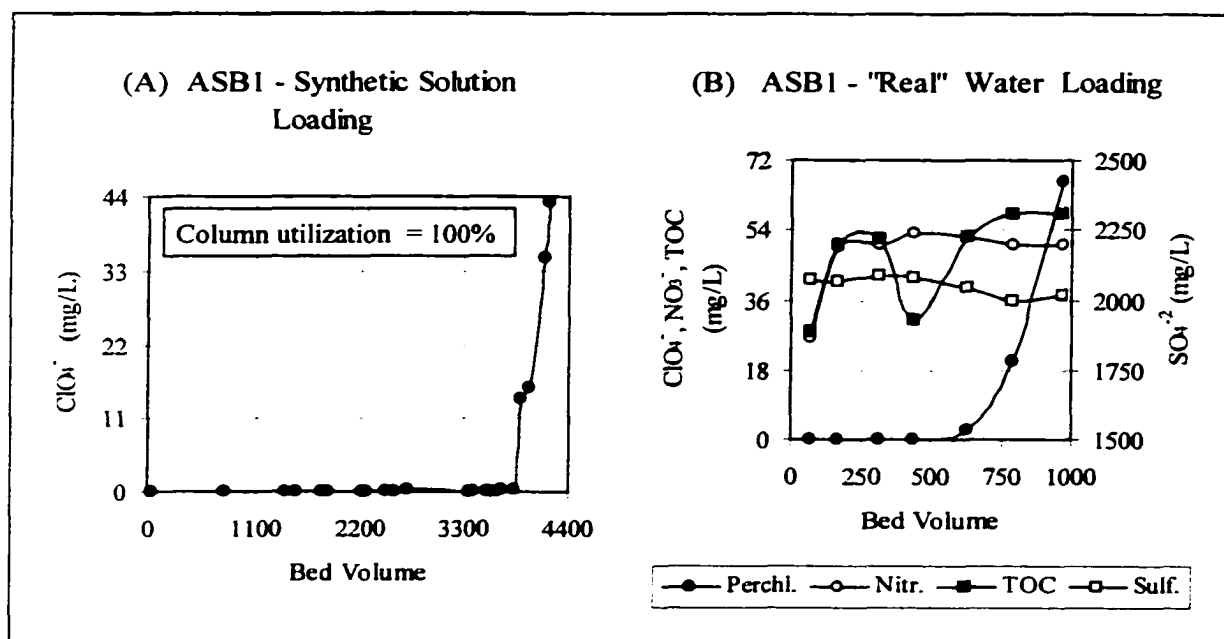


Figure 4.4.1 Exhaustion of ASB1 resin (styrenic DVB – quaternary amine); (A) fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.9 minutes, BV = 117.84 cm³, total column utilization and column utilization to breakthrough = 100% and (B) fed with the “real” water, EBCT = 4.4 minutes, BV = 114.42 cm³, total column utilization for perchlorate was 48% while the column utilization to breakthrough was 22.1%.

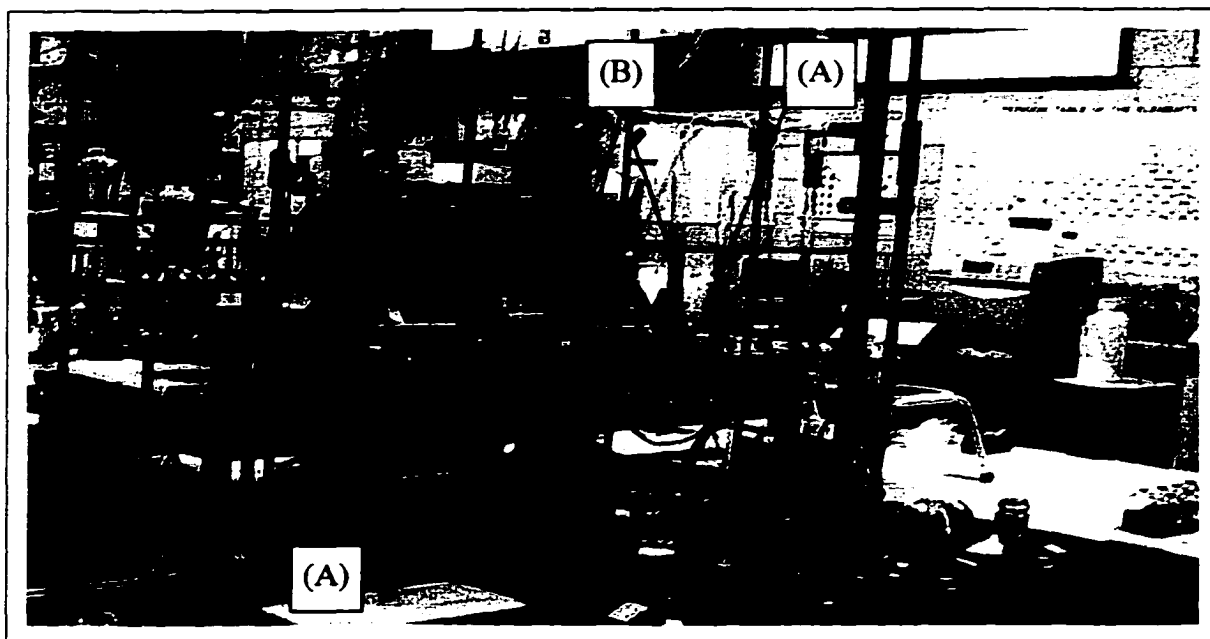


Figure 4.4.2 ASB1 and ASB2 resins when loaded with (A) synthetic perchlorate solution (columns with yellow resins on left and right) and (B) when loaded with the "real" water solution (resin bed brownish on the center).

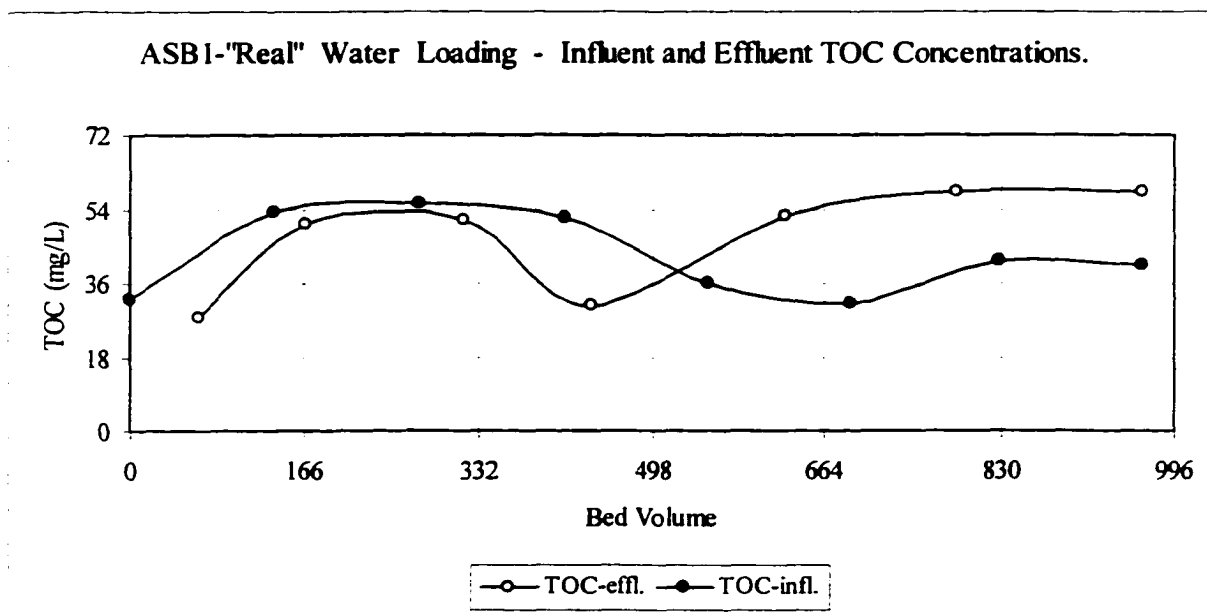


Figure 4.4.3 Influent and effluent TOC concentrations when ASB1 resin (styrenic DVB – quaternary amine) was fed with the "real" water, EBCT = 4.4 minutes and BV = 114.42 cm³.

The regeneration results for the ASB1 resin when loaded with 40 mg/L synthetic perchlorate solution and with the “real” water are displayed in Figure 4.4.4. After exhaustion with the “real” water, the resin regeneration was performed with 12% sodium chloride (NaCl) and the EBCT was about 8.7 minutes. Observe that the regeneration efficiency for perchlorate was not high [Regeneration efficiency (ϵ) = 18.0%, Figure 4.4.4 (B)] and was about half of the regeneration efficiency when the column was loaded with the perchlorate synthetic solution [Regeneration efficiency (ϵ) = 37.6%, Figure 4.4.4 (A)]. Only small amounts of sulfate and nitrate were present in the regenerant brine. This is expected since not much of the nitrate was exchanged and sulfate is continuously being pushed out by perchlorate. Based on the influent concentrations of TOC, that were very small compared to the influent concentrations of sulfate, on the amount of TOC in the regenerant brine and on the difficulty to recover the humic substances from the resins, it is suspected that considerable amounts of TOC exchanged with the resins. In addition, the perchlorate regeneration curve for resins loaded with the “real” water were not as sharp as those generated with the synthetic solutions. This indicates that the release of perchlorate from the resin may be hindered by the presence of humic substances.

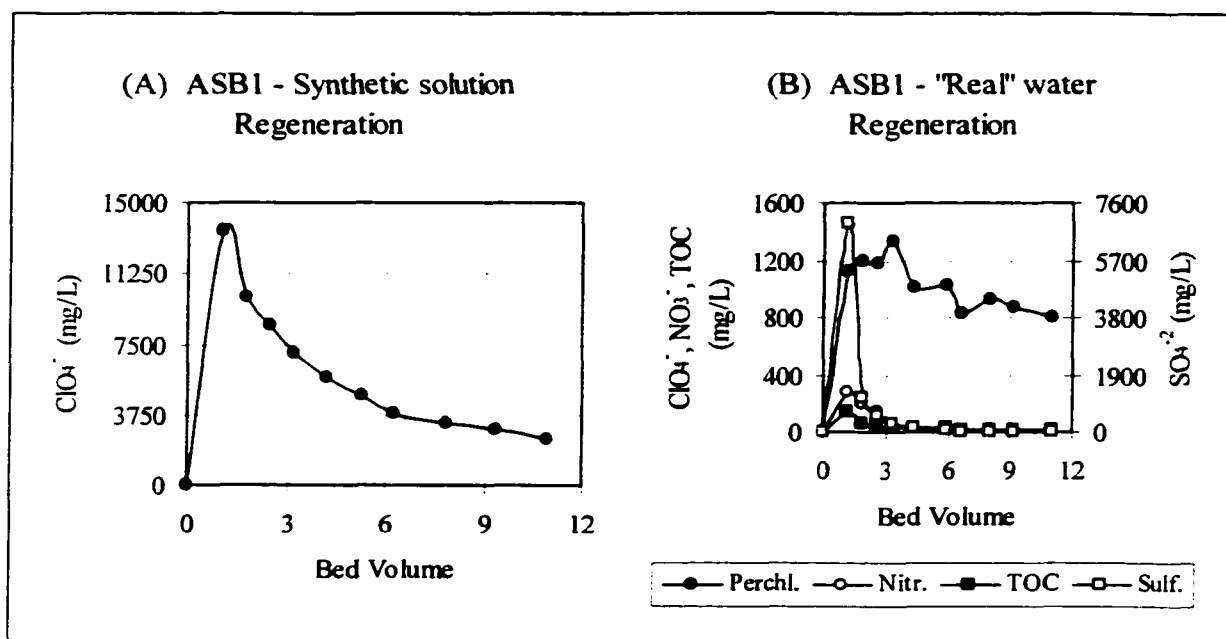


Figure 4.4.4 Regeneration of ASB1 resin (styrenic DVB – quaternary amine) with 12% NaCl; (A) EBCT = 7.8 minutes, BV = 96.94 cm³, and ϵ = 37.6% (B) EBCT = 8.7 minutes, BV = 108.34 cm³ and ϵ = 18.0%.

4.4.2 ASB2 resin (Strong base - Styrenic DVB – Dimethylethanolamine).

The loading of a strong base anionic exchange styrenic type II resin (ASB 2, Sybron Chemicals) with the “real” water is shown in Figure 4.4.5. Notice that when the “real” water was used the total column utilization is only 36% (Figure 4.4.5 - B). When the 40 ppm perchlorate synthetic solution was loaded, 100% of the column capacity was utilized (Figure 4.4.5 - A). Again, nitrate did not exchange to great extent and sulfate is continuously exchanging with perchlorate.

Similar to ASB1, this resin also became dark (Figure 4.4.2), due to the presence of humic substances. The influent and the effluent concentrations of total organic carbon (TOC) when “real” water was loaded to ASB2 resins are shown in Figure 4.4.6. Again, it is observed that considerable portion of TOC is exchanged with the resin. After about 480 BV the humic substances started increasing in the effluent, similar to what was

observed with ASB1 resin. This is the point at which perchlorate concentration increase and it suggests perchlorate pushes the humic acids out of the resin bed. The regeneration was performed with 12% NaCl and EBCT equals to 9.2 minutes. Figure 4.4.7 shows the concentration of anions in the regenerant solution from the ASB2 resin. The amount of perchlorate recovered ($\epsilon = 25\%$, Figure 4.4.7 - B) was slightly higher than that for the ASB1 resin ($\epsilon = 18\%$, Figure 4.4.4 - B), but it was below the regeneration efficiency when the synthetic solution was loaded. ($\epsilon = 43.2\%$, Figure 4.4.7 - A).

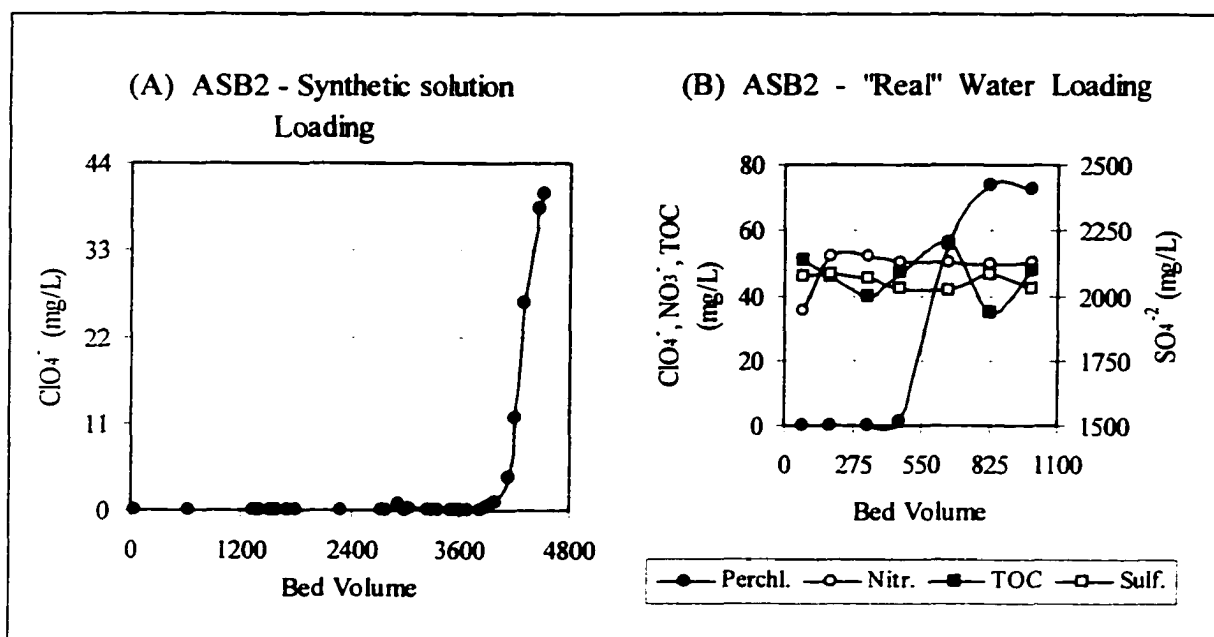


Figure 4.4.5 Loading of ASB2 resin (styrenic DVB – Dimethylethanolamine); (A) fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.5 minutes, BV = 123.54 cm³, and $\epsilon = 100\%$ (B) fed with the “real” water, EBCT = 4.2 minutes and BV = 116.7 cm³. The total column utilization for perchlorate was 36% while the column utilization to breakthrough was 19.2%.

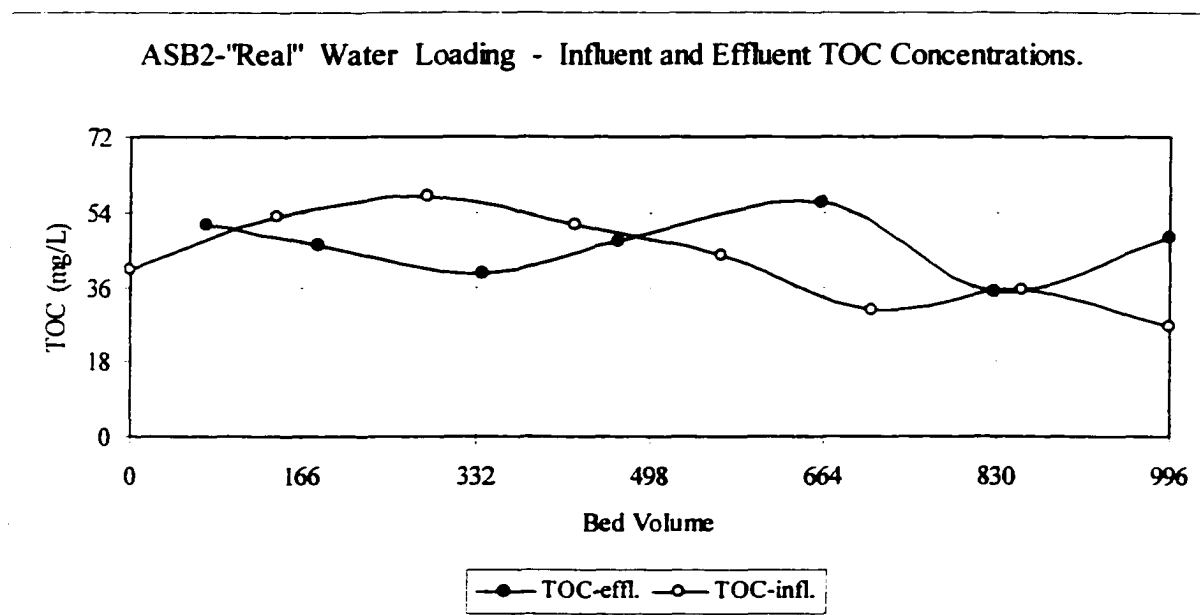


Figure 4.4.6 Influent and effluent TOC concentrations when ASB2 resin (styrenic DVB – Dimethylethanolamine) was fed with the “real” water, EBCT = 4.2 minutes and BV = 116.7 cm³.

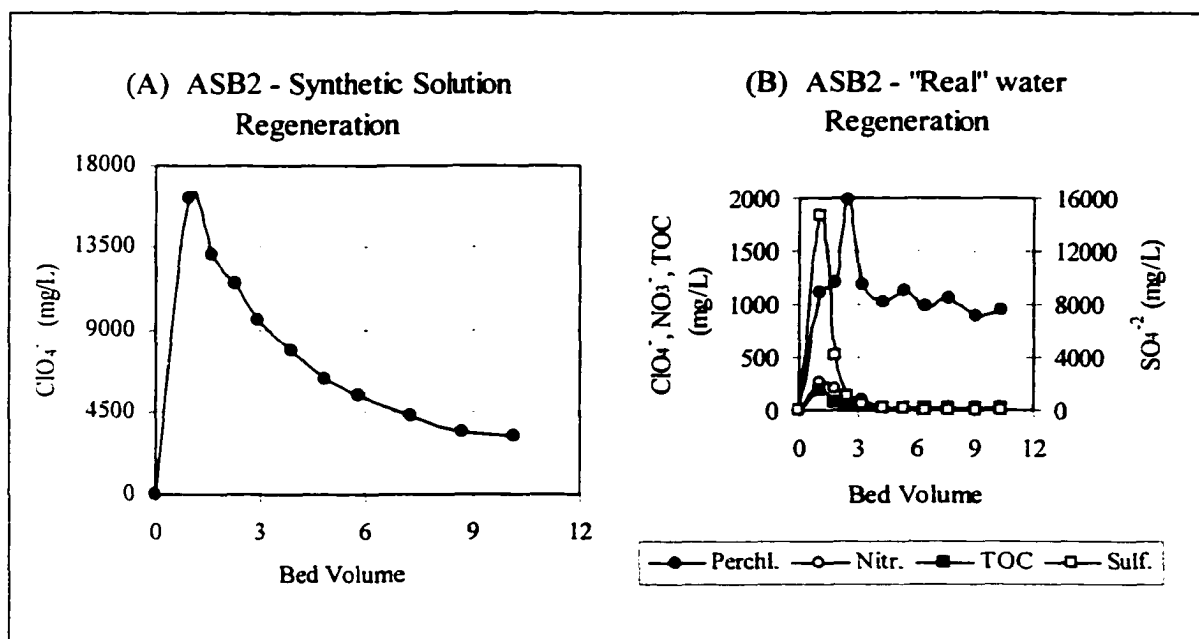


Figure 4.4.7 Regeneration of ASB2 resin (styrenic DVB – Dimethylethanolamine) with 12% NaCl; (A) EBCT = 7.6 minutes, BV = 104.54 cm³, and $\epsilon = 43.2\%$. (B) EBCT = 9.2 minutes, BV = 110.24 cm³, and $\epsilon = 25\%$ for perchlorate.

4.4.3 ASB1 PC resin (Strong base - Styrenic DVB – Quaternary amine).

Figure 4.4.8 shows the loading for a styrenic strong base anionic exchange resin (ASB1 PC, Sybron Chemicals) with a trimethyl quaternary amine functional group. This resin was chosen because it has high porosity, which makes it resistant to organic fouling and therefore it should show some improvement in perchlorate removal. The resin was in the chloride form and the minimum total exchange capacity as given by its manufacture is 1.2 eq/L. The EBCT and the BV for this test loading were 4.5 minutes and 52.31 cm³, respectively. Notice that about 21% of the column capacity was utilized by perchlorate. Again, sulfate and nitrate behaved as in the other resins and there is also indication of the influence of humic substances in the exchange process. The influence of humic substances is shown in Figure 4.4.9 with the plots of the influent and effluent TOC concentrations. Observe that this was the resin that exchanged more TOC, as it can be noted from the difference in the influent and effluent TOC concentrations. No significant change in color was observed when this resin was loaded. Similar to that observed previously, the results in this test show that apparently perchlorate pushes the humic acids out of the resins. This resin has not been exhausted with perchlorate synthetic solution and therefore comparisons cannot be made. Regeneration with 12% NaCl was able to remove 55% of the loaded perchlorate and the EBCT for the regeneration was 8.9 minutes.

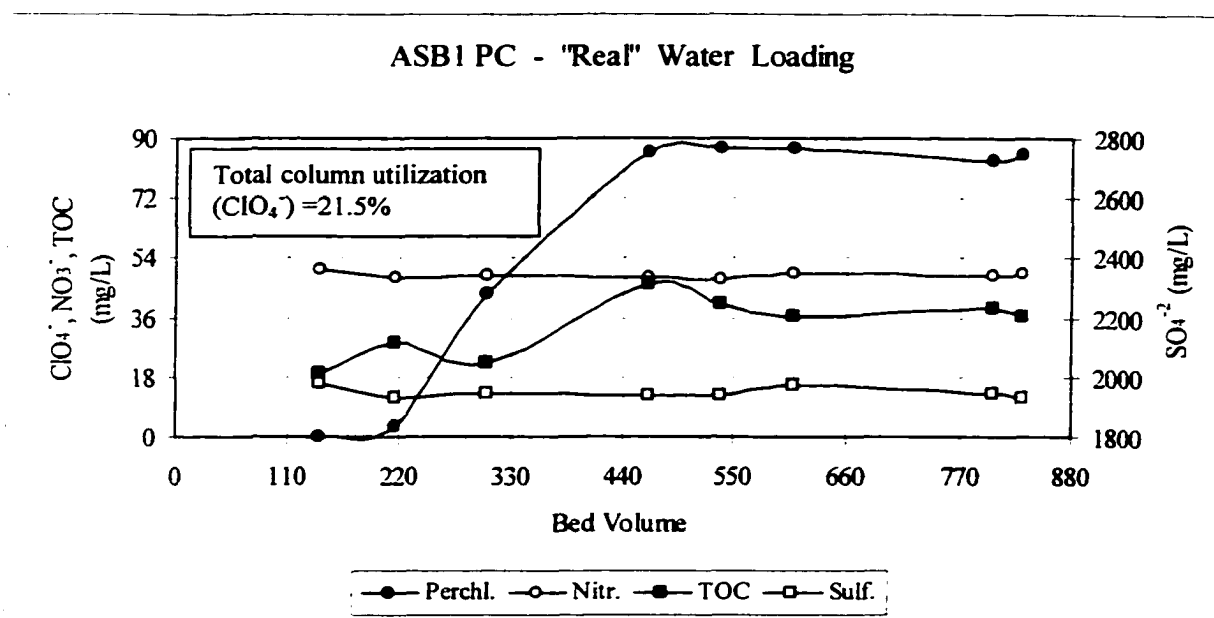


Figure 4.4.8 Loading of ASB1 PC resin (styrenic DVB – Quaternary amine); fed with the “real” water, EBCT = 4.5 minutes and BV = 52.31 cm³. The total column utilization for perchlorate was 21.5% while the column utilization to breakthrough was 0%.

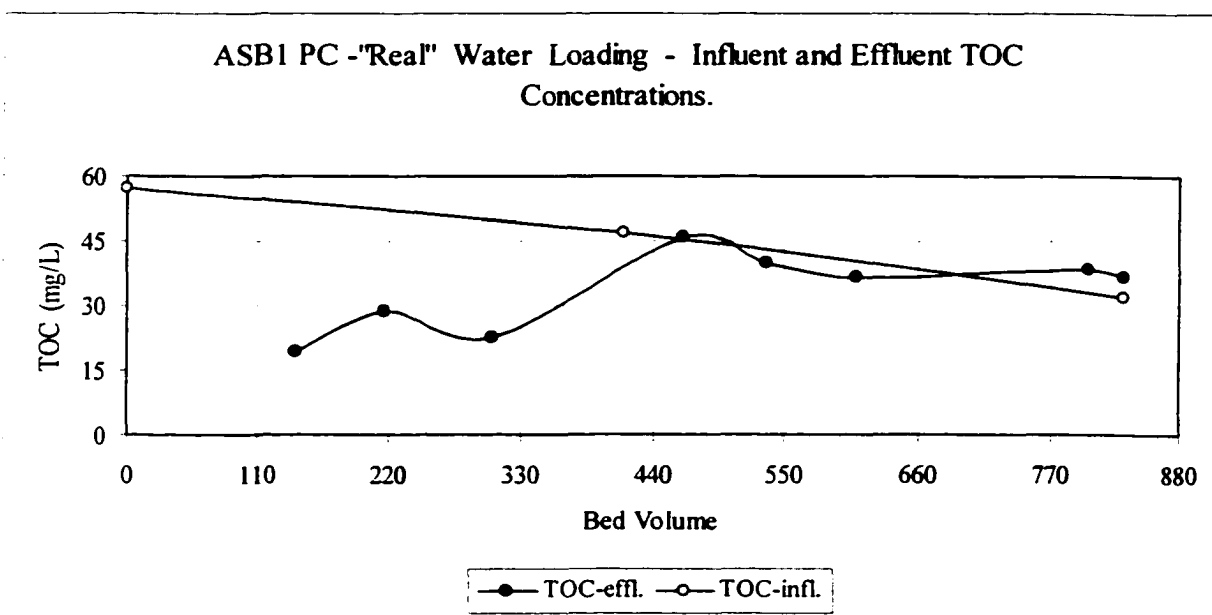


Figure 4.4.9 Influent and effluent TOC concentrations when ASB1 PC resin (styrenic DVB – Quaternary amine) was fed with the “real” water, EBCT = 4.5 minutes and BV = 52.31 cm³.

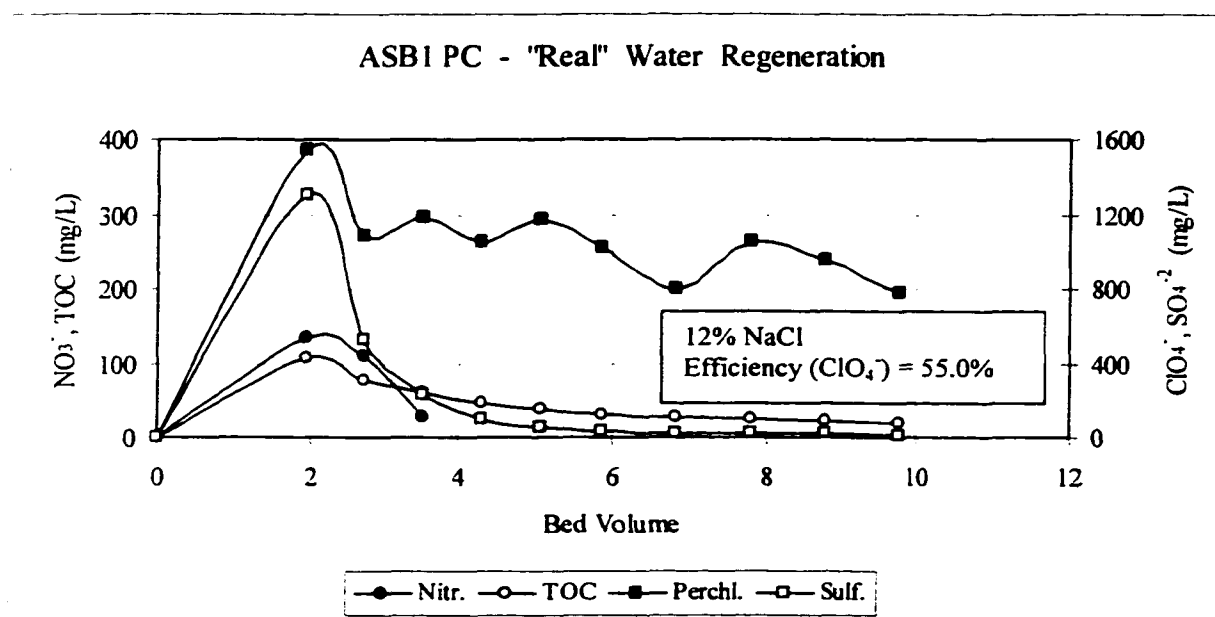


Figure 4.4.10 Regeneration of ASB1 PC resin (styrenic DVB – Quaternary amine) with 12% NaCl and EBCT equals to 8.9 minutes.

4.4.4 AFP 329 resin (Weak base - Styrenic DVB Macroporous – Tertiary amine).

Figure 4.4.11 shows the results of column testing using styrenic weak-base anionic exchange resin (AFP 329, Sybron Chemicals). Observe that the total column utilization for this resin loaded with the “real” water is very poor, about 15% (Figure.4.4.11 B) and when loaded with 40 mg/L synthetic perchlorate solution was about 18% (Figure 4.4.11 A). The “real” water test was performed with an EBCT equals to 4.6 minutes and a BV of 54.43 cm^3 . Sulfate and nitrate behaved as in the other resins and the resin became darker indicating the presence of humic substances. The TOC concentrations in the influent feed “real” water solution and in the effluent after passing through the resin bed are shown in Figure 4.4.12. Note that comparing both curves, it does not appear that TOC was exchanged as much as when the ASB1 PC resin was used.

Regeneration with 12% NaCl was able to remove approximately 44.0% of the loaded perchlorate (Figure 4.4.13 – B) that is considerably less than the regeneration of AFP 329 when exhausted with the 40 mg/L synthetic perchlorate solution (61.6% - Figure 4.4.13 – A). Nitrate was not present in the regenerant brine while TOC and sulfate were present in low concentrations compared to perchlorate. The EBCT used for regeneration was 10 minutes and the BV was 55.67 cm³.

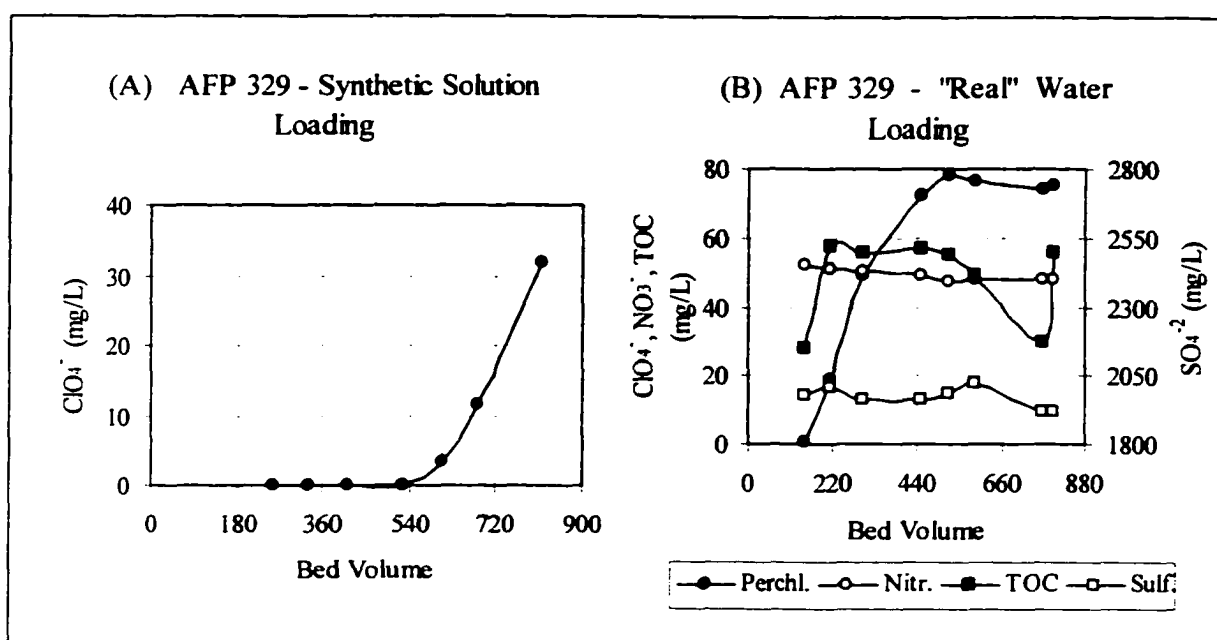


Figure 4.4.11 Exhaustion of AFP 329 resin (styrenic DVB – Tertiary amine); (A) fed with 40 mg/L synthetic perchlorate solution, EBCT = 5.5 minutes, BV = 53.01 cm³, column utilization to breakthrough = 11.2%, and total column utilization = 18.2%. The influent feed solution was carbonated; (B) fed with the "real" water, EBCT = 4.6 minutes and BV = 54.43 cm³. The total column utilization for perchlorate was 15.5% while the column utilization to breakthrough was 0%.

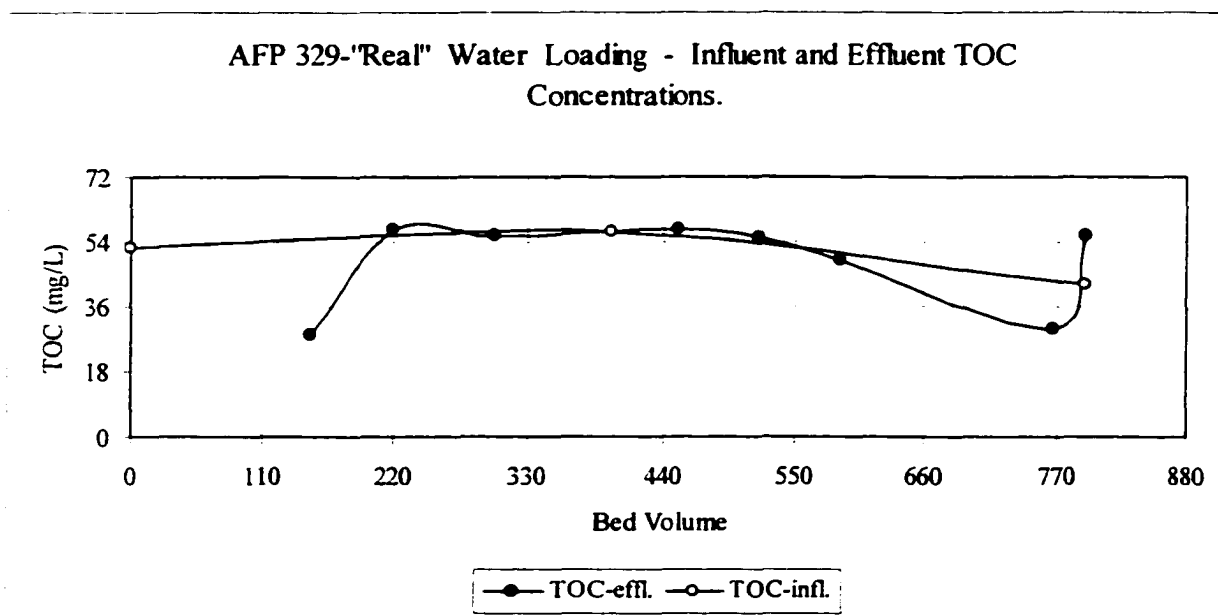


Figure 4.4.12 Influent and effluent TOC concentrations when AFP 329 resin (styrenic DVB – Tertiary amine) was fed with the “real” water, EBCT = 4.6 minutes and BV = 54.43 cm³.

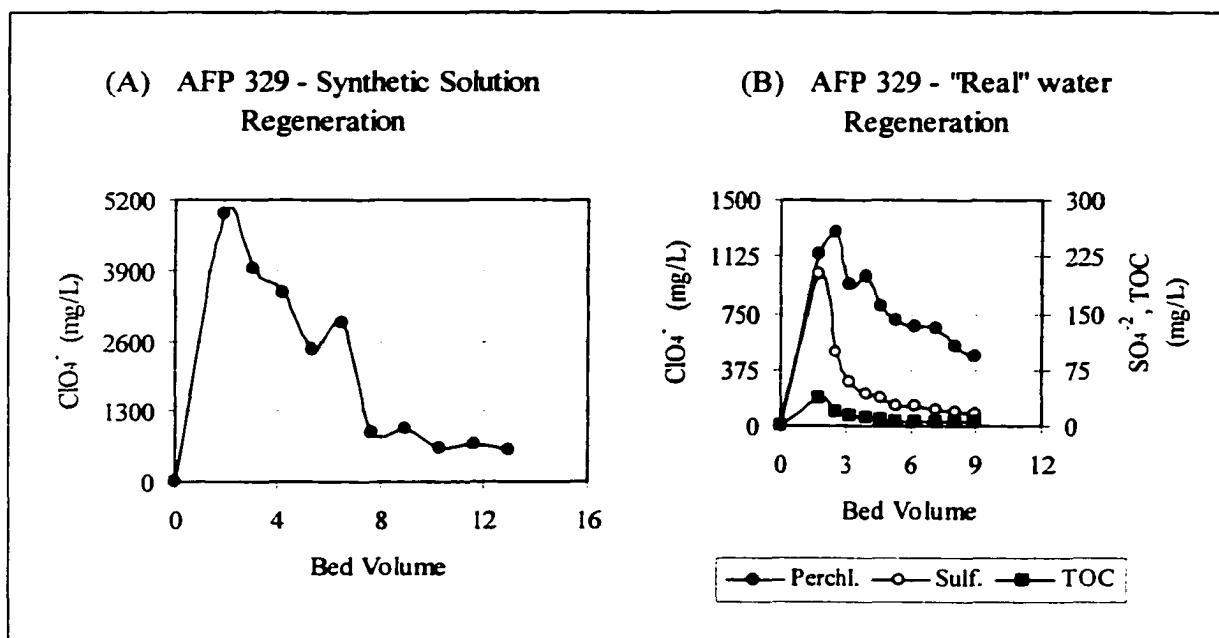


Figure 4.4.13 Regeneration of AFP 329 resin (styrenic DVB – Tertiary amine) with 12% NaCl; (A) EBCT = 18.9 minutes, BV = 52.14 cm³, and $\epsilon = 61.6\%$; (B) EBCT = 10.0 minutes, BV = 55.67 and $\epsilon = 44.0\%$. Nitrate was not present in the regeneration brine of the “real” water exhaustion.

4.4.5 Macro T resin (Strong base - Polyacrylic – Quaternary amine).

The loading data for an acrylic strong-base anionic exchange resin with a quaternary amine group (Macro T, Sybron Chemicals) is shown in Figure 4.4.14. The EBCT for this test was 4.5 minutes and the BV was 55.49 cm³. When the resin was loaded with the “real” water, no perchlorate could exchange with the resin bed (Figure 4.4.14 B). On the other hand, the total column utilization when the resin was exhausted with 40 mg/L perchlorate synthetic solution was about 92% (Figure 4.4.14 A). Sulfate and nitrate behaved as in the other resins. These observations suggest that the efficiency of acrylic quaternary amine type resins is significantly affected by the presence of humic substances contained in the “real” water. Figure 4.3.15 shows the behavior of the TOC in the influent and effluent solutions. Notice that the exchange of TOC with the resin is significant and it can be graphically visualized by comparing the influent and effluent TOC concentrations. Regeneration was performed with 12% NaCl and EBCT equals to 9.0 minutes (Figure 4.4.16). This was the resin that showed higher concentration of TOC in the regenerant brine. In addition to the measurements, the color of the regenerant brine was the darkest yellow of all regenerant brines. The results show that acrylic type resins can be easily regenerated when compared to styrenic resins. This observation is valid for both water tested, synthetic and “real”. Again, nitrate was not present in the regenerant brine of the Macro T resin while perchlorate and sulfate were present in low concentrations.

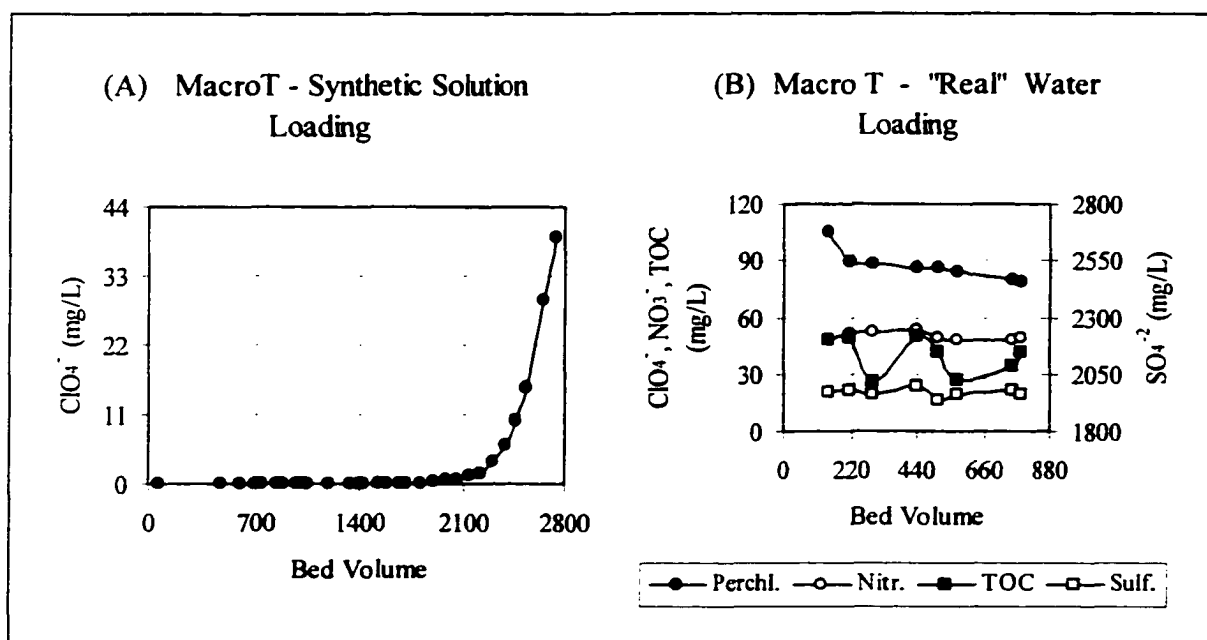


Figure 4.4.14 Loading of Macro T resin (Polyacrylic – Quaternary amine); (A) fed with 40 mg/L synthetic perchlorate solution, EBCT = 4.2 minutes, BV = 54.78 cm³, column utilization to breakthrough = 53.9% and total column utilization = 92.7%; (B) fed with the “real” water, EBCT = 4.5 minutes and BV = 55.49 cm³. The total column utilization for perchlorate approached 0%, therefore the column utilization to breakthrough was 0%.

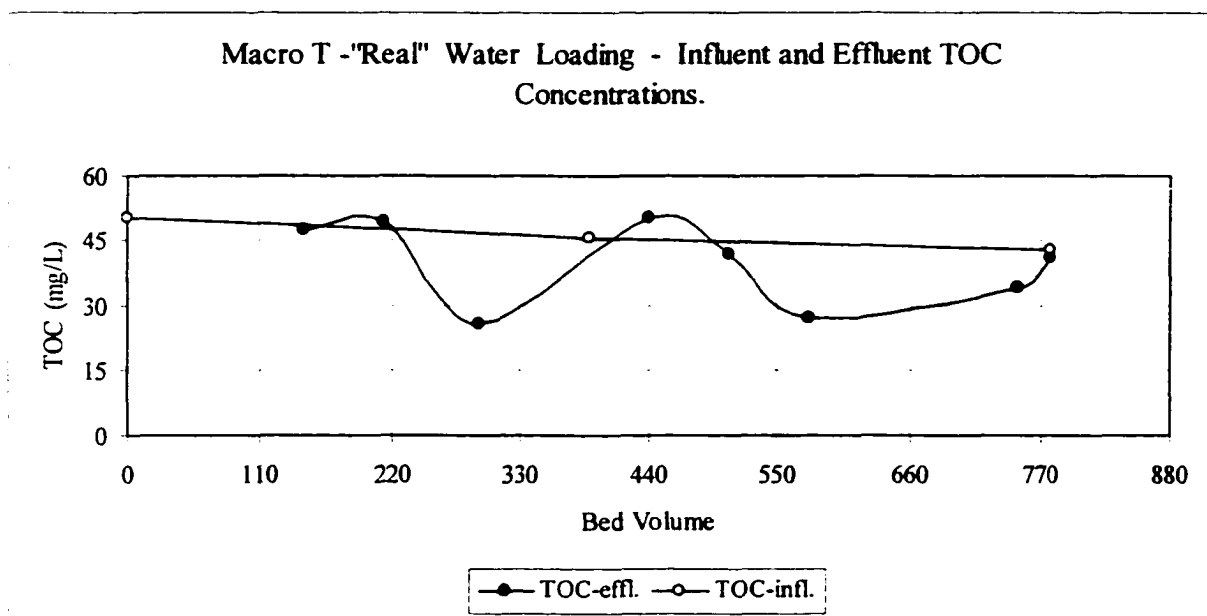


Figure 4.4.15 Influent and effluent TOC concentrations when Macro T resin (Polyacrylic – Quaternary amine) was fed with the “real” water, EBCT = 4.5 minutes and BV = 55.49 cm³.

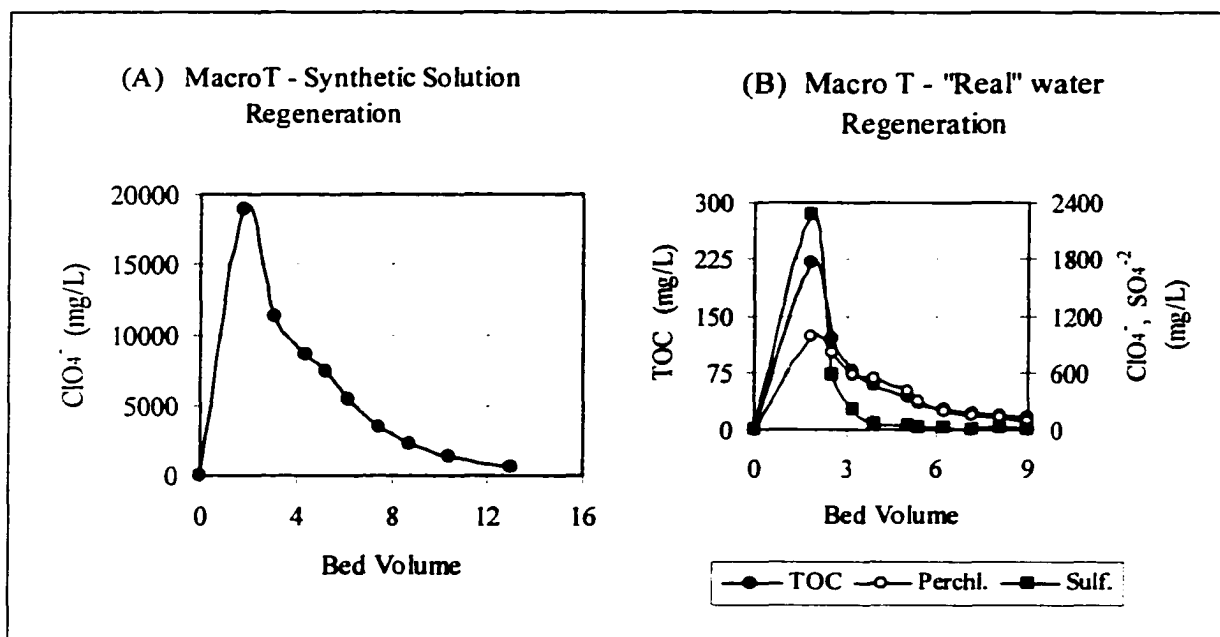


Figure 4.4.16 Regeneration of Macro T resin (Polyacrylic – Quaternary amine) with 12% NaCl; (A) EBCT = 4.4 minutes, BV = 54.78 cm³, and $\epsilon = 100\%$; (B) EBCT = 9.0 minutes and BV = 55.67 cm³.

4.4.6 Expression of the Mass of Contaminants Present in the Regenerant Solution on an Equivalent Basis

Table 4.4.2 and Figures 4.4.17 and 4.4.18 show the mass of contaminants in the regenerant solutions on an equivalent basis. These calculations were performed because the columns used did not contain the same amount of resin. Although several interactions are taking place due to the large amount of anions present, the combination of these calculations with the breakthrough curves lead to some valuable conclusions regarding the behavior of the resins tested in the presence of the “real” water. More relevant conclusions could be drawn if binary solutions of perchlorate with the anions in question were tested.

As noticed in Table 4.4.2 (column (f)) the largest mass of perchlorate, sulfate, nitrate and TOC were recovered from the ASB1 PC resin, Macro T, ASB1, and Macro T, respectively. Combined to the breakthrough curves these calculations reveal that Macro T is the resin that exchanges the largest amount of TOC and sulfate and the smallest amount of perchlorate. The ASB1 PC resin exchanged a lot of TOC, and a lot of perchlorate could be stripped out of the resin. Although the ASB1 PC resin did not exchange a lot of perchlorate (Figure 4.4.8), the regeneration of perchlorate from this resin is much more efficient than that for the other styrenic resins (ASB1 and ASB2).

Table 4.4.2 Calculation of the amount of anions released in the regenerant solution on an equivalent of resin basis

Resin Type (a)	Bed Volume (ml) (b)	Exchange Capacity (eq/L) (c)	Equivalents (d) = [(b)*(c)]/1000	Mass of anions in the regenerant brine (mg) (e)				amount of anions released per equivalent of resin (mg/eq) (f) = (e)/(d)			
				ClO ₄ ⁻	SO ₄ ⁻²	NO ₃ ⁻	TOC	ClO ₄ ⁻	SO ₄ ⁻²	NO ₃ ⁻	TOC
ASB1	114.42	1.4	0.1602	1374.3	2277.5	99.0	55.4	8579.3	14217.7	618.0	345.8
ASB2	116.7	1.4	0.1634	1454.7	3693.7	90.4	61.5	9603.8	22608.0	553.3	376.4
ASB1 PC	52.31	1.2	0.0628	740.9	1346.6	5.5	31.7	11803.0	21739.0	87.6	505.0
Macro T	55.49	1.1	0.0610	295.8	1700.7	2.3	85.1	4846.1	27862.5	37.7	1394.2
AFP 329	54.43	1.6	0.0871	594.3	122.4	0	15.7	6824.1	1405.5	0	180.3

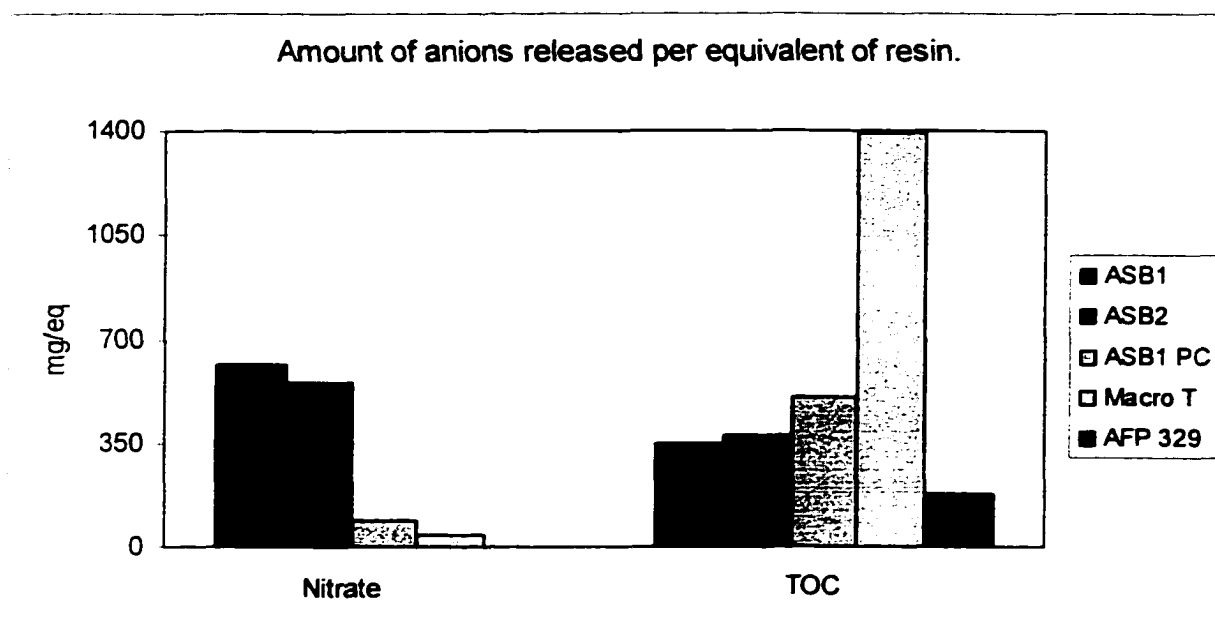


Figure 4.4.17 Amount of anions released per equivalent of resin indicates the best regeneration for certain resin. This figure shows the regeneration for nitrate and total organic carbon.

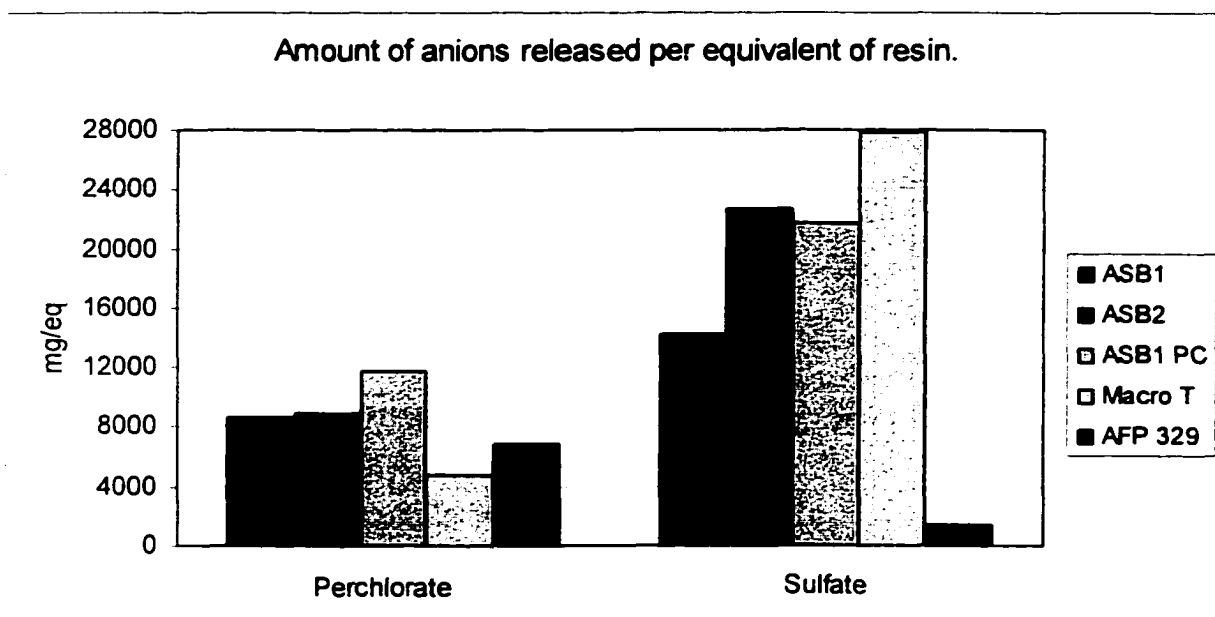


Figure 4.4.18 Amount of anions released per equivalent of resin indicates the best regeneration for certain resin. This figure shows the regeneration for perchlorate and sulfate.

4.4.7 Discussion

Table 4.4.3 summarizes the results for the resins exhausted with the “real” water solution. The table includes the resin type, column utilization to breakthrough and total column utilization, regeneration efficiency and the total mass of TOC, and anions recovered in the regenerant solution used.

Table 4.4.3 Summary of the results for all the resins tested with the “real” water contaminated with perchlorate and synthetic perchlorate solutions.

Resin Type	Perchlorate Synthetic Solution (40 mg/L)				“Real” Water							
					Perchlorate Analysis				Mass of anions in the regenerant brine (mg)			
	BV to BKT (a)	Column Util. to BKT (b)	Total Column Util. (c)	Reg. Efficiency with 12% NaCl (d)	BV to BKT (e)	Column Util. to BKT (f)	Total Column Utili. (g)	Reg. Efficiency with 12% NaCl (h)	ClO ₄ ⁻ (i)	SO ₄ ⁻² (j)	NO ₃ ⁻ (k)	TOC (l)
ASB1 Strong-Base styrenic	3,486	100%	>100%	37.6%	392	22.1%	48.0%	18%	1374.3	2277.5	99.0	55.4
ASB2 Strong-Base styrenic	3,520	100%	>100%	43.2%	338	19.2%	36%	25%	1454.7	3693.7	90.4	61.5
ASB1 PC Strong-Base styrenic	Not tested	Not tested	Not tested	Not tested	0	0.0%	21.5%	55.0%	740.9	1364.6	5.5	31.7
Macro T Strong-Base acrylic	1438	52.6%	93.1%	100%	0	0.0%	0.0%	Immediate ClO ₄ ⁻ BKT**	295.8	1700.7	2.3	85.1
AFP 329 Weak-Base styrenic	477	12.0%	17.8%	61.6%	0	0.0%	15.5%	44.0%	594.3	122.4	0.0	15.7
**The first effluent sample from this test already had ClO ₄ ⁻ concentration equals to the influent ClO ₄ ⁻ concentration. Thus, it was not possible to calculate the amount of ClO ₄ ⁻ exchanged with the resin, and this value would approach zero.												

The data show that the capacity for perchlorate of all resins was adversely affected by the presence of humic substances as it can be observed comparing columns (a), (b), (c) with (e), (f) and (g) in Table 4.4.2. It further show that the high sulfate concentration in the water (about 2000 mg/L) quickly saturated the resin but perchlorate continuously replaced the sulfate and could also be removed. Thus, theoretically, a resin could be preloaded with sulfate for perchlorate removal purposes, just like chloride is currently used.

A very significant effect of humic acids on perchlorate exchange was observed for the acrylic Macro T resins. Compared to 93.1% total column utilization when no humic acids were present, the column utilization literally decreased to 0%. This column is the one from which the largest amount of humic acids per equivalent of resins could be removed in the regeneration process (Figure 4.4.17). This result was not unexpected since several researchers (Kunin and Suffet, 1980; Boening *et.al.*, 1980;) have found that humic acids is more easily removed from acrylic than from styrenic resins.

The strong-base styrenic resins ASB1 and ASB2 behaved very similarly in the presence of humic acids and their capacity for perchlorate was reduced to about 50% (columns (b) and (g) in Figure 4.4.2). The regeneration of the resin with 12% sodium chloride did not remove much of the exchanged humic acids.

The capacity of the styrenic weak-base resin (AFP 329) for perchlorate was moderately affected by the presence of humic acids as compared to the other resins. This resin did not take up much humic acids.

The macro porous styrenic strong-base resin ASB1 PC exchanged considerable amount of humic acids and perchlorate and both anions could be stripped out more easily

from ASB1 PC than from ASB1 and ASB2. The macro porous resins are manufactured to avoid resin fouling by allowing the large humic acids molecules to pass through the resin bead. For the “real” water in question, some of the humic acids were retained indicating that probably the size of the humic acids molecules were larger than the nominal macro pore of the resin.

Therefore, the presence of humic acids in waters may significantly affect the removal of perchlorate by ion exchange resins.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from this research:

5.1 Strong-base anionic exchange resins

1. Strong-base styrenic type resins were found to be very effective in removing perchlorate from water. For two styrenic resins, ASB1 and ASB2 with trimethyl and dimethylethanol functional groups respectively, 100% of the resin capacity was utilized by perchlorate. However, these resins do not regenerate well. Only about 40% of the loaded perchlorate was removed during regeneration indicating that perchlorate attaches very strongly to these resins.
2. A styrenic resin with a tripropyl functional group, SR-7 showed average column utilization. Regeneration with 12% NaCl was ineffective and only about 20% of the loaded perchlorate could be stripped out of the resin.
3. The column utilization for Macro T (a strong base acrylic resin) was 52.6% in average for duplicate tests and regeneration with 12% NaCl was able to

remove 100% of the loaded perchlorate. This shows that strong-base acrylic resins regenerate better than the styrenic counterpart.

4. Reloading of Macro T resin showed that it is possible to reuse the resin. However, the column utilization to breakthrough for the second loading of the resins was 36.2% as compared to 67.7% in the first loading. It seems that in the second exhaustion the kinetics of exchange was slower causing the resin to lose its capability of removing perchlorate to very low concentrations (i.e. below 20 $\mu\text{g/L}$). Regeneration of the perchlorate loaded to the resin with 12% NaCl was 100% efficient.
5. A strong-base acrylic resin, A-850 showed an average column utilization of 64.5% in duplicate tests. Regeneration of one of the columns with 12% NaCl had impressive results with 100% of the loaded perchlorate being stripped out of the resin. On the other hand, the regeneration of the other column with 1% NaOH was able to remove only 38% of the loaded perchlorate. The good performance of this acrylic resin confirms that acrylic resins loaded with perchlorate regenerate better than styrenic ones.
6. In an independent test with A-850, the column utilization to breakthrough for the first exhaustion was about 3 times larger than that for the second exhaustion. Similar to the Macro T resin, it appears that in the second exhaustion the resin lost the capability of removing perchlorate to very low concentrations (i.e. below 20 ppb). Regeneration of this resin with 12% NaCl was 100% efficient.

5.2 Weak-base anionic exchange resins

1. The column utilization to breakthrough for a styrenic weak-base (AFP-329) resin was very poor, 12% in average for duplicate tests. Carbonation of the resin prior to loading did not result in increased column utilization. Regeneration of the resin with 1% NaOH was able to remove only 12.4 % of the loaded perchlorate. However, regeneration with 12% NaCl was able to remove 61.6% of the loaded perchlorate. These results were unexpected, since the perchlorate loaded to the weak base anionic exchange resin should be removed by NaOH. The manufacturer of this resin reports that the composition of AFP-329 contains about 16% strong base groups (Sybron Chemicals, 1999). Calculations have shown that the amount of perchlorate exchanged is roughly equal the strong-base capacity of the resin. Thus, this styrenic weak base resin does not remove perchlorate very well.
2. Acrylic weak-base resin (A-830) showed an averaged column utilization of 35.1% for duplicate tests. Regeneration with 1% NaOH was able to remove about 76% of the loaded perchlorate. Regeneration with 12% NaCl removed 100% of the loaded perchlorate. These results show that acrylic weak base resins have relatively high column capacity for perchlorate and regenerate easily with both caustic solutions and sodium chloride. It is likely that a higher concentration of NaOH would promote very similar removal efficiency to that of sodium chloride. If caustic solutions are used as the

regenerant, acrylic weak-base resins would generate regenerant solutions that are potentially treated biologically.

3. For duplicate tests with a polyacrylic weak base (A-365) resin, the column utilization to breakthrough was equal 0%. This type of resin was not able to remove perchlorate from waters. Similarly to A 365-type resin, another weak-base type resin (XR-405) was not able to remove perchlorate from the 40 mg/L perchlorate synthetic solution with and without carbonation. For both tests the resin utilization to breakthrough was equal 0%.
4. The performance of both acrylic and styrenic weak-base resins did not seem to be affected much by carbonation. The mechanisms of perchlorate exchange with weak-base resins are subjected for further research. It is possible that carbonation of the water may occur as the water drips into the top of the resin column, but this has not been proven experimentally.

5.3 “Real” water testing

1. The total column utilization for two styrenic strong-base resins (ASB1 and ASB2) were only 48% and 36% respectively when loaded with the “real” water and it was 100% when loaded with 40 mg/L perchlorate synthetic solution. This indicates that approximately 50% of the resin capacity was occupied by anions other than perchlorate.

2. Yellow coloration of the resins during the loading suggested the presence of humic materials. This was confirmed by measuring the TOC concentrations of the “real” water that was found to be in average 45 mg/L.
3. The high concentration of sulfate in the water rapidly saturated the resin. Perchlorate was continuously removed from the water by pushing sulfate out of the resin. Thus, despite the affinity of resins for sulfate, perchlorate can still be removed from waters containing high concentrations of this anion. One could then pre-load a resin with sulfate in order to remove perchlorate from waters.
4. For a macroporous strong base styrenic resin (ASB1 PC), about 21% of the column capacity was utilized by perchlorate. Nitrate did not exchange at greater extent and sulfate saturated the resin bed quickly. ASB1 PC exchanged considerable amount of humic acids and perchlorate. Both humic acids and perchlorate anions could be stripped out easier from ASB1 PC than from the ASB1 and ASB2 resins. Regeneration with 12% NaCl was able to remove 55% of the loaded perchlorate.
5. The capacity of the styrenic weak-base resin (AFP 329) for perchlorate was moderately affected by the presence of humic acids as compared to the other resins. The total column utilization for this resin loaded with the “real” water was about 15% and when loaded with 40 mg/L synthetic perchlorate solution was about 18%. Nitrate was not present in the regenerant brine while TOC

and sulfate were present in low concentrations compared to perchlorate. Humic acids were not exchanged with this resin.

6. When Macro T, a strong-base acrylic resin, was loaded with the “real” water, no perchlorate was exchanged with the resin bed. The total column utilization for this resin exhausted with 40 mg/L perchlorate synthetic solution was about 92%. The efficiency of a strong-base acrylic quaternary amine type resins is significantly affected by the presence of humic substances contained in the “real” water.
7. The presence of humic acids in waters may significantly affect the removal of perchlorate by ion exchange resins. However, humic substances could be removed from the water by pre-treatment with activated carbon.

5.4 Recommendations for Further Research

Based on the results and on the need for an economically feasible technology for perchlorate removal from waters, the following experiments are recommended for further research:

1. Test the most promising resins at lower empty bed contact times (EBCT) to evaluate whether larger volumes of water can be treated in a shorter period of time.
2. Exhaust and load the Macro T and A-850 resins at higher EBCT's to confirm that the exchange kinetics is slower.

3. Evaluate the influence of strong-base groups on perchlorate removal and regeneration of weak-base anionic styrenic resins.
4. Regenerate weak-base acrylic resin (A-830) with higher concentration of caustic solutions (3-5%) to achieve 100% regeneration efficiency.
5. Investigate the mechanisms of perchlorate removal by weak-base anionic exchange resins.
6. Investigate the extent of carbonation needed to promote the removal of perchlorate by weak-base anionic exchange resins using acrylic resins (e.g. A-830)
7. Examine the effects of humic acids on perchlorate removal by ion exchange resins, by using binary synthetic solutions of humic acids and different anions at different concentrations.
8. Investigate the feasibility and kinetics of biodegradation of caustic regenerant solutions from weak-base resins.
9. Study the feasibility and kinetics of biodegradation of weak-base resins brine regenerant solutions. That includes efforts towards isolating microorganisms (halophiles) capable of degrading perchlorate in the presence of high salinity.

APPENDIX A

ION CHROMATOGRAPHY PERCHLORATE ANALYSIS METHOD



Analysis of Low Concentrations of Perchlorate in Drinking Water and Ground Water by Ion Chromatography

INTRODUCTION

Perchlorate (as ammonium perchlorate), which is widely used in solid rocket propellants, has recently been found in drinking water wells in areas where aerospace materials and munitions have been manufactured and tested.¹ Perchlorate is a health concern, as it interferes with the production of thyroid hormones. Current data suggest that an exposure level range of 4 to 18 µg/L (ppb) is acceptable.² Although perchlorate is not yet regulated in the U.S. under the Federal Safe Drinking Water Act, the State of California requires remedial action for drinking water sources containing greater than 18 µg/L of perchlorate.

This Application Note details a new method developed to quantify low levels of perchlorate. A large loop injection (1000 µL) is used with an IonPac[®] AS11 column and suppressed conductivity detection to quantify perchlorate in drinking water down to approximately 2.5 µg/L.

EQUIPMENT

Dionex DX-500 Ion Chromatography system consisting of:

- GP40 Gradient Pump
- CD20 Conductivity Detector
- AS40 Automated Sampler
- LC20 Chromatography Enclosure with a rear-loading valve

- 4-L Plastic bottle assemblies (two for external water mode)
- PeakNet Chromatography Workstation

REAGENTS AND STANDARDS

Deionized water (DI H₂O), Type I reagent grade, 18 MΩ-cm resistance or better

Sodium hydroxide, 50% (w/w) aqueous solution (Fisher Scientific or other)

Sodium perchlorate, 99% ACS reagent grade or better (Aldrich or other)

Potassium sulfate, 1000 mg/L aqueous solution (Ultra Scientific or other)

CONDITIONS

Columns: IonPac AS11 Analytical,
4 x 250 mm (P/N 44076)
IonPac AG11 Guard,
4 x 50 mm (P/N 44078)

Eluent: 100 mM Sodium hydroxide

Run Time: 12 min

Flow Rate: 1.0 mL/min

Sample Volume: 1000 µL

Detection: Suppressed conductivity, ASRS[®] (4 mm AutoSuppression[®] external water mode)

System

Backpressure: 600ñ900 psi (3.95ñ5.93 MPa)

Background

Conductance: 2ñ5 µS

PREPARATION OF SOLUTIONS AND REAGENTS

Standard Solution

Stock perchlorate standard solution (1000 mg/L)

Dissolve 1.231 g of sodium perchlorate in 1000 mL of deionized water to prepare a 1000 mg/L standard. Standard is stable for at least one month when stored at 4 °C.

Working Standard Solutions

Dilute 1000 mg/L standard solution as required with deionized water to prepare the appropriate working standards.

Eluent Solution

100.0 mM Sodium hydroxide

Weigh 992.0 g of deionized water into an eluent bottle. Degas water for approximately 5 minutes. Carefully add 8.0 g of 50% sodium hydroxide directly to the bottle. Mix then quickly transfer the eluent bottle to the instrument and pressurize the bottle with helium at 8 psi (0.055 MPa).

RESULTS AND DISCUSSION

For the best performance at low-ppb levels, it is critical that baseline noise be kept to a minimum. To minimize baseline noise, it is necessary to use the ASRS in external water mode rather than the recycle mode. An equilibrated system will produce a background conductance between 2nS μ S. Peak-to-peak noise is typically 10 nS and system backpressure is 600n900 psi (3.95n5.93 MPa). A system blank is determined by using deionized water as a sample. This blank establishes the baseline and confirms the lack of contamination in the system. The linear concentration range was determined to ensure accurate quantification of perchlorate in the 2.5n100 μ g/L range. Figure 1 shows the results of a linearity study.

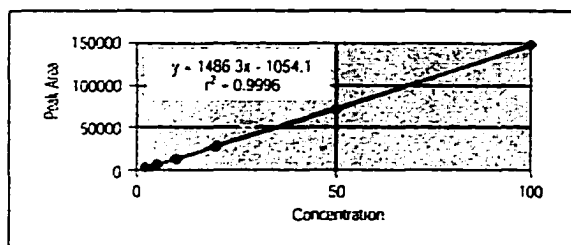


Figure 1 Perchlorate calibration

This plot demonstrates that calibration of perchlorate is linear in the low-ppb range. Figure 2 shows a typical chromatogram of a 20 μ g/L perchlorate standard. To determine the method detection limit (MDL), seven injections of the 2.5 μ g/L perchlorate standard were made. Table 1 shows the results of a method detection limit study. The 1000 μ L injection is large enough to achieve the desired detection limit without overloading the column. Note that this method is not intended for use with high (ppm) levels of perchlorate. The calculated MDL equals 254 ng/L (ppt).

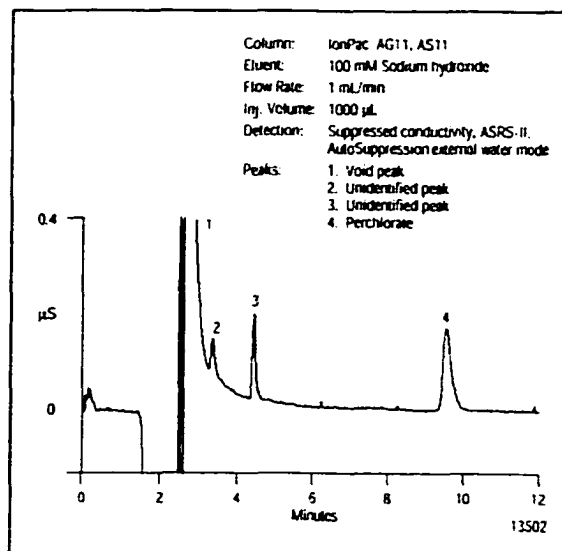


Figure 2 20 μ g/L Perchlorate standard

Injection #	Area counts	Retention time (min)
1	3391	9.48
2	3405	9.57
3	3504	9.50
4	3503	9.45
5	3435	9.47
6	3301	9.52
7	3315	9.43
Average	3408	9.49
SD	81	0.05
RSD	2.38	0.49

MDL = 254 ng/L (ppt). MDL = $SD \cdot t_{1.65}$ where $t_{1.65} = 3.14$ for $n=7$

2 Analysis of Low Concentrations of Perchlorate in Drinking Water and Ground Water by Ion Chromatography

Figures 3 through 5 show chromatograms obtained for 2.5 $\mu\text{g/L}$ perchlorate in three different matrices. Figure 3 shows the chromatogram of 2.5 $\mu\text{g/L}$ perchlorate in deionized water. Figure 4 shows 2.5 $\mu\text{g/L}$ perchlorate in tap water. Note that all other anions present in tap water elute in the void volume and do not interfere with perchlorate determination. Some environmental samples may contain low levels of perchlorate in the presence of a large amount of sulfate. Figure 5 shows the determination of 2.5 $\mu\text{g/L}$ perchlorate in the presence of 700 mg/L sulfate. The high concentration of sulfate does not affect perchlorate recovery or the detection limit.

SUMMARY

The method outlined in this Application Note allows the determination of low- $\mu\text{g/L}$ (ppb) levels of perchlorate. Linear concentration ranges have been established to accurately quantify perchlorate in drinking water and ground water samples.

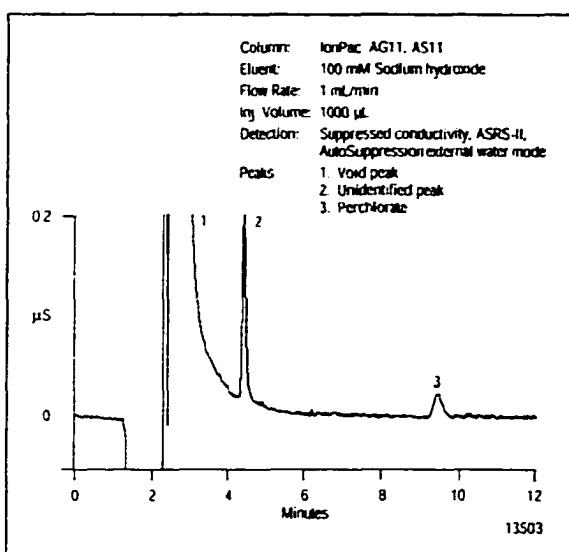


Figure 3 2.5 $\mu\text{g/L}$ Perchlorate standard

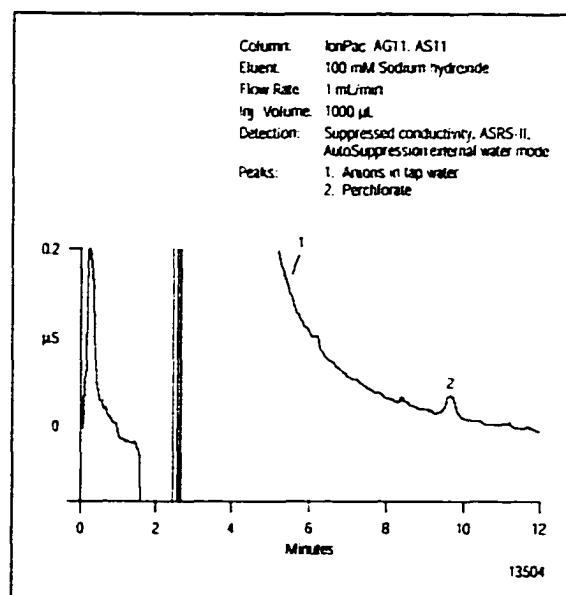


Figure 4 2.5 $\mu\text{g/L}$ Perchlorate in tap water

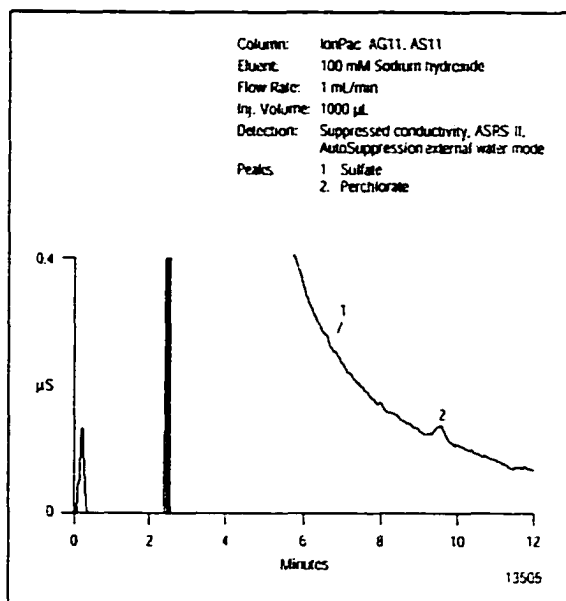


Figure 5 2.5 $\mu\text{g/L}$ Perchlorate and 700 mg/L Sulfate

REFERENCES

1. 1 Perchlorate in California Drinking Water ; California Department of Health Services, September 1997.
2. Correspondence from Joan S. Dollarhide, National Center for Environmental Assessment, Office of Research and Development, to Mike Gizzard, Chairman, Perchlorate Study Group, U.S. EPA, 1995.

LIST OF SUPPLIERS

Aldrich Chemical Company, Inc., 1001 West Saint Paul Avenue, P.O. Box 355, Milwaukee, Wisconsin, 53233, USA. Tel: 1-800-558-9160.

Fisher Scientific, 711 Forbes Ave., Pittsburgh, Pennsylvania, 15219-4785, USA.
Tel: 1-800-766-7000.

Ultra Scientific, 250 Smith Street, North Kingstown, Rhode Island, 02852, USA. Tel: 401-294-9400.

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APPENDIX B

DATA TABLES OF EXPERIMENTAL RESULTS

UNIVERSITY OF NEVADA LAS VEGAS
HOWARD R. HUGHES COLLEGE OF ENGINEERING
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.1

Test-----> Adsorption of Perchlorate	Column diameter-----> 2.2 cm
Resin type-----> ASB1	Height-----> 31 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 117.84 ml
Period-----> 09/27/1999 to 10/24/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
27-Sep	13:14	17:15		241	5420	5.77	5420	45.99	0.00	22.5	5.2	1
		21:34		259	5890	5.28	11310	95.98	0.00	22.7	5.2	2
28-Sep		7:47		613	14028	5.4	25338	215.02	0.00	22.9	5.1	3
		12:52		305	7049	5.44	32387	274.84	0.00	23.1	5.1	4
		16:54		242	5580	5.45	37967	322.19	0.00	23.1	5.1	5
		21:28		274	6400	5.37	44367	376.50	0.00	23.4	5.0	6
29-Sep		7:16		588	13780	5.51	58147	493.44	0.00	23.4	5.0	7
		11:42		266	6280	5.5	64427	546.73	0.00	23.6	5.0	8
		16:16		274	6500	5.59	70927	601.89	0.00	23.7	5.0	9
		20:41		265	6170	5.57	77097	654.25	4.32	23.3	5.1	10
30-Sep		8:02		681	16290	5.7	93387	792.49	0.00	23.9	4.9	11
		10:38	10:50	156	3360	5.73	96747	821.00	0.00	21.5	5.5	12
04-Oct	12:55	16:07		192	4510	5.91	101257	859.28	0.00	23.5	5.0	13
		20:46		279	6540	5.64	107797	914.77	0.00	23.4	5.0	14
05-Oct		8:25		699	17760	5.84	125557	1,065.49	0.00	25.4	4.6	15
		12:49		264	6250	5.75	131807	1,118.53	0.00	23.7	5.0	16
		17:37		288	6800	5.74	138607	1,176.23	0.00	23.6	5.0	17

Continued

Date	Time:		Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled Stopped									
		21:50	253	7000	5.65	145607	1,235.63	4.84	27.7	4.3	18
06-Oct		7:55	605	15370	6.18	160977	1,366.06	0.00	25.4	4.6	19
		12:24	269	6370	5.71	167347	1,420.12	8.24	23.7	5.0	20
		17:08	284	6690	5.67	174037	1,476.89	0.00	23.6	5.0	21
		21:39	271	6340	5.68	180377	1,530.69	8.55	23.4	5.0	22
07-Oct		8:12	633	15220	5.81	195597	1,659.85	0.00	24.0	4.9	23
11-Oct	21:06	-	-	-	-	-	-	-	-	-	-
12-Oct		8:27	681	17630	5.94	213227	1,809.46	6.77	25.9	4.6	24
		12:43	256	6570	5.9	219797	1,865.22	0.00	25.7	4.6	25
		16:43	240	6000	5.78	225797	1,916.13	0.00	25.0	4.7	26
13-Oct		21:25	282	7110	5.7	232907	1,976.47	0.44	25.2	4.7	27
		8:20	655	16300	5.7	249207	2,114.79	0.00	24.9	4.7	28
		12:32	252	6280	5.64	255487	2,168.08	4.85	24.9	4.7	29
		16:58	266	6590	5.68	262077	2,224.01	0.00	24.8	4.8	30
14-Oct		21:18	260	6520	5.63	268597	2,279.34	0.00	25.1	4.7	31
		8:22	664	15735	5.94	284332	2,412.86	0.00	23.7	5.0	32
		13:28	306	7320	5.59	291652	2,474.98	0.00	23.9	4.9	33
		17:03	215	5120	5.66	296772	2,518.43	1.68	23.8	4.9	34
15-Oct		21:25	202	6140	5.64	302912	2,570.54	7.67	30.4	3.9	35
		8:27	720	15825	5.67	318737	2,704.83	348	22.0	5.4	36
		13:10	283	6710	5.64	325447	2,761.77	0.00	23.7	5.0	37
17-Oct		16:43	213	5100	5.63	330547	2,805.05	0.96	23.9	4.9	38
18-Oct	21:17	-	-	-	-	-	-	-	-	-	-
		8:32	675	17000	5.69	347547	2,949.31	2.24	25.2	4.7	39
		13:10	278	6790	5.79	354337	3,006.93	0.00	24.4	4.8	40
		16:32	202	4950	5.6	359287	3,048.94	0.00	24.5	4.8	41
19-Oct		20:54	262	6330	5.67	365617	3,102.66	0.00	24.2	4.9	42
		7:55	661	16100	5.72	381717	3,239.28	1.13	24.4	4.8	43
19-Oct		13:14	319	7740	5.73	389457	3,304.96	4.36	24.3	4.9	44
		17:05	231	5550	5.76	395007	3,352.06	7	24.0	4.9	45

Continued

Date	Time:		Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled Stopped									
20-Oct		21:25	260	7330	5.74	402337	3,414.27	8	28.2	4.2	46
		8:25	660	16100	5.67	418437	3,550.89	31	24.4	4.8	47
		12:00	215	5130	5.68	423567	3,594.42	46	23.9	4.9	48
		16:18	258	6340	5.72	429907	3,648.23	73	24.6	4.8	49
21-Oct		21:33	315	6740	5.75	436647	3,705.42	143	21.4	5.5	50
		8:29	656	16007	5.79	452654	3,841.26	278	24.4	4.8	51
		13:30	301	7100	5.71	459754	3,901.51	14030	23.6	5.0	52
24-Oct		20:52	442	12130	5.71	471884	4,004.45	15600	27.4	4.3	53
	21:25	-	-	-	-	-	-	-	-	-	-
		8:38	675	16540	5.98	488424	4,144.81	35000	24.5	4.8	54
		14:04	326	6360	5.74	494784	4,198.78	43020	19.5	6.0	55

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.2

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB1	Height*-----> 31 cm, 24 cm, 27 cm
Regenerant-----> 12% Sodium Chloride - 1500 ml DI and 180 g NaCl	Bed Volume (BV)-----> 96.94 ml
Date-----> 10/30/1999	

Regenerant solution pH: 8.15	* before loading, after loading and before
Spent regenerant solution pH: 6.68	regeneration, after regeneration.

Date:	Time:			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld:	stopped:								
30-Oct	15:32	15:40		8	100	100	13460	1.03	12.5	7.76	1
		15:47		7	70	170	9950	1.75	12.9	7.54	2
		15:54		7	70	240	8520	2.48	12.9	7.54	3
		16:01		7	70	310	6970	3.20	12.9	7.54	4
		16:11		10	100	410	5738	4.23	12.0	8.08	5
		16:21		10	100	510	4771	5.26	12.0	8.08	6
		16:31		10	100	610	3800	6.29	12.0	8.08	7
		16:45		14	150	760	3254	7.84	12.1	7.98	8
		17:00		15	150	910	2961	9.39	11.3	8.55	9
		17:12	17:14	12	150	1060	2480	10.93	14.2	6.84	10
						1060	5520			7.8 (ave.)	Mixed
RINSE											
30-Oct	18:55:00	19:08:00			290	290		41.7			
		19:42:00			730	1020		1.26			

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.3

Test-----> Adsorption of Perchlorate	Column diameter-----> 2.2 cm
Resin type-----> ASB2	Height-----> 32.5 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 123.54 ml
Period-----> 09/27/1999 to 10/25/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
27-Sep	13:14	17:26		252	7040	5.94	7040	56.99	0.00	27.9	4.4	1
		21:40		254	7130	5.49	14170	114.70	0.00	28.1	4.4	2
28-Sep		7:59		619	17470	5.63	31640	256.11	0.00	28.2	4.4	3
		12:38		279	7830	5.51	39470	319.49	0.00	28.1	4.4	4
		16:55		257	7210	5.45	46680	377.85	0.00	28.1	4.4	5
		21:22		267	7470	5.51	54150	438.32	0.00	28.0	4.4	6
29-Sep		7:04		582	16500	5.61	70650	571.88	0.00	28.4	4.4	7
		11:30		266	7500	5.5	78150	632.59	0.00	28.2	4.4	8
		16:01		271	7700	5.64	85850	694.92	0.00	28.4	4.3	9
		20:34		273	7600	5.6	93450	756.44	1.90	27.8	4.4	10
30-Sep		7:53		679	17865	5.74	111315	901.04	0.00	26.3	4.7	11
		10:40	10:50	167	4900	5.64	116215	940.71	0.00	29.3	4.2	12
04-Oct	12:55	16:01		186	5205	6.94	121420	982.84	0.00	28.0	4.4	13
		20:52		291	9160	5.6	130580	1,056.99	0.00	31.5	3.9	14
05-Oct		8:14		682	18320	5.84	148900	1,205.28	0.00	26.9	4.6	15
		12:42		278	7340	5.8	156240	1,264.69	0.00	26.4	4.7	16
		17:27		285	8010	5.83	164250	1,329.53	0.00	28.1	4.4	17
		21:42		255	8140	5.78	172390	1,395.42	78.31	31.9	3.9	18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
06-Oct		7:54		612	17060	6.05	189450	1,533.51	0.00	27.9	4.4	19
		12:18		264	7370	5.77	196820	1,593.17	30.60	27.9	4.4	20
		17:01		283	7930	5.67	204750	1,657.36	0.00	28.0	4.4	21
		21:32		271	7800	5.71	212550	1,720.50	0.00	28.8	4.3	22
07-Oct		8:02	8:16	630	10030	5.78	222580	1,801.68	1.47	15.9**	7.8	23
11-Oct	21:06	-	-	-	-	-	-	-	-	-	-	-
12-Oct		8:14		728	18380	5.91	240960	1,950.46	0.00	25.2	4.9	24
		12:30		262	7670	5.81	248630	2,012.55	0.00	29.3	4.2	25
		16:36		246	7030	5.77	255660	2,069.45	0.00	28.6	4.3	26
		21:19		283	8790	5.77	264450	2,140.60	0.00	31.1	4.0	27
13-Oct		8:16		657	18890	5.78	283340	2,293.51	0.21	28.8	4.3	28
		12:25		249	7220	5.76	290560	2,351.95	0.00	29.0	4.3	29
		16:51		266	7560	5.82	298120	2,413.15	0.00	28.4	4.3	30
		21:11		260	7510	5.75	305630	2,473.94	0.00	28.9	4.3	31
14-Oct		8:13		662	18145	5.92	323775	2,620.81	0.00	27.4	4.5	32
		13:13		300	8110	5.77	331885	2,686.46	0.00	27.0	4.6	33
		16:58		225	6150	5.72	338035	2,736.24	1.13	27.3	4.5	34
		21:18		260	7100	5.86	345135	2,793.71	0.93	27.3	4.5	35
15-Oct		8:18		642	17650	5.76	362785	2,936.58	733.00	27.5	4.5	36
		13:02		284	7690	5.74	370475	2,998.83	0.62	27.1	4.6	37
		16:37	17:21	215	5860	5.72	376335	3,046.26	168.00	27.3	4.5	38
17-Oct	21:17	-	-	-	-	-	-	-	-	-	-	-
18-Oct		8:29		672	19510	5.74	395845	3,204.18	0.00	29.0	4.3	39
		13:02		273	7550	5.83	403395	3,265.30	1.09	27.7	4.5	40
		16:28		206	5610	5.64	409005	3,310.71	1.34	27.2	4.5	41
		21:00		272	7450	5.7	416455	3,371.01	4.75	27.4	4.5	42
19-Oct		7:49		649	17730	5.72	434185	3,514.53	18.78	27.3	4.5	43
		13:09		320	8780	5.8	442965	3,585.60	36.49	27.4	4.5	44
19-Oct		17:00		231	6360	5.76	449325	3,637.08	55.39	27.5	4.5	45
		21:32		272	6410	5.73	455735	3,688.97	79.90	23.6	5.2	46

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
20-Oct		8:20		648	18004	5.86	473739	3,834.70	127.00	27.8	4.4	47
		11:55		215	5880	5.82	479619	3,882.30	251.00	27.3	4.5	48
		16:13		258	7120	5.85	486739	3,939.93	521.00	27.6	4.5	49
		21:25		312	7630	5.86	494369	4,001.69	1166	24.5	5.1	50
21-Oct		8:25		660	17830	5.76	512199	4,146.02	4050	27.0	4.6	51
		13:12		287	7950	5.88	520149	4,210.37	11830	27.7	4.5	52
		20:45	21:01	453	13540	5.81	533689	4,319.97	26220	29.9	4.1	53
24-Oct	21:25	-	-	-	-	-	-	-	-	-	-	-
25-Oct		8:37		674	18800	6.12	552489	4,472.15	38340	27.9	4.4	54
		13:58	14:08	321	7140	5.71	559629	4,529.94	40060	22.2	5.6	55

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.4

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB2	Height*-----> 32.5 cm, 26.5 cm, 28.5 cm
Regenerant-----> 12% Sodium Chloride - 1500 ml DI and 180 g NaCl	Bed Volume (BV)-----> 104.54 ml
Date-----> 10/30/1999	

Regenerant solution pH: 8.15	* before loading, after loading and before
Spent regenerant solution pH: 6.68	regeneration, after regeneration.

Date:	Time:			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld:	stopped:								
30-Oct	14:44	14:51		7	100	100	16190	0.96	14.286	7.32	1
		14:57		6	70	170	13070	1.63	15.000	6.97	2
		15:03		6	70	240	11528	2.30	15.000	6.97	3
		15:10		7	70	310	9504	2.97	12.857	8.13	4
		15:19		9	100	410	7808	3.92	13.333	7.84	5
		15:28		9	100	510	6267	4.88	13.333	7.84	6
		15:37		9	100	610	5415	5.84	13.333	7.84	7
		15:49		12	150	760	4222	7.27	14.167	7.38	8
		16:02		13	150	910	3344	8.70	13.077	7.99	9
		16:14	16:17	12	150	1060	3124	10.14	14.167	7.38	10
						1060	6930			7.57 (ave.)	Mixed
RINSE											
30-Oct	6:55 PM	19:10:00			300	300	21.22				
		19:32:00			700	1000	0.46				

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.5 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> SR7 - Column 1	Height-----> 32.5 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 57.43 ml
Period-----> 11/28/1998 to 01/30/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
28-Nov	12:20	14:51	-	151	1930	7.18	1930	33.6	0.00	12.8	4.49323	1
	-	18:11	18:22	200	2620	6.96	4550	79.2	0.00	13.1	4.38397	2
29-Nov	10:42	11:52	-	81	1030	7.15	5580	97.2	0.00	12.7	4.51634	3
	-	13:43	13:56	111	1440	7.23	7020	122.2	0.00	13.0	4.4269	4
30-Nov	9:32	15:21	-	362	4740	7.28	11760	204.8	0.00	13.1	4.386	5
	-	19:32	20:01	251	3320	6.45	15080	262.6	0.00	13.2	4.34185	6
01-Dec	9:52	15:15	-	352	4630	6.65	19710	343.2	0.00	13.2	4.36617	7
	-	19:27	19:44	252	3320	6.43	23030	401.0	0.00	13.2	4.35914	8
02-Dec	9:32	12:11	12:26	176	2295	6.16	25325	441.0	0.00	13.0	4.40422	9
03-Dec	9:44	16:07	-	398	5210	6.45	30535	531.7	0.00	13.1	4.38717	10
	-	20:16	20:45	249	3290	6.16	33825	589.0	0.00	13.2	4.34653	11
04-Dec	8:59	13:02	13:15	272	4485	6.40	38310	667.1	0.00	16.5	3.48293	12
05-Dec	9:56	12:00	12:50	137	2230	6.39	40540	705.9	0.00	16.3	3.52821	13
07-Dec	9:29	-	12:35	-	-	-	-	-	-	-	-	-
08-Dec	9:35	12:03	12:33	384	6290	6.41	46830	815.4	0.00	16.4	3.50606	14
22-Dec	10:58	15:42	16:14	314	4920	6.52	51750	901.1	0.00	15.7	3.66525	15
14-Jan	11:41	17:31	18:05	382	4410	6.82	56160	977.9	0.00	11.5	4.97466	16
18-Jan	11:16	-	12:48	-	-	-	-	-	-	-	-	-

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
19-Jan	14:30	17:54	18:24	330	4280	6.61	60440	1052.4	0.00	13.0	4.42801	17
20-Jan	11:31	16:59	17:22	358	4770	6.32	65210	1135.5	8.50	13.3	4.31026	18
21-Jan	17:45	-	18:55	-	-	-	-	-	-	-	-	-
22-Jan	15:02	-	16:16	-	-	-	-	-	-	-	-	-
23-Jan	10:43	12:39	13:50	283	3625	6.35	68835	1198.6	28.60	12.8	4.4835	19
24-Jan	11:59	-	13:19	-	-	-	-	-	-	-	-	-
25-Jan	9:19	13:19	13:54	320	5450	6.24	74285	1293.5	212.0	17.0	3.37204	20
26-Jan	17:19	22:22	22:42	338	4890	5.55	79175	1378.6	856.0	14.5	3.9696	21
27-Jan	10:32	14:46	-	274	4000	6.11	83175	1448.3	2891.0	14.6	3.93396	22
	-	19:19	19:51	273	4025	5.61	87200	1518.4	9364.0	14.7	3.89525	23
28-Jan	9:00	13:52	15:57	264	5780	6.83	92980	1619.0	38960	21.9	2.6231	24
30-Jan	15:29	18:54	19:18	390	4920	5.74	97900	1704.7	41770	12.6	4.55238	25

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.5 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> SR7 - Column 2	Height-----> 31.5 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 55.67 ml
Period-----> 11/28/1998 to 01/30/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
28-Nov	12:20	14:55	-	153	1870	6.99	1870	33.6	0.00	12.22	4.55	1
	-	18:13	18:22	204	2430	7.20	4300	77.2	0.00	11.91	4.67	2
29-Nov	10:42	11:56	-	85	990	7.13	5290	95.0	0.00	11.65	4.78	3
	-	13:50	13:56	118	1390	7.23	6680	120.0	0.00	11.78	4.73	4
30-Nov	9:32	15:28	-	369	4475	7.00	11155	200.4	0.00	12.13	4.59	5
	-	19:40	20:01	259	3140	6.53	14295	256.8	0.00	12.12	4.59	6
01-Dec	9:52	15:21	-	365	4340	6.17	18635	334.7	0.00	11.89	4.68	7
	-	19:33	19:44	265	3140	6.10	21775	391.1	0.00	11.85	4.70	8
02-Dec	9:32	12:16	12:26	181	2160	5.99	23935	429.9	0.00	11.93	4.66	9
03-Dec	9:44	16:18	-	409	4970	5.97	28905	519.2	0.00	12.15	4.58	10
	-	20:22	20:45	255	3025	5.98	31930	573.6	0.00	11.86	4.69	11
04-Dec	8:59	13:02	13:15	272	4160	6.06	36090	648.3	0.00	15.29	3.64	12
05-Dec	9:56	12:06	12:50	143	2220	6.04	38310	688.2	0.00	15.52	3.59	13
07-Dec	9:29	-	12:35	-	-	-	-	-	-	-	-	-
08-Dec	9:35	12:11p	12:33	392	6050	5.90	44360	796.8	0.00	15.43	3.61	14
22-Dec	10:58	15:49	16:14	321	4650	5.85	49010	880.4	0.00	14.49	3.84	15
14-Jan	11:41	17:41	18:05	392	4290	6.74	53300	957.4	0.00	10.94	5.09	16
18-Jan	11:16	-	12:48	-	-	-	-	-	-	-	-	-

continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
19-Jan	14:30	18:02	18:24	338	4045	6.37	57345	1030.1	0.00	11.97	4.65	17
20-Jan	11:31	17:07	17:22	406	4510	6.25	61855	1111.1	4.27	11.11	5.01	18
21-Jan	17:45	-	18:55	-	-	-	-	-	-	-	-	-
22-Jan	15:02	-	16:16	-	-	-	-	-	-	-	-	-
23-Jan	10:43	12:47	13:50	291	3440	6.29	65295	1172.9	11.96	11.82	4.71	19
24-Jan	11:59	-	13:19	-	-	-	-	-	-	-	-	-
25-Jan	9:19	13:25	13:54	326	5140	6.17	70435	1265.2	121	15.77	3.53	20
26-Jan	17:19	10:27	22:42	343	4625	5.91	75060	1348.3	559	13.48	4.13	21
27-Jan	10:32	14:52	-	280	3800	5.16	78860	1416.6	1702	13.57	4.10	22
	-	19:25	19:51	279	3820	5.29	82680	1485.2	5592	13.69	4.07	23
28-Jan	9:00	13:58	15:57	270	5520	5.95	88200	1584.3	30780	20.44	2.72	24
30-Jan	15:29	19:01	19:18	397	4650	5.50	92850	1667.9	42130	11.71	4.75	25

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.6

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Rsin type-----> SR7 - Column 1	Height*-----> 32.5 cm
Regenerant-----> 12% Sodium Chloride - (84g/700mL of H ₂ O)	Bed Volume (BV)-----> 57.43 ml
Date-----> 02/06/1999	

Regenerant solution pH: NA	* before loading
Spent regenerant solution pH: NA	

Date:	Time:			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
06-Feb	NA	NA		NA	135	135	1,060	2.4	NA	NA	1
		NA		NA	25	160	1,065	2.8	NA	NA	2
		NA		NA	140	300	676	5.2	NA	NA	3
		NA		NA	50	350	614	6.1	NA	NA	4
		NA		NA	50	400	586	7.0	NA	NA	5
		NA		NA	50	450	537	7.8	NA	NA	6
		NA		NA	70	520	450	9.1	NA	NA	7
		NA		NA	80	600	460	10.4	NA	NA	8
		NA	NA	NA	100	700	417	12.2	NA	NA	9
					700	700	840	12.2			Combined

Approximated EBCT:	Vol. (ml)	T. (min)	Flow (ml/min)	EBCT
	1570	125	12.56	4.57
	920	71	12.96	4.43

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.7 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Column 1	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.78 ml
Period-----> 11/16/1998 to 01/30/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
16-Nov	8:59	14:23	-	322	3955	6.88	3955	72.1979	0.00	12.3	4.5	1
	-	20:47	23:40	384	4805	6.78	8760	159.912	0.00	12.5	4.4	2
17-Nov	8:40	10:26	-	279	3595	6.44	12355	225.539	0.00	12.9	4.3	3
	-	19:55	21:04	569	7140	7.12	19495	355.878	0.00	12.5	4.4	4
18-Nov	8:42	11:55	-		3250	6.94	22745	415.206	0.00			5
	-	13:18	-		1000	6.48	23745	433.461	0.00			6
	-	14:39	-	81	1000	6.95	24745	451.716	0.00	12.3	4.4	7
	-	16:00	-		1000	6.55	25745	469.971	0.00			8
	-	17:05	17:13		800	6.59	26545	484.575	0.00			9
19-Nov	8:54	10:08	-		1000	6.34	27545	502.829	0.00			10
	-	11:30	-		1000	6.40	28545	521.084	0.00			11
	-	12:51	-		1000	6.14	29545	539.339	0.00			12
	-	14:13	-	82	1010	6.12	30555	557.777	0.00	12.3	4.4	13
	-	15:34	16:10		1005	6.14	31560	576.123	0.00			14
24-Nov	10:20	23:39	-		1710	6.07	33270	607.338	0.00			15
	-	15:01	-		3370	6.06	36640	668.857	0.00			16
	-	17:25	-	144	2370	5.95	39010	712.121	0.00	16.5	3.3	17
	-	19:24	19:33		1960	6.16	40970	747.901	0.00			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
25-Nov	8:54	11:50	-		3030	6.08	44000	803.213	0.00			19
	-	14:49	15:29	179	2940	6.08	46940	856.882	0.00	16.4	3.3	20
26-Nov	13:00	15:13	15:23		2270	6.28	49210	898.321	0.00			21
27-Nov	12:37	15:09	-		1980	6.01	51190	934.465	0.00			22
	-	18:15	18:29	186	2335	6.21	53525	977.09	6.19	12.6	4.4	23
28-Nov	12:20	15:00	-		2200	6.11	55725	1017.25	0.00			24
	-	16:39	-		1260	6.18	56985	1040.25	13.53			25
	-	17:59	18:22	80	1000	6.08	57985	1058.51	0.00	12.5	4.4	26
29-Nov	10:42	11:39	-		1000	6.43	58985	1076.76	0.00			27
	-	12:58	13:56	79	1000	6.09	59985	1095.02	0.00	12.7	4.3	28
30-Nov	9:32	12:07	-		2740	6.00	62725	1145.03	0.00			29
	-	15:34	-		2880	6.13	65405	1193.96	0.00			30
	-	17:00	-		1105	6.18	66510	1214.13	0.00			31
	-	19:46	20:01	166	2160	6.04	68670	1253.56	0.00	13.0	4.2	32
01-Dec	9:52	15:28	-		4520	5.96	73190	1336.07	0.00			33
	-	19:35	19:44	247	3200	5.90	76390	1394.49	12.67	13.0	4.2	34
02-Dec	9:32	12:18	12:26		2260	6.01	78650	1435.74	14.69			35
03-Dec	9:44	16:24	-		5260	5.88	83910	1531.76	27.85			36
	-	20:32	20:45	248	3205	5.97	87115	1590.27	42.73	12.9	4.2	37
04-Dec	8:59	13:04	13:15		4245	6.00	91360	1667.76	125.72			38
05-Dec	9:56	12:12	12:50		2410	5.93	93770	1711.76	na			39
07-Dec	9:29	-	12:35		-	-	-	-	-			-
08-Dec	9:35	12:18	12:33		5960	5.95	99730	1820.6	134			40
22-Dec	10:58	15:49	16:14		4785	5.85	104515	1907.9				41
14-Jan	11:41	17:49	18:05		4530	6.31	109045	1990.6	585			42
18-Jan	11:16	-	12:48		-	-	-	-	-			-
19-Jan	14:30	18:09	18:24	327	4185	6.28	113230	2067.0	750	12.8	4.3	43
20-Jan	11:31	17:14	17:22		4670	6.27	117900	2152.2	1185			44
21-Jan	17:45	-	18:55		-	-	-	-	-			-
22-Jan	15:02	-	16:16		-	-	-	-	-			-

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
23-Jan	10:43	12:54	13:50		3565	6.39	121465	2217.3	1596			45
24-Jan	11:59	-	13:19		-	-	-	-	-			-
25-Jan	9:19	13:32	13:54		5320	5.99	126785	2314.4	3712			46
26-Jan	17:19	22:33	22:42	396	4790	5.59	131575	2401.9	6270	12.1	4.5	47
27-Jan	10:32	14:58	-		3930	5.62	135505	2473.6	10100			48
	-	19:31	19:51		3940	5.37	139445	2545.5	15130			49
28-Jan	9:00	14:05	15:57		5770	5.71	145215	2650.9	29080			50
30-Jan	15:29	19:07	19:18	330	4740	5.65	149955	2737.4	39060	14.4	3.8	51

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.7 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Column 2	Height-----> 30.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 53.01 ml
Period-----> 11/16/1998 to 01/30/1999	

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
16-Nov	8:59	14:32	-	342	3770	6.08	3770	71.1	0.00	11.02	4.81	1
	-	20:55	23:40	392	4440	6.19	8210	154.9	0.00	11.33	4.68	2
17-Nov	8:40	10:33	-	286	3320	6.06	11530	217.5	0.00	11.61	4.57	3
	-	20:05	21:04	579	6715	6.35	18245	344.2	0.00	11.60	4.57	4
18-Nov	8:42	12:05	-		3025	6.60	21270	401.2	0.00			5
	-	13:34	-		1000	6.07	22270	420.1	0.00			6
	-	15:04	-	86	1045	6.06	23315	439.8	0.00	12.15	4.36	7
	-	16:30	-		1000	6.34	24315	458.7	0.00			8
	-	17:07	17:13		410	6.27	24725	466.4	0.00			9
19-Nov	8:54	10:16	-		1000	6.05	25725	485.3	0.00			10
	-	11:44	-		1000	6.00	26725	504.2	0.00			11
	-	13:10	-		1000	6.06	27725	523.0	0.00			12
	-	14:33	-	92	970	6.03	28695	541.3	0.00	10.54	5.03	13
	-	16:00	16:10		1000	6.10	29695	560.2	0.00			14
24-Nov	10:20	11:45	-		1470	6.05	31165	587.9	4.77			15
	-	15:07	-		3320	6.15	34485	650.5	0.00			16
	-	17:25	-	144	2220	5.90	36705	692.4	0.00	15.42	3.44	17
	-	19:28	19:33		1965	5.95	38670	729.5	0.00			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
25-Nov	8:54	11:56	-		3030	6.01	41700	786.6	0.00			19
	-	14:56	15:29	186	2890	6.00	44590	841.2	0.00	15.54	3.41	20
26-Nov	13:00	15:15	15:23		2100	6.04	46690	880.8	0.00			21
27-Nov	12:37	15:14	-		1965	5.97	48655	917.8	3.68			22
	-	18:21	18:29	192	2220	6.01	50875	959.7	6.35	11.56	4.58	23
28-Nov	12:20	15:10	-		2160	5.84	53035	1000.5	5.85			24
	-	16:44	-		1160	6.01	54195	1022.4	4.35			25
	-	18:07	18:22	88	1000	5.90	55195	1041.2	4.32	11.36	4.66	26
29-Nov	10:42	23:50	-		1000	5.98	56195	1060.1	0.00			27
	-	13:12	13:56	93	1000	5.92	57195	1078.9	0.00	10.75	4.93	28
30-Nov	9:32	12:13	-		2530	5.91	59725	1126.7	0.00			29
	-	15:40	-		2560	5.93	62285	1175.0	0.00			30
	-	17:04	-		1020	5.95	63305	1194.2	0.00			31
	-	19:52	20:01	172	2080	5.98	65385	1233.4	0.00	12.09	4.38	32
01-Dec	9:52	15:34	-		4330	5.94	69715	1315.1	0.00			33
	-	19:35	19:44	247	2935	5.90	72650	1370.5	27.88	11.88	4.46	34
02-Dec	9:32	12:18	12:26		2175	5.93	74825	1411.5	27.28			35
03-Dec	9:44	16:35	-		5150	5.89	79975	1508.7	54.68			36
	-	20:39	20:45	255	3010	5.94	82985	1565.5	na	11.80	4.49	37
04-Dec	8:59	13:04	13:15		4160	5.98	87145	1643.9	na			38
05-Dec	9:56	12:18	12:50		2420	5.83	89565	1689.6	na			39
07-Dec	9:29	-	12:35		-	-	-	-	-			-
08-Dec	9:35	12:25	12:33		6240	5.93	95805	1807.3	~226			40
22-Dec	10:58	15:49	16:14		4720	5.85	100525	1896.3	na			41
14-Jan	11:41	17:56	18:05		3750	6.14	104275	1967.1	712			42
18-Jan	11:16	-	12:48		-	-	-	-	-			-
19-Jan	14:30	18:16	18:24	334	4120	6.22	108395	2044.8	1107	12.34	4.30	43
20-Jan	11:31	17:14	17:22		4480	6.26	112875	2129.3	1376			44
21-Jan	17:45	-	18:55		-	-	-	-	-			-
22-Jan	15:02	-	16:16		-	-	-	-	-			-

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
23-Jan	10:43	13:01	13:50		3770	6.34	116645	2200.4	2424			45
24-Jan	11:59	-	13:19		-	-	-	-	-			-
25-Jan	9:19	13:39	13:54		5580	5.90	122225	2305.7	4591			46
26-Jan	17:19	22:33	22:42	396	4890	5.59	127115	2397.9	7900	12.35	4.29	47
27-Jan	10:32	15:04	-		4200	5.38	131315	2477.2	11240			48
	-	19:37	19:51		4100	5.31	135415	2554.5	16620			49
28-Jan	9:00	14:13	15:57		6140	5.60	141555	2670.3	30480			50
30-Jan	15:29	19:07	19:18	330	4810	5.65	146365	2761.1	40100	14.58	3.64	51

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.8 - Column 1

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Column 1	Height*-----> 31.0 cm
Regenerant-----> 12% Sodium Chloride - (90g/750mL of H ₂ O)	Bed Volume (BV)-----> 54.78 ml
Date-----> 02/06/1999	

Regenerant solution pH: NA	* before loading
Spent regenerant solution pH: NA	

Date:	Time:			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
NA	NA	NA		NA	100	100	19,010	1.7	NA	NA	1
		NA		NA	75	175	11,300	3.0	NA	NA	2
		NA		NA	75	250	8,550	4.4	NA	NA	3
		NA		NA	50	300	7,360	5.2	NA	NA	4
		NA		NA	50	350	5,350	6.1	NA	NA	5
		NA		NA	75	425	3,415	7.4	NA	NA	6
		NA		NA	75	500	2,270	8.7	NA	NA	7
		NA		NA	100	600	1,283	10.4	NA	NA	8
		NA	NA	NA	150	750	541	13.1	NA	NA	9
					750	750	7,150				combined

Approximated EBCT:	Vol. (ml)	T. (min)	Flow (ml/min)	EBCT
	1550	127	12.20472441	4.49
	980	77	12.73	4.30

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.9 - First Exhaustion

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Test 2	Height-----> 31.5 cm
Feed-----> 190 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 55.7 ml
Period-----> 04/04/2000 to 04/06/2000	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
04-Apr	15:41	23:19		458	5450	6.78	5450	97.8	20.64	11.9	4.7	1
05-Apr		8:17		538	6500	6.88	11950	214.5	3.56	12.1	4.6	2
		11:46		209	2550	6.73	14500	260.3	2.24	12.2	4.6	3
		13:10		84	1000	6.88	15500	278.3	2.78	11.9	4.7	4
		14:47		97	1150	6.80	16650	298.9	3.36	11.9	4.7	5
		16:12		85	1000	6.60	17650	316.9	0.00	11.8	4.7	6
		18:12		120	1400	6.78	19050	342.0	10.64	11.7	4.8	7
		20:23		131	1560	6.23	20610	370.0	5.83	11.9	4.7	8
		21:48		85	1000	6.60	21610	388.0	13.90	11.8	4.7	9
06-Apr		0:09		141	1690	6.62	23300	418.3	166	12.0	4.6	10
		9:23		554	6660	6.63	29960	537.9	105250	12.0	4.6	11
		11:13	11:25	110	1290	6.67	31250	561.0	193500	11.7	4.7	12

Average 11.9 4.7

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.9 - Second Exhaustion

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Test 2	Height-----> 30.0 cm
Feed-----> 190 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 53.01 ml
Period-----> 04/07/2000 to 04/09/2000	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
07-Apr	14:15	18:46		271	3240	6.49	3240	61.1	7.0	12.0	4.43	1
		23:21		275	3290	6.38	6530	123.2	3.8	12.0	4.43	2
08-Apr		9:30		609	7240	6.65	13770	259.8	40.8	11.9	4.46	3
		13:54		264	3100	6.79	16870	318.2	1082.3	11.7	4.51	4
		18:33		279	3300	6.95	20170	380.5	1162.2	11.8	4.48	5
09-Apr		1:40		427	5000	7.02	25170	474.8	10830.0	11.7	4.53	6
		10:38		538	6250	7.84	31420	592.7	142700.0	11.6	4.56	7
		15:07	15:07	269	3100	7.04	34520	651.2	203700.0	11.5	4.60	8

11.8 4.5 Average

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.10

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> Macro T - Test 2	Height*-----> 31.5 cm, 24.2 cm, 30.0 cm
Regenerant-----> 12% Sodium Chloride - (60g/500mL of H ₂ O)	Bed Volume (BV)-----> 47.89 ml
Date-----> 04/06/2000	

Regenerant solution pH: 6.45	* before loading, after loading and before regeneration, after regeneration.
Spent regenerant solution pH: 7.03	
Spent regenerant solution conductivity: > 50,000 μ mhos	

Date	Time			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
6-Apr	18:35	18:58		23	100	100	31,570	2.1	4.3	11.0	1
		19:09		11	30	130	18,490	2.7	4.5	10.5	2
		19:21		12	50	180	12,550	3.8	5.8	8.2	3
		19:35		14	40	220	6,108	4.6	4.3	11.2	4
		19:46		11	40	260	4,154	5.4	5.5	8.8	5
		19:58		12	40	300	2,337	6.3	5.0	9.6	6
		20:11		13	50	350	1,322	7.3	5.4	8.9	7
		20:26		15	60	410	766	8.6	5.3	9.0	8
		20:47	20:51	21	90	500	222	10.4	5.2	9.1	9
									5.0	9.6	Average

500	10,300		combined
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Rinse							
6-Apr	22:23	23:09	23:21	NA	550		μ mhos
						710	30

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.11 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Column 1	Height-----> 30.5 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻ (pH = 6.21-5.82)	Bed Volume (BV)-----> 53.90 ml
Period-----> 03/13/1999 to 06/07/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
13-Mar	11:33	19:14	19:47	461	5700	4.44	5700	106	0.00	12.36	4.36	1
14-Mar	8:27	16:10	-		6120	4.53	11820	219	0.00			2
		21:23	21:42	313	3890	4.65	15710	291	0.00	12.43	4.34	3
15-Mar	9:34	17:09	-		5850	4.75	21560	400	0.00			4
		22:30	22:43	321	4000	4.85	25560	474	0.00	12.46	4.33	5
16-Mar	9:10	17:25	-		6370	4.90	31930	592	0.00			6
		20:29	20:41	184	2310	5.06	34240	635	0.00	12.55	4.29	7
17-Mar	9:18	17:15	17:25		6100	5.70	40340	748	0.00			8
18-Mar	9:34	17:27	17:41	483	5260	5.09	45600	846	0.00	10.89	4.95	9
19-Mar	17:20	-	22:21	-	-	-	-	-	-	-	-	-
20-Mar	13:14	18:19	18:46		7180	5.21	52780	979	0.00			10
24-May	13:16	20:34	20:51	465	5730	5.07	58510	1086	0.00	12.32	4.37	11
25-May	9:35	14:58	-		4420	5.19	62930	1168	0.00			12
		21:34	21:59	396	5200	5.15	68130	1264	0.00	13.13	4.10	13
26-May	9:13	16:09	-		5770	5.19	73900	1371	0.00			14
		22:44	23:06	395	5170	5.25	79070	1467	0.00	13.09	4.12	15
27-May	9:46	16:38	20:32		4190	5.27	83260	1545	0.00			16
28-May	12:30	18:03	18:19		7230	5.36	90490	1679	0.00			17

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
01-Jun	12:26	-	-	-	-	-	-	-	-	-	-	-
02-Jun		8:32	-	1206	14950	5.44	105440	1956	9.89	12.40	4.35	18
03-Jun		9:21	-	1489	18330	5.71	123770	2296	179.8	12.31	4.38	19
04-Jun		9:59	16:03		18000	6.25	141770	2630	3193			20
05-Jun	13:51	-	19:49	-	-	-	-	-	-	-	-	-
06-Jun	8:56	-	15:17	-	-	-	-	-	-	-	-	-
07-Jun	10:06	15:23	16:28	1420	17550	6.42	159320	2956	35110	12.36	4.36	21

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.11 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Column 2	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻ (pH = 6.21-5.82)	Bed Volume (BV)-----> 54.8 ml
Period-----> 03/13/1999 to 06/07/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
13-Mar	11:33	19:29	19:47	476	5280	4.33	5280	96	0.00	11.1	4.9	1
14-Mar	8:28	16:22	-		6410	4.48	11690	213	0.00			2
		21:32	21:42	322	4070	4.59	15760	288	0.00	12.6	4.3	3
15-Mar	9:34	17:11	-		6120	4.72	21880	399	0.00			4
		22:32	22:43	323	4220	4.82	26100	476	0.00	13.1	4.2	5
16-Mar	9:11	17:27	-		6720	4.90	32820	599	0.00			6
		20:31	20:41	186	2420	5.02	35240	643	0.00	13.0	4.2	7
17-Mar	9:18	17:17	17:25		6450	5.71	41690	761	0.00			8
18-Mar	9:34	17:29	17:41	485	5490	5.07	47180	861	0.00	11.3	4.8	9
19-Mar	17:20	-	22:21		-	-	-	-	-			-
20-Mar	13:14	18:28	18:46		7610	5.22	54790	1000	0.00			10
24-May	13:16	20:40	20:51	471	6200	5.09	60990	1113	0.00	13.2	4.2	11
25-May	9:35	15:06	-		4700	5.17	65690	1199	0.00			12
		21:41	21:59	403	5460	5.20	71150	1298	0.00	13.5	4.0	13
26-May	9:13	16:16	-		6060	5.33	77210	1409	0.00			14
		22:51	23:06	402	5400	5.28	82610	1507	0.00	13.4	4.1	15
27-May	9:46	16:45	20:32		4320	5.27	86930	1586	0.00			16
28-May	12:30	18:11	18:19		7590	5.32	94520	1725	0.00			17

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
01-Jun	12:26	-	-		-	-	-	-	-	-	-	-
02-Jun		8:46	-	1220	15750	5.44	110270	2012	5.33	12.9	4.2	18
03-Jun		9:35	-	1503	19160	5.70	129430	2362	250	12.7	4.3	19
04-Jun		10:20	16:03		18970	6.12	148400	2708	5047.0			20
05-Jun	13:51	-	19:49		-	-	-	-	-			-
06-Jun	8:56	-	15:17		-	-	-	-	-			-
07-Jun	10:06	15:23	16:28	1420	18210	6.27	166610	3040	37790	12.8	4.3	21

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.12 - Column 1

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Column 1	Height*-----> 30.5 cm, 24.8 cm, 30.5 cm
Regenerant-----> 1% NaOH - (10g / 1000 mL of H ₂ O)	Bed Volume (BV)-----> 48.90 ml
Date-----> 06/11/1999	

Regenerant solution pH: 13.10	* before loading, after loading and before
Spent regenerant solution pH: 12.94	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped								
11-Jun	16:17	16:27	16:30	10	100	100	6730	2.0	10.00	4.89	1
	16:51	16:57		6	60	160	4970	3.3	10.00	4.89	2
		17:03		6	60	220	3558	4.5	10.00	4.89	3
		17:08		5	60	280	2942	5.7	12.00	4.08	4
		17:14		6	60	340	2474	7.0	10.00	4.89	5
		17:20		6	60	400	2300	8.2	10.00	4.89	6
		17:26		6	70	470	1883	9.6	11.67	4.19	7
		17:37		11	110	580	1465	11.9	10.00	4.89	8
		17:45		8	80	660	1450	13.5	10.00	4.89	9
		17:54	17:56	9	80	740	1398	15.1	8.89	5.50	10
					740	740	2963				Combined

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.12 - Column 2

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Column 2	Height*-----> 31.0 cm, 24.3 cm, 30.8 cm
Regenerant-----> 12% NaCl - (96g / 800 mL of H ₂ O)	Bed Volume (BV)-----> 48.69 ml
Date-----> 07/16/1999	

Regenerant solution pH: 8.52	* before loading, after loading and before
Spent regenerant solution pH: 7.84	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped								
16-Jul	17:34	17:46		12	80	80	28920	1.6	6.7	7.3	1
		17:56		10	50	130	25530	2.7	7.0	7.0	2
		18:06		10	50	180	14700	3.7	7.0	7.0	3
		18:14		8	40	220	13720	4.5	7.5	6.5	4
		18:23		9	40	260	8089	5.3	6.7	7.3	5
		18:31		8	40	300	7011	6.2	7.5	6.5	6
		18:41		10	50	350	4772	7.2	7.0	7.0	7
		18:52		11	60	410	2750	8.4	7.3	6.7	8
		19:05		13	70	480	1645	9.9	6.9	7.0	9
		19:19	19:22	14	80	560	909	11.5	7.1	6.8	10
										6.9	Average
						560	10323				Mixed

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.13 - First Exhaustion

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Test 2	Height-----> 31.0 cm
Feed-----> 190 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.8 ml
Period-----> 04/04/2000 to 04/06/2000	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
04-Apr	15:41	23:25		464	6210	4.23	6210	113.3	4.73	13.4	4.1	1
05-Apr		8:26		541	7290	4.75	13500	246.4	0.00	13.5	4.1	2
		14:56		390	5300	5.00	18800	343.1	8.29	13.6	4.0	3
		18:41		225	3010	5.05	21810	398.0	2.25	13.4	4.1	4
		20:35		114	1500	5.11	23310	425.4	34.9	13.2	4.2	5
06-Apr		0:12		217	2920	5.68	26230	478.6	191	13.5	4.1	6
		9:35		563	7530	6.55	33760	616.1	172000	13.4	4.1	7
		11:13	11:25	98	1290	6.69	35050	639.6	193750	13.2	4.2	8

13.4	4.1	Ave.
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.13 - Second Exhaustion

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Test 2	Height-----> 31.5 cm
Feed-----> 190 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 55.7 ml
Period-----> 04/07/2000 to 04/09/2000	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate (ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
07-Apr	14:15	18:46		271	3690	5.75	3690	66.2	110.9	13.6	4.1	1
		23:21		275	3710	5.93	7400	132.9	21.0	13.5	4.1	2
08-Apr		9:30		609	8180	5.91	15580	279.7	234.7	13.4	4.1	3
		13:54		264	3500	6.20	19080	342.5	921.0	13.3	4.2	4
		18:33		279	3770	6.18	22850	410.2	4,654.4	13.5	4.1	5
09-Apr		1:40		427	5620	6.37	28470	511.1	27,300	13.2	4.2	6
		10:38		538	7040	6.68	35510	637.5	161,350	13.1	4.3	7
		15:07	15:07	269	3470	6.74	38980	699.8	193,300	12.9	4.3	8

13.3	4.2	Aver.
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.2.14

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> A 850 - Test 2	Height*-----> 31.0 cm, 25.5 cm, 31.5 cm
Regenerant-----> 12% Sodium Chloride - (60g/500mL of H ₂ O)	Bed Volume (BV)-----> 50.40 ml
Date-----> 04/06/2000	

Regenerant solution pH: 6.45	* before loading, after loading and before regeneration, after regeneration.
Spent regenerant solution pH: 8.01	
Spent regenerant solution conductivity: > 50,000 μ mhos	

	Time			Minutes	Volume (ml)	Cum. Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped								
06-Apr	19:28	19:46		18	100	100	31,950	2.0	5.56	9.07	1
		19:56		10	30	130	16,250	2.6	5.00	10.08	2
		20:10		14	50	180	10,890	3.6	5.00	10.08	3
		20:20		10	40	220	7,771	4.4	6.00	8.40	4
		20:32		12	40	260	4,911	5.2	5.00	10.08	5
		20:43		11	40	300	2,878	6.0	5.45	9.24	6
		20:57		14	50	350	1,254	6.9	5.00	10.08	7
		21:12		15	60	410	910	8.1	5.33	9.45	8
		21:27	21:31	15	60	470	225	9.3	5.33	9.45	9
							12,200				Comb.
									5.30	9.5	Aver.

Rinse							Cond. (μ mhos)
06-Apr	22:23	23:21			550	550	15
			23:38		170	720	

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.1 - Column 1

Test-----> Adsorption of Perchlorate	Column circumference-----> 9.0 cm
Resin type-----> AFP 329 - Column 1	Column diameter-----> 2.87 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Height-----> 32.5 cm
Period-----> 09/28/1998 to 10/08/1998	Bed Volume (BV)-----> 209.49 cm ³

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
28-Sep	NA	NA		NA	1000	7.27	1000	4.8	0			1
28-Sep		1:52 PM		NA	1000	6.87	2000	9.5	0			2
28-Sep		2:27 PM		35	1000	7.00	3000	14.3	0	28.6	7.3	3
28-Sep		3:04 PM		37	1000	6.94	4000	19.1	0	27.0	7.8	4
28-Sep		3:38 PM		34	1000	6.89	5000	23.9	0	29.4	7.1	5
28-Sep		4:14 PM		36	1000	7.08	6000	28.6	0	27.8	7.5	6
28-Sep		4:50 PM		36	1000	7.09	7000	33.4	0	27.8	7.5	7
28-Sep		7:03 PM		133	3890	7.35	10890	52.0	0	29.2	7.2	8
28-Sep		9:26 PM	NA	143	4235	7.38	15125	72.2	0	29.6	7.1	9
29-Sep	NA	10:58 AM			4810	7.46	19935	95.2	0			10
29-Sep		12:58 PM			3650	7.36	23585	112.6	0			11
29-Sep		3:04 PM		126	3840	7.40	27425	130.9	0	30.5	6.9	12
29-Sep		4:51 PM			3300	7.40	30725	146.7	0			13
29-Sep		7:26 PM	7:53 PM		4750	7.57	35475	169.3	0			14
30-Sep	9:09 AM	10:55 AM			4030	7.63	39505	188.6	0			15
30-Sep		12:59 PM			3750	7.44	43255	206.5	0			16
30-Sep		3:01 PM		122	3730	7.40	46985	224.3	0	30.6	6.9	17
30-Sep		4:49 PM			3350	8.47	50335	240.3	0			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
30-Sep		7:12 PM	7:41 PM		4390	8.53	54725	261.2	0			19
1-Oct	9:14 AM	10:55 AM			3960	7.54	58685	280.1	0			20
1-Oct		1:00 PM			3810	8.15	62495	298.3	0			21
1-Oct		3:00 PM		120	3690	8.58	66185	315.9	0	30.8	6.8	22
1-Oct		5:03 PM			3770	8.36	69955	333.9	0			23
1-Oct		7:18 PM	7:43 PM		4110	8.34	74065	353.5	0			24
2-Oct	8:55 AM	11:12 AM			4930	8.83	78995	377.1	0			25
2-Oct		1:05 PM			3500	8.77	82495	393.8	0			26
2-Oct		3:04 PM		119	3670	8.95	86165	411.3	0	30.8	6.8	27
2-Oct		5:27 PM	5:33 PM		4410	9.07	90575	432.4	0			28
3-Oct	10:36 AM	12:37 PM			3850	9.12	94425	450.7	0			29
3-Oct		2:41 PM		116	3850	9.23	98275	469.1	3.26	33.2	6.3	30
3-Oct		5:11 PM	5:36 PM		4610	9.24	102885	491.1	1508			31
04-Oct	9:15 PM	10:02 PM	10:22 PM		2180	9.27	105065	501.5	32			32
05-Oct	9:22 AM	10:36 AM			2910	9.33	107975	515.4	6195			33
05-Oct		12:41 PM		123	3750	9.31	111725	533.3	11804	30.5	6.9	34
05-Oct		3:34 PM			5330	9.06	117055	558.8	20241			35
05-Oct		5:40 PM	6:02 PM		3880	8.80	120935	577.3	25954			36
06-Oct	9:05 AM	10:53 AM			3970	8.94	124905	596.2	30971			37
06-Oct		12:48 PM			3530	8.02	128435	613.1	33106			38
06-Oct		3:00 PM		132	4070	8.63	132505	632.5	34695	30.8	6.8	39
06-Oct		5:01 PM			3700	7.56	136205	650.2	36250			40
06-Oct		7:05 PM	7:31 PM		3800	7.28	140005	668.3				41
07-Oct	9:23 AM	11:06 AM			3925	8.92	143930	687.0	35681			42
07-Oct		1:04 PM			3600	7.23	147530	704.2	38238			43
07-Oct		3:23 PM		139	4275	7.35	151805	724.6	37700	30.8	6.8	44
07-Oct		5:31 PM	5:37 PM		3920	8.05	155725	743.4	37820			45
08-Oct	9:08 AM	12:11 PM			5820	8.84	161545	771.1	37070			46
08-Oct		2:29 PM		138	4230	6.91	165775	791.3	37810	30.7	6.8	47
08-Oct		4:52 PM	5:17 PM		4430	7.04	170205	812.5	37630			48

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.1 - Column 2

Test-----> Adsorption of Perchlorate	Column circumference-----> 9.0 cm
Resin type-----> AFP 329 - Column 2	Column diameter-----> 2.87 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Height-----> 32.5 cm
Period-----> 09/28/1998 to 10/08/1998	Bed Volume (BV)-----> 209.49 cm ³

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
28-Sep	NA	NA			1000	7.14	1000	4.77	0.00			1
28-Sep		13:57			1000	6.96	2000	9.55	0.00			2
28-Sep		14:33		36	1000	7.03	3000	14.32	0.00	27.8	7.5	3
28-Sep		15:12			1000	7.06	4000	19.09	0.00			4
28-Sep		15:50			1000	7.03	5000	23.87	0.00			5
28-Sep		16:27		37	1000	6.97	6000	28.64	0.00	27.0	7.8	6
28-Sep		17:05			1000	7.14	7000	33.41	0.00			7
28-Sep		19:14			3515	7.25	10515	50.19	0.00			8
28-Sep		21:35	NA	141	3840	7.32	14355	68.52	0.00	27.2	7.7	9
29-Sep	NA	11:07			4480	7.29	18835	89.91	0.00			10
29-Sep		13:04			3305	7.32	22140	105.69	0.00			11
29-Sep		15:11		127	3600	7.12	25740	122.87	0.00	28.3	7.4	12
29-Sep		16:57			3035	7.07	28775	137.36	0.00			13
29-Sep		19:34	7:53 PM		4465	7.69	33240	158.67	0.00			14
30-Sep	9:09 AM	11:01			3740	7.10	36980	176.52	0.00			15
30-Sep		13:05			3500	7.25	40480	193.23	0.00			16
30-Sep		15:07		122	3470	7.22	43950	209.80	0.00	28.4	7.4	17
30-Sep		16:54			3070	8.01	47020	224.45	0.00			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
30-Sep		19:20	7:41 PM		4180	7.76	51200	244.40	0.00			19
01-Oct	9:14 AM	11:01			3600	6.99	54800	261.59	0.00			20
01-Oct		13:08			3640	7.77	58440	278.96	0.00			21
01-Oct		15:07		119	3370	7.47	61810	295.05	0.00	28.3	7.4	22
01-Oct		17:08			3440	7.73	65250	311.47	0.00			23
01-Oct		19:24	7:43 PM		3890	7.17	69140	330.04	0.00			24
02-Oct	8:55 AM	11:17			4530	8.72	73670	351.66	0.00			25
02-Oct		13:10			3230	8.53	76900	367.08	0.00			26
02-Oct		15:10		120	3410	8.83	80310	383.36	0.00	28.4	7.4	27
02-Oct		17:28	5:33 PM		3955	8.87	84265	402.24	0.00			28
03-Oct	10:36 AM	12:43			3720	9.08	87985	420.00	0.00			29
03-Oct		14:48		125	3600	8.99	91585	437.18	0.00	28.8	7.3	30
03-Oct		17:17	5:36 PM		4270	9.29	95855	457.56	0.00			31
04-Oct	9:15 PM	22:07	10:22 PM	52	1980	9.05	97835	467.02	0.00	38.1	5.5	32
05-Oct	9:22 AM	10:44			2760	9.24	100595	480.19	16			33
05-Oct		12:48		124	3510	9.39	104105	496.94	2137	28.3	7.4	34
05-Oct		15:41			4960	9.35	109065	520.62	8570			35
05-Oct		17:46	6:02 PM		3590	9.29	112655	537.76	11780			36
06-Oct	9:05 AM	10:59			3690	9.02	116345	555.37	15250			37
06-Oct		12:57			3390	8.45	119735	571.55	23850			38
06-Oct		15:16			3980	8.67	123715	590.55	31020			39
06-Oct		17:07			3170	8.84	126885	605.69	33170			40
06-Oct		19:11	7:31 PM	124	3550	7.05	130435	622.63	35380	28.6	7.3	41
07-Oct	9:23 AM	11:13			3650	8.51	134085	640.05	36140			42
07-Oct		13:10		117	3340	7.15	137425	656.00	37730	28.5	7.3	43
07-Oct		15:30			3980	7.85	141405	675.00	36430			44
07-Oct		17:32	5:37 PM		3500	7.57	144905	691.70	36140			45
08-Oct	9:08 AM	12:18			5510	7.44	150415	718.01	36900			46
08-Oct		14:33		135	3860	7.15	154275	736.43	34470	28.6	7.3	47
08-Oct		16:58	5:17 PM	145	4140	7.1	158415	756.19	37610	28.6	7.3	48

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.2

Test-----> Regeneration of Resin	Column circumference-----> 9.0 cm
Resin type-----> AFP 329 - Column 1	Column diameter-----> 2.87 cm
Regenerant-----> 12% Sodium Chloride - (60g/500mL of H2O)	Height*-----> 32.5 cm
Date-----> 10/28/1998	Bed Volume (BV)-----> 209.49 ml

Regenerant solution pH: NA	
Spent regenerant solution pH: NA	

Date	Time			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped								
10/28	NA	NA		NA	100	100	1704	0.5	NA	NA	1
		NA		NA	50	150	191120	0.7	NA	NA	2
		NA		NA	50	200	3144000	1.0	NA	NA	3
		NA		NA	50	250	1651000	1.2	NA	NA	4
		NA		NA	50	300	2115000	1.4	NA	NA	5
		NA		NA	50	350	2129000	1.7	NA	NA	6
		NA		NA	50	400	1372000	1.9	NA	NA	7
		NA		NA	50	450	816000	2.1	NA	NA	8
		NA		NA	50	500	519000	2.4	NA	NA	9
		NA	NA	NA	50	550	267400	2.6	NA	NA	10

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.3 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> AFP 329 - Column 1 - Test 2	Height-----> 30.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 53.01 cm ³
Period-----> 04/26/1999 to 04/29/1999	

Date	Started	Time		Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
		Sampled	Stopped									
26-Apr	11:10	-	-	-	-	-	-	-	-	-	-	-
27-Apr	-	9:04	-	1314	13540	7.90	13540	255	0.00	10.3	5.1	1
	-	16:02	-	418	4180	7.59	17720	334	0.00	10.0	5.3	2
	-	23:01	-	419	4220	8.30	21940	414	0.00	10.1	5.3	3
28-Apr	-	9:26	-	625	6120	8.97	28060	529	70.06	9.8	5.4	4
	-	16:55	-	449	4130	9.13	32190	607	3295.0	9.2	5.8	5
29-Apr	-	0:07	-	442	4070	9.12	36260	684	11640	9.2	5.8	6
	-	13:23	13:23	796	7100	7.86	43360	818	31940	8.9	5.9	7

5.5 Ave.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.3 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> AFP 329 - Column 2 - Test 2	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.78 cm ³
Period-----> 06/19/1999 to 06/22/1999	

Date	Started	Time		Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
		Sampled	Stopped									
19-Jun	11:25 AM	6:29 PM		424	5690	6.86	5690	104	0.00	13.4	4.1	1
		11:38 PM		309	3790	7.24	9480	173	0.00	12.3	4.5	2
20-Jun		10:38 AM		660	8250	8.82	17730	324	0.00	12.5	4.4	3
		7:00 PM		458	6350	8.91	24080	440	0.00	13.9	4.0	4
		11:48 PM		288	3610	8.96	27690	505	0.00	12.5	4.4	5
21-Jun		7:43 AM		475	5900	8.77	33590	613	2570	12.4	4.4	6
		6:43 PM		660	7860	7.32	41450	757	33810	11.9	4.6	7
22-Jun		12:19 AM		336	3720	7.78	45170	825	37880	11.1	4.9	8
		6:21 AM	6:30 AM	362	3710	7.69	48880	892	39010	10.2	5.3	9

4.5 ave

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.4 - Column 1

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> AFP 329 - Test 2 - Column 1	Height*-----> 30.0 cm, 29.5 cm, 30.8 cm
Regenerant-----> 12% Sodium Chloride - (84g NaCl / 700	Bed Volume (BV)-----> 52.14 ml
Date-----> 05/01/1999	

Regenerant solution pH: 8.13	* before loading, after loading and before
Spent regenerant solution pH: 9.14	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped								
01-May	10:09	10:38	-	29	100	100	4943	1.92	3.4	15.1	1
-	-	11:03	-	25	60	160	3910	3.07	2.4	21.7	2
-	-	11:24	-	21	60	220	3505	4.22	2.9	18.2	3
-	-	11:40	-	16	60	280	2446	5.37	3.8	13.9	4
-	-	12:00	-	20	60	340	2943	6.52	3.0	17.4	5
-	-	12:23	-	23	60	400	899	7.67	2.6	20.0	6
-	-	12:48	-	25	70	470	973	9.01	2.8	18.6	7
-	-	13:13	-	25	70	540	622	10.36	2.8	18.6	8
-	-	13:49	-	36	70	610	680	11.70	1.9	26.8	9
-	-	14:14	14:20	25	70	680	590	13.04	2.8	18.6	10
										18.9	Ave.

680

1038

combined

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.4 - Column 2

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type----> AFP 329 - Test 2 - Column 2	Height*-----> 31.0 cm, 31.0 cm, 30.6 cm
Regenerant---> 1% Sodium Hydroxide - (8g NaOH / 800 ml DI)	Bed Volume (BV)-----> 54.43 ml
Date-----> 07/08/1999	

Regenerant solution pH: 12.92	* before loading, after loading and before
Spent regenerant solution pH: 12.9	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
08-Jul	12:07	12:27		20	100	100	461.00	1.8	5.00	10.89	1
		12:36		11	60	160	307.00	2.9	5.45	9.98	2
		12:44		12	60	220	205.00	4.0	5.00	10.89	3
		12:53		9	60	280	113.66	5.1	6.67	8.16	4
		13:02		9	60	340	88.10	6.2	6.67	8.16	5
		13:11		9	60	400	73.60	7.3	6.67	8.16	6
		13:21		10	70	470	63.94	8.6	7.00	7.78	7
		13:31		10	70	540	56.86	9.9	7.00	7.78	8
		13:41		10	70	610	50.43	11.2	7.00	7.78	9
		13:51	13:54	10	70	680	45.30	12.5	7.00	7.78	10
										8.73	Ave.

680	680	315.00	12.5		Combined
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.5

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> AFP 329 - Test 3	Height-----> 28.8 cm
Feed-----> 10 ppm ClO_4^- and 50 ppm NO_3^-	Bed Volume (BV)-----> 50.9 cm^3
Period-----> 07/24/1999 to 10/18/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppb)	NO_3^- (ppb)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
24-Jul	11:31	14:00		149	1890	6.83	1890	37	0	0.595	12.7	4.0	1
		17:46		226	2900	6.71	4790	94	0	1.078	12.8	4.0	2
		21:41		235	3020	6.8	7810	153	0	1.099	12.9	4.0	3
		23:51		130	1680	6.8	9490	186	0	2.822	12.9	3.9	4
25-Jul		10:00		591	7880	7.6	17370	341	0	44.627	13.3	3.8	5
		14:20		260	3380	6.82	20750	408	0	48.819	13.0	3.9	6
		17:42		212	2610	6.84	23360	459	0	49.176	12.3	4.1	7
26-Jul		1:11		449	5780	6.75	29140	572	0	45.401	12.9	4.0	8
		9:22		501	6340	7.7	35480	697	0	44.75	12.7	4.0	9
		19:42	19:42	620	8080	7.38	43560	856	0	48.567	13.0	3.9	10
1-Aug	21:13	-	-		-	-	-	-	-	-			-
2-Aug		7:58			8320	7.63	51880	1019	0	47.188			11
		14:44		406	5130	8.58	57010	1120	0	46.539	12.6	4.0	12
		23:51		547	7220	8.45	64230	1262	0	45.996	13.2	3.9	13
3-Aug	-	-	0:01		-	-	-	-	-	-			-
11-Sep	13:22	14:37	23:48	85	850	7.54	65080	1279	6.97	51.62	10.0	5.1	14
12-Sep	11:59	13:01	16:14	613	4880	6.96	69960	1374	20.36	54.48	8.0	6.4	15
13-Sep	11:00	19:38	21:35		7060	6.89	77020	1513	3.41	54.644			16

Continued

Date	Started	Time		Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO ₂ ⁻ (ppb)	NO ₃ ⁻ (ppb)	Flow rate(ml/min)	EBCT (min)	#
		Sampled	Stopped										
14-Sep	7:53	-	23:49		-	-	-	-	-	-	-	-	-
18-Sep	13:29	13:58	14:15		4400	7.75	81420	1600	1.7	53.36			17
21-Sep	8:44	15:30	15:43	423	4800	7.64	86220	1694	6.28	54.65	11.3	4.5	18
25-Sep	14:53	-	17:20		-	-	-	-	-	-	-	-	-
26-Sep	12:52	16:49	17:08		4930	7.16	91150	1791	24.33	53.029			19
27-Sep	10:17	13:49	14:18	229	2620	7.47	93770	1842	171.28	52.896	11.4	4.4	20
1-Oct	12:16	-	14:01		-	-	-	-	-	-	-	-	-
2-Oct	11:47	18:00	18:05		5040	7.35	98810	1941	773	55.532			21
3-Oct	15:51	7:20	19:46	214	1450	7.02	100260	1970	656	52.257	6.8	7.5	22
8-Oct	13:15	18:19	18:28		3660	6.71	103920	2042	1865	51.807			23
9-Oct	14:47	17:29	17:37	171	2100	6.39	106020	2083	2234	51.36	12.3	4.1	24
10-Oct	10:45	19:12	19:20		6460	6.56	112480	2210	3554	49.769			25
11-Oct	12:09	20:40	20:48	519	6500	6.92	118980	2338	4594	50.438	12.5	4.1	26
12-Oct	19:49	15:35	15:43		5770	6.71	124750	2451	5632	48.79			27
17-Oct	10:25	21:01	-		7500	6.66	132250	2598	6350	48.619			28
18-Oct	-	20:07	8:16	666	7740	7.13	139990	2750	10422	48.834	11.6	4.4	29
													Av.
													4.4

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.6

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> AFP 329 - Test 3 - Competition	Height*-----> 28.8 cm, 28.0 cm, 30.0 cm
Regenerant-----> 1% Sodium Hydroxide - (8g NaOH / 80	Bed Volume (BV)-----> 51.25 ml
Date-----> 12/24/1999	

Regenerant solution pH: 13.00	* before loading, after loading and before
Spent regenerant solution pH: 13.18	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO ₄ ⁻ (ppm)	NO ₃ ⁻ (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
24-Dec	11:16	11:37		21	100	100	221.10	347.42	2.0	4.8	10.8	1
		11:48		11	40	140	90.80	133.65	2.7	5.5	9.4	2
		0:00		12	40	180	56.80	65.98	3.5	5.0	10.3	3
		12:13		13	40	220	41.30	42.86	4.3	4.6	11.1	4
		12:24		11	40	260	34.30	35.37	5.1	5.5	9.4	5
		12:35		11	40	300	29.44	29.97	5.9	5.5	9.4	6
		12:48		13	50	350	26.26	25.50	6.8	5.4	9.5	7
		13:01		13	50	400	22.59	21.08	7.8	5.4	9.5	8
		13:18		17	70	470	21.16	17.05	9.2	5.3	9.7	9
		13:32	13:37	14	60	530	18.90	15.42	10.3	5.7	9.0	10
											9.8	Aver.
Rinse							205.71	222.80				Mixed
	14:38	15:04			100	100	4.51	3.07	2.0			Rinse1
		15:57	16:01		250	350	0.035	0.04	6.8			Rinse2

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.8 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A-830 - Column 1	Height-----> 32.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 56.55 cm ³
Period-----> 03/20/1999 to 06/07/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
20-Mar	19:00	23:59	-	299	3820	2.89	3820	68	0.00	12.8	4.4	1
21-Mar	-	10:09	-	670	7790	3.01	11610	205	4.43	11.6	4.9	2
	-	16:20	-	371	4680	3.07	16290	288	na	12.6	4.5	3
	-	23:19	-	419	5290	3.16	21580	382	na	12.6	4.5	4
22-Mar	-	9:17	-	598	7540	3.24	29120	515	0.00	12.6	4.5	5
	-	16:48	-	451	5700	3.29	34820	616	0.00	12.6	4.5	6
23-Mar	-	0:41	-	473	6010	3.33	40830	722	0.00	12.7	4.5	7
	-	10:25	-	584	7340	3.42	48170	852	2.21	12.6	4.5	8
	-	19:32	-	547	6890	3.46	55060	974	0.00	12.6	4.5	9
24-Mar	-	1:14		342	4360	3.51	59420	1051	0.00	12.7	4.4	10
	-	13:02	-	708	8930	3.60	68350	1209	0.00	12.6	4.5	11
	-	23:21	-	619	7800	3.68	76150	1347	0.00	12.6	4.5	12
25-Mar	-	10:54	-	693	8720	3.76	84870	1501	0.00	12.6	4.5	13
	-	23:37	-	763	9640	3.83	94510	1671	0.00	12.6	4.5	14
26-Mar	-	11:15	-	698	8790	3.90	103300	1827	0.00	12.6	4.5	15
	-	18:21	18:40	426	5400	3.95	108700	1922	0.00	12.7	4.5	16
24-May	13:16	20:10	20:51	433	5450	3.98	114150	2019	0.00	12.6	4.5	17
25-May	9:35	14:46	-		4690	4.08	118840	2102	3.26			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
	-	21:21	21:59	395	5320	4.12	124160	2196	2.09	13.5	4.2	19
26-May	9:13	15:54	-		5880	4.13	130040	2300	7.68			20
	-	22:31	23:06	397	5350	4.17	135390	2394	22.91	13.5	4.2	21
27-May	9:46	15:50	20:32	399	3840	4.16	139230	2462	23.5	9.6	5.9	22
28-May	12:30	17:44	18:19		7760	4.23	146990	2599	197.00			23
01-Jun	12:26		21:19		-	-	-	-	-			-
02-Jun	8:09	8:14	22:32	611	7180	4.26	154170	2726	367	11.8	4.8	24
03-Jun	9:09	17:12	0:15		16970	4.57	171140	3026	17150			25
04-Jun	9:49	-	16:03		-	-	-	-	-			-
05-Jun	13:51	-	19:49		-	-	-	-	-			-
06-Jun	8:56	-	15:17		-	-	-	-	-			-
07-Jun	10:06	14:52	16:17	1900	22990	5.00	194130	3433	40010	12.1	4.7	26

4.6 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.8 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A-830 - Column 2	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.78 cm ³
Period-----> 03/20/1999 to 06/07/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
20-Mar	19:00	0:07	-	307	3720	2.88	3720	68	10.33	12.1	4.5	1
21-Mar	-	10:18	-	679	7340	3.01	11060	202	0.00	10.8	5.1	2
	-	16:26	-	377	4230	3.07	15290	279	0.00	11.2	4.9	3
	-	23:26	-	426	5010	3.15	20300	371	0.00	11.8	4.7	4
22-Mar	-	9:27	-	608	7180	3.23	27480	502	0.00	11.8	4.6	5
	-	16:54	-	465	5320	3.28	32800	599	0.00	11.4	4.8	6
23-Mar	-	0:48	-	480	5670	3.32	38470	702	0.00	11.8	4.6	7
	-	10:32	-	591	6910	3.39	45380	828	0.00	11.7	4.7	8
	-	19:38	-	553	6490	3.45	51870	947	4.39	11.7	4.7	9
24-Mar	-	1:34	-	362	4290	3.49	56160	1025	4.19	11.9	4.6	10
	-	13:06	-	712	8230	3.57	64390	1175	0.00	11.6	4.7	11
	-	23:28	-	626	7400	3.65	71790	1311	0.00	11.8	4.6	12
25-Mar	-	10:58	-	697	8200	3.73	79990	1460	0.00	11.8	4.7	13
	-	23:43	-	769	9110	3.80	89100	1627	0.00	11.8	4.6	14
26-Mar	-	11:18	-	701	8250	3.88	97350	1777	0.00	11.8	4.7	15
	-	18:27	18:40	432	5110	3.90	102460	1870	0.00	11.8	4.6	16
24-May	13:16	20:21	20:51	444	5460	3.96	107920	1970	0.00	12.3	4.5	17
25-May	9:35	14:52	-		4420	4.05	112340	2051	2.38			18

Continued

Date	Time:			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
	-	21:27	21:59	401	5070	4.09	117410	2143	2.77	12.6	4.3	19
26-May	9:13	16:01	-		5660	4.08	123070	2247	7.57			20
	-	22:38	23:06	404	5090	4.12	128160	2340	20.9	12.6	4.3	21
27-May	9:46	15:56	20:32	405	3640	4.15	131800	2406	29.35	9.0	6.1	22
28-May	12:30	17:55	18:19		7280	4.18	139080	2539	132.25			23
01-Jun	12:26	-	21:19		-	-	-	-	-			-
02-Jun	8:09	8:25	22:32	622	6830	4.22	145910	2664	203.00	11.0	5.0	24
03-Jun	9:09	17:26	0:15		16120	4.41	162030	2958	8620.0			25
04-Jun	9:49	-	16:03		-	-	-	-	-			-
05-Jun	13:51	-	19:49		-	-	-	-	-			-
06-Jun	8:56	-	15:17		-	-	-	-	-			-
07-Jun	10:06	14:52	16:17	1900	21730	4.94	183760	3355	41030.0	11.4	4.8	26

4.7 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.9 - Column 1

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type----> A 830 - Column 1	Height*-----> 32.0 cm, 30.5 cm, 30.5 cm
Regenerant---> 1% NaOH - (10g NaOH / 1000 ml DI)	Bed Volume (BV)-----> 53.9 ml
Date-----> 06/11/1999	

Regenerant solution pH: 13.00	* before loading, after loading and before
Spent regenerant solution pH: 12.76	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
11-Jun	13:52	14:04		12	100	100	21610	1.9	8.3	6.5	1
		14:11	14:16	7	60	160	22340	3.0	8.6	6.3	2
	2:18	14:21		8	60	220	16540	4.1	7.5	7.2	3
		14:28		7	60	280	20330	5.2	8.6	6.3	4
		14:35		7	60	340	9570	6.3	8.6	6.3	5
		14:43		8	60	400	5750	7.4	7.5	7.2	6
		14:52		9	70	470	3050	8.7	7.8	6.9	7
		15:02		10	90	560	1342	10.4	9.0	6.0	8
		15:10		8	60	620	870	11.5	7.5	7.2	9
		15:24	15:26	14	110	730	373.8	13.5	7.9	6.9	10

6.7	Aver.
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730	730	5820	Combined
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.9 - Column 2

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type----> A 830 - Column 2	Height*-----> 31.0 cm, 29.0 cm, 30.5 cm
Regenerant---> 12% NaCl - (96g NaCl / 800 ml DI)	Bed Volume (BV)-----> 52.58 ml
Date-----> 07/15/1999	

Regenerant solution pH: 8.43	* before loading, after loading and before
Spent regenerant solution pH: 7.86	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	C (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped								
15-Jul	12:11	12:26		15	95	95	23480	1.8	6.3	8.3	1
		NA			25	120	19850	2.3			2
		12:41			40	160	13710	3.0			3
		12:50		9	40	200	8170	3.8	6.7	7.9	4
		12:59		9	40	240	6490	4.6	6.7	7.9	5
		13:07		8	40	280	5220	5.3	7.5	7.0	6
		13:19		12	60	340	2932	6.5	6.7	7.9	7
		13:30		11	60	400	2118	7.6	7.3	7.2	8
		13:44		14	70	470	1111	8.9	6.4	8.2	9
		13:58	14:01	14	80	550	1253	10.5	7.1	7.4	10

7.7 Aver.

560	11811		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.10 / 4.3.12 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 830 - Test 2	Height-----> 31.5 cm
Feed-----> 10 ppm ClO_4^- + anions	Bed Volume (BV)-----> 55.67cm ³
Period-----> 07/24/1999 to 07/28/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppb)	NO_3^- (ppb)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
24-Jul	11:31	14:00		149	1850	3.15	1850	33.2	0	0	12.4	4.5	1
		17:46		226	2780	3.15	4630	83.2	0	0	12.3	4.5	2
		21:41		235	2880	3.19	7510	134.9	0	0.02	12.3	4.5	3
		23:51		130	1620	3.21	9130	164.0	0	0.03	12.5	4.5	4
25-Jul		10:00		609	7540	3.33	16670	299.4	0	0	12.4	4.5	5
		14:20		260	3320	3.38	19990	359.1	0	0.03	12.8	4.4	6
		17:42		202	2480	3.40	22470	403.6	0	0	12.3	4.5	7
26-Jul		1:11		449	5510	3.45	27980	502.6	4.64	0	12.3	4.5	8
		9:22		491	6040	3.59	34020	611.1	6.99	2.098	12.3	4.5	9
		19:42		620	7670	3.73	41690	748.9	7.35	1.037	12.4	4.5	10
27-Jul		6:27		645	7820	4.11	49510	889.3	103	79.399	12.1	4.6	11
		21:21		894	11040	4.14	60550	1087.7	1764	97.502	12.3	4.5	12
28-Jul		7:31	7:49	610	7570	4.13	68120	1223.6	6788	94.889	12.4	4.5	13

4.50 Ave.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.10 - Cl^- and SO_4^{2-}

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A 830 - Test 2	Height-----> 31.5 cm
Feed-----> 10 ppm ClO_4^- + anions	Bed Volume (BV)-----> 55.67cm ³
Period-----> 07/24/1999 to 07/28/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Cl^- (ppb)	SO_4^{2-} (ppb)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
24-Jul	11:31	14:00		149	1850	3.15	1850	33.2	173.99	34.118	12.4	4.5	1
		17:46		226	2780	3.15	4630	83.2	182.975	51.88	12.3	4.5	2
		21:41		235	2880	3.19	7510	134.9	183.395	57.948	12.3	4.5	3
		23:51		130	1620	3.21	9130	164.0	137.76	1.527	12.5	4.5	4
25-Jul		10:00		609	7540	3.33	16670	299.4	130.43	0.446	12.4	4.5	5
		14:20		260	3320	3.38	19990	359.1	131.49	1.538	12.8	4.4	6
		17:42		202	2480	3.40	22470	403.6	160.42	99.351	12.3	4.5	7
26-Jul		1:11		449	5510	3.45	27980	502.6	159.945	67.214	12.3	4.5	8
		9:22		491	6040	3.59	34020	611.1	202.945	198.2	12.3	4.5	9
		19:42		620	7670	3.73	41690	748.9	145.23	94.064	12.4	4.5	10
27-Jul		6:27		645	7820	4.11	49510	889.3	92.405	51.848	12.1	4.6	11
		21:21		894	11040	4.14	60550	1087.7	76.64	52.945	12.3	4.5	12
28-Jul		7:31	7:49	610	7570	4.13	68120	1223.6	94.19	102.69	12.4	4.5	13

4.50 Ave.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.11 AND 4.3.13

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> A 830 - Test 2	Height*-----> 31.5 cm, 30.4 cm, 28.5 cm
Regenerant-----> 1% NaOH - (8g NaOH / 800 ml DI)	Bed Volume (BV)-----> 52.05 ml
Date-----> 08/02/1999	

Regenerant solution pH: NA	* before loading, after loading and before
Spent regenerant solution pH: NA	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO ₄ ⁻ (ppm)	NO ₃ ⁻ (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
02-Aug	21:12	21:30			80	80	319	3775	1.5			1
		21:44			50	130	339	5714	2.5			2
		21:58			50	180	599	7259	3.5			3
		22:11			40	220	1574	2814	4.2			4
		22:24			40	260	2946	1245.5	5.0			5
		22:37			40	300	2328	584.7	5.8			6
		22:51			50	350	1288	364.1	6.7			7
		23:08			60	410	513	43.73	7.9			8
		23:26	11:40		70	480	323	3380	9.2			9

540	854	4844		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.11 - Cl^- and SO_4^{2-}

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> A 830 - Test 2	Height*-----> 31.5 cm, 30.4 cm, 28.5 cm
Regenerant-----> 1% NaOH - (8g NaOH / 800 ml DI)	Bed Volume (BV)-----> 52.05 ml
Date-----> 08/02/1999	

Regenerant solution pH: NA	* before loading, after loading and before
Spent regenerant solution pH: NA	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	Cl^- (ppm)	SO_4^{2-} (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
02-Aug	21:12	21:30			80	80	34900	124352	1.5			1
		21:44			50	130	24530	87658	2.5			2
		21:58			50	180	30450	113099	3.5			3
		22:11			40	220	253	7361.7	4.2			4
		22:24			40	260	2920	18660.6	5.0			5
		22:37			40	300	573	7113	5.8			6
		22:51			50	350	2109	9136	6.7			7
		23:08			60	410	17.4	495.81	7.9			8
		23:26	11:40		70	480	38370	101922	9.2			9

540	38170	140486	Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.14 - Column 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A-365 - Column 1	Height-----> 29.5 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 52.13 cm ³
Period-----> 11/16/1998 to 11/19/1998	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
16-Nov	8:59	14:09	-	310	3880	7.60	3880	74.4	12060	12.5	4.2	1
	-	20:31	23:40	382	4860	8.67	8740	167.7	36350	12.7	4.1	2
17-Nov	8:40	10:08	-		3620	8.74	12360	237.1	36940			3
	-	19:34	21:04	562	7240	8.66	19600	376.0	37810	12.9	4.0	4
18-Nov	8:42	11:30	-		3285	8.48	22885	439.0	38300			5
	-	12:51	-	81	1000	8.70	23885	458.2	38920	12.3	4.2	6
	-	14:10	-	80	1000	8.41	24885	477.4	NA	12.5	4.2	7
	-	15:30	-		1000	8.19	25885	496.5	NA			8
	-	16:50	17:13		1000	8.67	26885	515.7	NA			9
19-Nov	8:54	9:51	-		1000	8.68	27885	534.9	NA			10
	-	11:11	-	80	1000	8.75	28885	554.1	NA	12.5	4.2	11
	-	12:41	-		1120	8.45	30005	575.6	NA			12
	-	14:01	-	80	1000	8.60	31005	594.8	NA	12.5	4.2	13
	-	15:26	16:10		1060	7.44	32065	615.1	33630			14

4.1 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.14 - Column 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> A-365 - Column 2	Height-----> 30.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 53.01 cm ³
Period-----> 11/16/1998 to 11/19/1998	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
16-Nov	8:59	14:16	-	317	3700	7.60	3700	69.8	31730	11.7	4.5	1
	-	20:39	23:40	383	4590	8.67	8290	156.4	NA	12.0	4.4	2
17-Nov	8:40	10:14	-		3370	8.74	11660	220.0	NA			3
	-	19:43	21:04	569	6830	8.66	18490	348.8	NA	12.0	4.4	4
18-Nov	8:42	11:48	-		3160	8.48	21650	408.4	NA			5
	-	13:14	-	86	1000	8.70	22650	427.3	NA	11.6	4.6	6
	-	14:38	-	84	1000	8.41	23650	446.1	NA	11.9	4.5	7
	-	16:02	-	84	1000	8.19	24650	465.0	NA	11.9	4.5	8
	-	17:02	17:13		710	8.67	25360	478.4	NA			9
19-Nov	8:54	10:06	-		970	8.68	26330	496.7	NA			10
	-	11:32	-	84	1000	8.75	27330	515.6	NA	11.9	4.5	11
	-	12:55	-	83	1000	8.45	28330	534.4	NA	12.0	4.4	12
	-	14:20	-	85	1000	8.60	29330	553.3	NA	11.8	4.5	13
	-	15:42	16:10	82	1000	7.44	30330	572.2	33440	12.2	4.3	14

4.5 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.15 - Test 1

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> XR-405 - Test 1	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.79 cm ³
Period-----> 06/19/1999 to 06/24/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
19-Jun	11:33	18:55		442	6280	6.62	6280	115	34870	14.2	3.9	1
		23:51		296	4160	6.67	10440	191	37500	14.1	3.9	2
20-Jun		10:58		667	8680	6.80	19120	349	39310	13.0	4.2	3
		19:25		517	7110	6.83	26230	479	37860	13.8	4.0	4
		23:53		268	3800	6.88	30030	548	36990	14.2	3.9	5
21-Jun		7:51		478	6700	6.85	36730	670	38210	14.0	3.9	6
		19:02		671	9400	7.09	46130	842	39470	14.0	3.9	7
22-Jun		0:24		322	4500	6.97	50630	924	40230	14.0	3.9	8
		15:29		905	12620	7.28	63250	1154	39670	13.9	3.9	9
		23:46		517	6920	7.05	70170	1281	40620	13.4	4.1	10
23-Jun		13:38		834	11660	7.05	81830	1494	39110	14.0	3.9	11
24-Jun		10:07		1229	17150	7.34	98980	1807	39430	14.0	3.9	12
		17:23	17:34	436	6010	6.94	104990	1916	38490	13.8	4.0	13

4.0 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.3.15 - Test 2

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> XR-405 - Test 2	Height-----> 31.0 cm
Feed-----> 40 ppm NaClO ₄ as ClO ₄ ⁻	Bed Volume (BV)-----> 54.79 cm ³
Period-----> 07/02/1999 to 07/04/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	Conc. (ppb)	Flow rate(ml/min)	EBCT (min)	Sample #
	Started	Sampled	Stopped									
02-Jul	4:50 PM	11:51 PM		421	6990	7.90	6990	128	35210	16.6	3.3	1
03-Jul		10:26 AM		635	7190	7.87	14180	259	38890	11.3	4.8	2
		6:33 PM		487	5460	7.30	19640	358	37460	11.2	4.9	3
04-Jul		12:40 AM		367	4110	7.23	23750	433	33110	11.2	4.9	4
		11:20 AM		640	7210	7.78	30960	565	30990	11.3	4.9	5
		10:24 PM	10:36 PM	664	7670	8.52	38630	705	38440	11.6	4.7	6

4.6 Ave

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.1 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate	Column diameter-----> 2.2 cm
Resin type-----> ASB 1	Height-----> 30.1 cm
Feed-----> "Real" water	Bed Volume (BV)-----> 114.42cm ³
Period-----> 10/31/1999 to 11/03/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppm)	NO_3^- (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
31-Oct	10:25	15:34		309	7500	8.19	7500	65.55	0.01	26.23	24.3	4.7	1
		22:56		442	11800	8.12	19300	168.7	0.01	49.78	26.7	4.3	2
01-Nov		9:58		662	17050	8.23	36350	317.7	0.01	50.04	25.8	4.4	3
		19:02		544	13770	8.98	50120	438.0	0.0264	53	25.3	4.5	4
02-Nov		8:16		794	21660	7.67	71780	627.3	2.67	52	27.3	4.2	5
		19:36		680	18520	7.53	90300	789.2	20.35	50	27.2	4.2	6
03-Nov		8:43	9:10	787	20300	7.71	110600	966.6	66.46	50.2	25.8	4.4	7

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.1 / 4.4.3 - SO_4^{2-} and TOC

Test-----> Adsorption of Perchlorate	Column diameter-----> 2.2 cm
Resin type-----> ASB 1	Height-----> 30.1 cm
Feed-----> "Real" water	Bed Volume (BV)-----> 114.42cm ³
Period-----> 10/31/1999 to 11/03/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	SO_4^{2-} (ppm)	TOC (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
31-Oct	10:25	15:34		309	7500	8.19	7500	65.55	2072	27.82	24.3	4.7	1
		22:56		442	11800	8.12	19300	168.68	2063	50.33	26.7	4.3	2
01-Nov		9:58		662	17050	8.23	36350	317.69	2087	51.45	25.8	4.4	3
		19:02		544	13770	8.98	50120	438.04	2078	30.69	25.3	4.5	4
02-Nov		8:16		794	21660	7.67	71780	627.34	2044	52.29	27.3	4.2	5
		19:36		680	18520	7.53	90300	789.20	1997	58.27	27.2	4.2	6
03-Nov		8:43	9:10	787	20300	7.71	110600	966.61	2019	58.34	25.8	4.4	7

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.4 - ClO_4^- and NO_3^-

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB 1	Height*-----> 30.1 cm, 28.5 cm, 27.5 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 108.34 ml
Date-----> 12/23/1999	

Regenerant solution pH: 8.41	* before loading, after loading and before
Spent regenerant solution pH: 8.33	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO_4^- (ppm)	NO_3^- (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
23-Dec	12:20	12:30		10	120	120	1120	274.7	1.11	12.0	9.0	1
		12:37		7	80	200	1194	202.3	1.85	14.3	7.6	2
		12:45		8	80	280	1184	136.4	2.58	12.5	8.7	3
		12:53		8	80	360	1334	60.6	3.32	12.5	8.7	4
		13:05		12	120	480	1006	34.8	4.43	11.7	9.3	5
		13:20		15	170	650	1022	-	6.00	12.7	8.6	6
		13:27		7	70	720	822	-	6.64	12.9	8.4	7
		13:41		14	150	870	921	-	8.03	12.1	8.9	8
		13:53		12	130	1000	873	-	9.23	12.5	8.7	9
		14:11	14:13	18	200	1200	797	-	11.07	12.2	8.9	10

8.7 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.4 - SO_4^{2-} and TOC

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB 1	Height*-----> 30.1 cm, 28.5 cm, 27.5 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 108.34 ml
Date-----> 12/23/1999	

Regenerant solution pH: 8.41	* before loading, after loading and before
Spent regenerant solution pH: 8.33	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	SO_4^{2-} (ppm)	TOC (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
23-Dec	12:20	12:30		10	120	120	6960.0	136.30	1.11	12.0	9.0	1
		12:37		7	80	200	1166.0	56.30	1.85	14.3	7.6	2
		12:45		8	80	280	510.0	37.51	2.58	12.5	8.7	3
		12:53		8	80	360	280.9	32.69	3.32	12.5	8.7	4
		13:05		12	120	480	112.5	27.96	4.43	11.7	9.3	5
		13:20		15	170	650	38.9	23.27	6.00	12.7	8.6	6
		13:27		7	70	720	21.0	19.78	6.64	12.9	8.4	7
		13:41		14	150	870	11.8	17.52	8.03	12.1	8.9	8
		13:53		12	130	1000	7.6	16.98	9.23	12.5	8.7	9
		14:11	14:13	18	200	1200	4.4	14.90	11.07	12.2	8.9	10

8.7 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.5 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate
Resin type-----> ASB 2
Feed-----> "Real" water
Period-----> 10/31/1999 to 11/03/1999

Column diameter-----> 2.2 cm
Height-----> 30.7 cm
Bed Volume (BV)-----> 116.7cm³

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppm)	NO_3^- (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
31-Oct	10:25	15:36		311	8740	8.13	8740	74.89	0.01	35.55	28.1	4.2	1
		23:01		445	12680	8.12	21420	183.55	0.01	51.82	28.5	4.1	2
01-Nov		10:05		664	17970	8.12	39390	337.53	0.02	51.90	27.1	4.3	3
		19:07		542	15260	7.83	54650	468.29	1.55	50.06	28.2	4.1	4
02-Nov		8:13		786	22580	7.59	77230	661.78	56.49	50.42	28.7	4.1	5
		19:26		673	19230	7.50	96460	826.56	73.93	49.42	28.6	4.1	6
03-Nov		8:51	9:18	805	19720	7.71	116180	995.54	72.50	50.00	24.5	4.8	7

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.5 and 4.4.6 - SO_4^{2-} and TOC

Test-----> Adsorption of Perchlorate	Column diameter-----> 2.2 cm
Resin type-----> ASB 2	Height-----> 30.7 cm
Feed-----> "Real" water	Bed Volume (BV)-----> 116.7cm ³
Period-----> 10/31/1999 to 11/03/1999	

Date	Time			Total Time(min)	Volume (mi)	pH	Cum. volume	BV run	SO_4^{2-} (ppm)	TOC (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
31-Oct	10:25	15:36		311	8740	8.13	8740	74.89	2075	51.06	28.1	4.2	1
		23:01		445	12680	8.12	21420	183.55	2080	45.83	28.5	4.1	2
01-Nov		10:05		664	17970	8.12	39390	337.53	2069	39.39	27.1	4.3	3
		19:07		542	15260	7.83	54650	468.29	2027	47.23	28.2	4.1	4
02-Nov		8:13		786	22580	7.59	77230	661.78	2020	56.12	28.7	4.1	5
		19:26		673	19230	7.50	96460	826.56	2082	34.99	28.6	4.1	6
03-Nov		8:51	9:18	805	19720	7.71	116180	995.54	2025	48.06	24.5	4.8	7

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.7 - ClO_4^- and NO_3^-

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB 2	Height*-----> 30.7 cm, 29.0 cm, 31.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 110.24 ml
Date-----> 12/23/1999	

Regenerant solution pH: 8.41	* before loading, after loading and before
Spent regenerant solution pH: 8.33	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO_4^- (ppm)	NO_3^- (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped									
23-Dec	16:00	16:09		9	120	120	1104	255.92	1.09	13.3	8.3	1
		16:17		8	80	200	1211	211.68	1.81	12.5	8.8	2
		16:26		9	80	280	1990	128.52	2.54	11.1	9.9	3
		16:35		9	80	360	1186	90.84	3.27	11.1	9.9	4
		16:47		12	120	480	1024	26.77	4.35	11.7	9.4	5
		16:59		12	120	600	1126	-	5.44	11.7	9.4	6
		17:10		11	120	720	975	-	6.53	12.7	8.7	7
		17:23		13	130	850	1052	-	7.71	11.5	9.6	8
		17:37		14	150	1000	883	-	9.07	12.1	9.1	9
		17:51	17:53	14	150	1150	946	-	10.43	12.1	9.1	10
											9.2	Ave.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.7 - SO_4^{2-} and TOC

Test-----> Regeneration of Resin	Column diameter-----> 2.2 cm
Resin type-----> ASB 2	Height*-----> 30.7 cm, 29.0 cm, 31.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 110.24 ml
Date-----> 12/23/1999	

Regenerant solution pH: 8.41	* before loading, after loading and before
Spent regenerant solution pH: 8.33	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	SO_4^{2-} (ppm)	TOC (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
23-Dec	16:00	16:09		9	120	120	14596	192.6	1.09	13.3	8.3	1
		16:17		8	80	200	4158	68.35	1.81	12.5	8.8	2
		16:26		9	80	280	1108	37.75	2.54	11.1	9.9	3
		16:35		9	80	360	475.36	28.77	3.27	11.1	9.9	4
		16:47		12	120	480	213.51	22.79	4.35	11.7	9.4	5
		16:59		12	120	600	146.52	20.84	5.44	11.7	9.4	6
		17:10		11	120	720	61.47	18.64	6.53	12.7	8.7	7
		17:23		13	130	850	28.35	16.71	7.71	11.5	9.6	8
		17:37		14	150	1000	15	15.13	9.07	12.1	9.1	9
		17:51	17:53	14	150	1150	8.23	15.06	10.43	12.1	9.1	10
											9.2	Ave.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.8 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> ASB1 - PC	Height-----> 29.6 cm
Feed-----> "Real" water (Bottles 3,6,9)	Bed Volume (BV)-----> 52.31cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppm)	NO_3^- (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:17		839	7390	7.68	7390	141.27	100	50.54	8.8	5.9	1
		14:37		320	3950	7.72	11340	216.78	3070	48.24	12.3	4.2	2
		21:13		396	4690	7.58	16030	306.44	43060	48.94	11.8	4.4	3
09-Nov		8:20		667	8320	7.71	24350	465.49	85710	48.3	12.5	4.2	4
		13:42		322	3730	7.72	28080	536.80	86760	47.6	11.6	4.5	5
		18:47		305	3820	7.6	31900	609.83	86940	49.32	12.5	4.2	6
10-Nov		8:15		808	10020	7.75	41920	801.38	83190	48.88	12.4	4.2	7
		10:28	10:41	133	1610	7.65	43530	832.15	85070	49.04	12.1	4.3	8

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.8 and 4.4.9 - SO_4^{2-} and TOC

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> ASB1 - PC	Height-----> 29.6 cm
Feed-----> "Real" water (Bottles 3,6,9)	Bed Volume (BV)-----> 52.31cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	SO_4^{2-} (ppm)	TOC (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:17		839	7390	7.68	7390	141.27	1980	19.13	8.8	5.9	1
		14:37		320	3950	7.72	11340	216.78	1930	28.38	12.3	4.2	2
		21:13		396	4690	7.58	16030	306.44	1941	22.34	11.8	4.4	3
09-Nov		8:20		667	8320	7.71	24350	465.49	1934	46.17	12.5	4.2	4
		13:42		322	3730	7.72	28080	536.80	1940	39.93	11.6	4.5	5
		18:47		305	3820	7.6	31900	609.83	1970	36.43	12.5	4.2	6
10-Nov		8:15		808	10020	7.75	41920	801.38	1945	38.6	12.4	4.2	7
		10:28	10:41	133	1610	7.65	43530	832.15	1929	36.46	12.1	4.3	8

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.10 - ClO_4^- and NO_3^-

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> ASB1 - PC	Height*-----> 29.6 cm, 29.0 cm, 33.5 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 51.25 ml
Date-----> 12/21/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 7.54	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO_4^- (ppm)	NO_3^- (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped									
21-Dec	15:57	16:10		13	100	100	1540	134.2	1.95	7.7	6.7	1
		16:21		11	40	140	1086	110	2.73	5.5	9.4	2
		16:32		11	40	180	1180	28.34	3.51	5.5	9.4	3
		16:43		11	40	220	1058	-	4.29	5.5	9.4	4
		16:53		10	40	260	1177	-	5.07	6.0	8.5	5
		17:04		11	40	300	1017	-	5.85	5.5	9.4	6
		17:16		12	50	350	801	-	6.83	5.8	8.8	7
		17:27		11	50	400	1048	-	7.80	6.4	8.1	8
		17:40		13	50	450	957	-	8.78	5.4	9.5	9
		17:53	17:57	13	50	500	784	-	9.76	5.4	9.5	10

8.9 Aver.

1056	-	Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.10 - SO_4^{2-} and TOC

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> ASB1 - PC	Height*-----> 29.6 cm, 29.0 cm, 33.5 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 51.25 ml
Date-----> 12/21/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 7.54	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	SO_4^{2-} (ppm)	TOC (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
21-Dec	15:57	16:10		13	100	100	1306.0	106.9	1.95	7.7	6.7	1
		16:21		11	40	140	527.8	77.2	2.73	5.5	9.4	2
		16:32		11	40	180	233.4	60.02	3.51	5.5	9.4	3
		16:43		11	40	220	99.3	47.47	4.29	5.5	9.4	4
		16:53		10	40	260	57.5	37.94	5.07	6.0	8.5	5
		17:04		11	40	300	37.3	30.67	5.85	5.5	9.4	6
		17:16		12	50	350	22.2	27.63	6.83	5.8	8.8	7
		17:27		11	50	400	16.6	23.34	7.80	6.4	8.1	8
		17:40		13	50	450	18.1	22.14	8.78	5.4	9.5	9
		17:53	17:57	13	50	500	12.2	19.02	9.76	5.4	9.5	10

45.233

2636.0	6.603	8.9	Aver.
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1056	-		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.11 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> AFP 329	Height-----> 30.8 cm
Feed-----> "Real" water (Bottles 1,4,7)	Bed Volume (BV)-----> 54.43cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppm)	NO_3^- (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:21		843	8150	7.92	8150	149.7	0.79	51.94	9.7	5.4	1
		14:37		316	3790	7.86	11940	219.4	18.68	51.02	12.0	4.4	2
		21:13		396	4550	7.76	16490	303.0	49.39	50.6	11.5	4.6	3
09-Nov		8:25		672	8150	7.79	24640	452.7	72.25	48.98	12.1	4.3	4
		13:42		317	3710	7.58	28350	520.9	78.38	47.56	11.7	4.5	5
		18:47		305	3700	7.68	32050	588.8	76.62	48	12.1	4.3	6
10-Nov		8:20		813	9700	7.65	41750	767.0	73.83	48	11.9	4.4	7
		10:32	10:41	132	1470	7.79	43220	794.0	75.42	48.12	11.1	4.7	8

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.11 and 4.4.12 - SO_4^{2-} and TOC

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> AFP 329	Height-----> 30.8 cm
Feed-----> "Real" water (Bottles 1,4,7)	Bed Volume (BV)-----> 54.43cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	SO_4^{2-} (ppm)	TOC (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:21		843	8150	7.92	8150	149.7	1977	27.85	9.7	5.4	1
		14:37		316	3790	7.86	11940	219.4	2007	57.49	12.0	4.4	2
		21:13		396	4550	7.76	16490	303.0	1963	55.54	11.5	4.6	3
09-Nov		8:25		672	8150	7.79	24640	452.7	1963	57.12	12.1	4.3	4
		13:42		317	3710	7.58	28350	520.9	1982	55.28	11.7	4.5	5
		18:47		305	3700	7.68	32050	588.8	2023	48.99	12.1	4.3	6
10-Nov		8:20		813	9700	7.65	41750	767.0	1920	29.71	11.9	4.4	7
		10:32	10:41	132	1470	7.79	43220	794.0	1918	55.7	11.1	4.7	8

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.13 - ClO_4^- and NO_3^-

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> AFP 329	Height*-----> 30.8 cm, 31.5 cm, 32.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 55.67 ml
Date-----> 12/22/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 8.31	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO_4^- (ppm)	NO_3^- (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampld	stopped									
22-Dec	11:27	11:48		21	100	100	1136	-	1.80	4.8	11.7	1
		12:01		13	40	140	1289	-	2.51	4.6	12.1	2
		12:13		12	40	180	940.5	-	3.23	5.0	11.1	3
		12:25		12	40	220	1000.6	-	3.95	5.0	11.1	4
		12:35		10	40	260	792.5	-	4.67	6.0	9.3	5
		12:46		11	40	300	701.4	-	5.39	5.5	10.2	6
		12:56		10	50	350	661.9	-	6.29	7.0	8.0	7
		13:06		10	50	400	644.2	-	7.19	7.0	8.0	8
		13:17		11	50	450	533.7	-	8.08	6.4	8.7	9
		13:30	13:34	13	50	500	459.4	-	8.98	5.4	10.3	10
											10.0	Aver.

-	-	862.3	-	-		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.13 - SO_4^{2-} and TOC

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> AFP 329	Height*-----> 30.8 cm, 31.5 cm, 32.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 55.67 ml
Date-----> 12/22/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 8.31	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	SO_4^{2-} (ppm)	TOC (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped									
22-Dec	11:27	11:48		21	100	100	200.94	38.43	1.80	4.8	11.7	1
		12:01		13	40	140	98.82	17.90	2.51	4.6	12.1	2
		12:13		12	40	180	57.17	13.80	3.23	5.0	11.1	3
		12:25		12	40	220	43.47	10.19	3.95	5.0	11.1	4
		12:35		10	40	260	38.06	7.41	4.67	6.0	9.3	5
		12:46		11	40	300	25.79	6.08	5.39	5.5	10.2	6
		12:56		10	50	350	26.07	5.55	6.29	7.0	8.0	7
		13:06		10	50	400	20.67	5.36	7.19	7.0	8.0	8
		13:17		11	50	450	19.15	4.70	8.08	6.4	8.7	9
		13:30	13:34	13	50	500	16.57	4.54	8.98	5.4	10.3	10
											10.0	Aver.

-	-	222.86	26.81	-		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.14 - ClO_4^- and NO_3^-

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T	Height-----> 31.4 cm
Feed-----> "Real" water (Bottles 2,5,8)	Bed Volume (BV)-----> 55.49 cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	ClO_4^- (ppm)	NO_3^- (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:19		841	8100	7.73	8100	145.97	105.3	48.0	9.6	5.4	1
		14:37		318	3750	7.77	11850	213.55	89.4	50.5	11.8	4.4	2
		21:13		396	4520	7.67	16370	295.01	88.2	52.1	11.4	4.6	3
09-Nov		8:22		669	8000	7.75	24370	439.18	85.9	53.0	12.0	4.4	4
		13:42		320	3830	7.6	28200	508.20	85.5	49.0	12.0	4.4	5
		18:47		305	3750	7.63	31950	575.78	84.4	47.6	12.3	4.3	6
10-Nov		8:18		811	9740	7.74	41690	751.31	79.8	47.8	12.0	4.4	7
		10:30	10:41	132	1580	7.75	43270	779.78	78.7	48.6	12.0	4.4	8

4.5 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.14 and 4.4.15 - SO_4^{2-} and TOC

Test-----> Adsorption of Perchlorate	Column diameter-----> 1.5 cm
Resin type-----> Macro T	Height-----> 31.4 cm
Feed-----> "Real" water (Bottles 2,5,8)	Bed Volume (BV)-----> 55.49 cm ³
Period-----> 11/07/1999 to 11/10/1999	

Date	Time			Total Time(min)	Volume (ml)	pH	Cum. volume	BV run	SO_4^{2-} (ppm)	TOC (ppm)	Flow rate(ml/min)	EBCT (min)	#
	Started	Sampled	Stopped										
07-Nov	19:18												
08-Nov		9:19		841	8100	7.73	8100	145.97	1971	47.45	9.6	5.4	1
		14:37		318	3750	7.77	11850	213.55	1975	49.18	11.8	4.4	2
		21:13		396	4520	7.67	16370	295.01	1956	25.75	11.4	4.6	3
09-Nov		8:22		669	8000	7.75	24370	439.18	1992	50.21	12.0	4.4	4
		13:42		320	3830	7.6	28200	508.20	1933	41.91	12.0	4.4	5
		18:47		305	3750	7.63	31950	575.78	1962	27.05	12.3	4.3	6
10-Nov		8:18		811	9740	7.74	41690	751.31	1974	33.81	12.0	4.4	7
		10:30	10:41	132	1580	7.75	43270	779.78	1959	40.89	12.0	4.4	8

4.5 Aver.

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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.16 - ClO_4^- and NO_3^-

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> Macro T	Height*-----> 31.4 cm, 31.5 cm, 35.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 55.67 ml
Date-----> 12/22/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 7.68	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	ClO_4^- (ppm)	NO_3^- (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped									
22-Dec	8:07	8:19		12	100	100	968.7	116.35	1.80	8.33	6.68	1
		8:28		9	40	140	803.8	-	2.51	6.67	8.35	2
		8:37		9	40	180	564.6	-	3.23	6.67	8.35	3
		8:49		12	40	220	526.3	-	3.95	5.00	11.13	4
		9:02		13	60	280	394.9	-	5.03	6.15	9.05	5
		9:08		6	20	300	300.9	-	5.39	6.67	8.35	6
		9:19		11	50	350	185.4	-	6.29	6.36	8.75	7
		9:32		13	50	400	145.8	-	7.19	5.38	10.34	8
		9:45		13	50	450	120.41	-	8.08	5.38	10.34	9
		9:56	10:00	11	50	500	90.04	-	8.98	6.36	8.75	10
											9.01	Aver.

427.5	-		Mixed
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Perchlorate Removal by Ion-Exchange Resins - Data for Figure 4.4.16 - SO_4^{2-} and TOC

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> Macro T	Height*-----> 31.4 cm, 31.5 cm, 35.0 cm
Regenerant-----> 12% NaCl	Bed Volume (BV)-----> 55.67 ml
Date-----> 12/22/1999	

Regenerant solution pH: 6.41	* before loading, after loading and before
Spent regenerant solution pH: 7.68	regeneration, after regeneration.

Date	Time			Minutes	Volume (ml)	Cumulated Volume	SO_4^{2-} (ppm)	TOC (ppm)	BV run	Flow Rate (ml/min)	EBCT (minutes)	Sample #
	started	sampled	stopped									
22-Dec	8:07	8:19		12	100	100	2276.0	221.1	1.80	8.33	6.68	1
		8:28		9	40	140	570.6	119.4	2.51	6.67	8.35	2
		8:37		9	40	180	214.4	77.25	3.23	6.67	8.35	3
		8:49		12	40	220	65.7	59.63	3.95	5.00	11.13	4
		9:02		13	60	280	32.8	41.46	5.03	6.15	9.05	5
		9:08		6	20	300	22.2	35.23	5.39	6.67	8.35	6
		9:19		11	50	350	12.4	27.22	6.29	6.36	8.75	7
		9:32		13	50	400	8.4	20.69	7.19	5.38	10.34	8
		9:45		13	50	450	20.5	18.01	8.08	5.38	10.34	9
		9:56	10:00	11	50	500	10.5	16.54	8.98	6.36	8.75	10
											9.01	Aver.

3272.0	144.7		Mixed
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APPENDIX C

EXAMPLE REGENERATION EFFICIENCY CALCULATION

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Regeneration Efficiency Calculation Example

Test-----> Regeneration of Resin	Column diameter-----> 1.5 cm
Resin type-----> SR7 - Column 1	Height-----> 32.5 cm
Regenerant-----> 12% Sodium Chloride	Bed Volume (BV)-----> 57.43 ml
Date-----> 02/06/1999	

A. Total Amount of Perchlorate Recovered in the Regeneration Process:

Sample #	Cum. Volume	C (mg/L)	Sample Volume (L)	ClO ₄ ⁻ Mass (mg)
1	135	1,060	0.02	21.20
2	160	1,065	0.02	21.30
3	300	676	0.02	13.52
4	350	614	0.02	12.28
5	400	586	0.02	11.72
6	450	537	0.02	10.74
7	520	450	0.02	9.00
8	600	460	0.02	9.20
9	700	417	0.02	8.34

ClO₄⁻ mass in the spent regeneration solution

Volume of spent regeneration solution = 700 mL

Perchlorate concentration = 840 mg/L

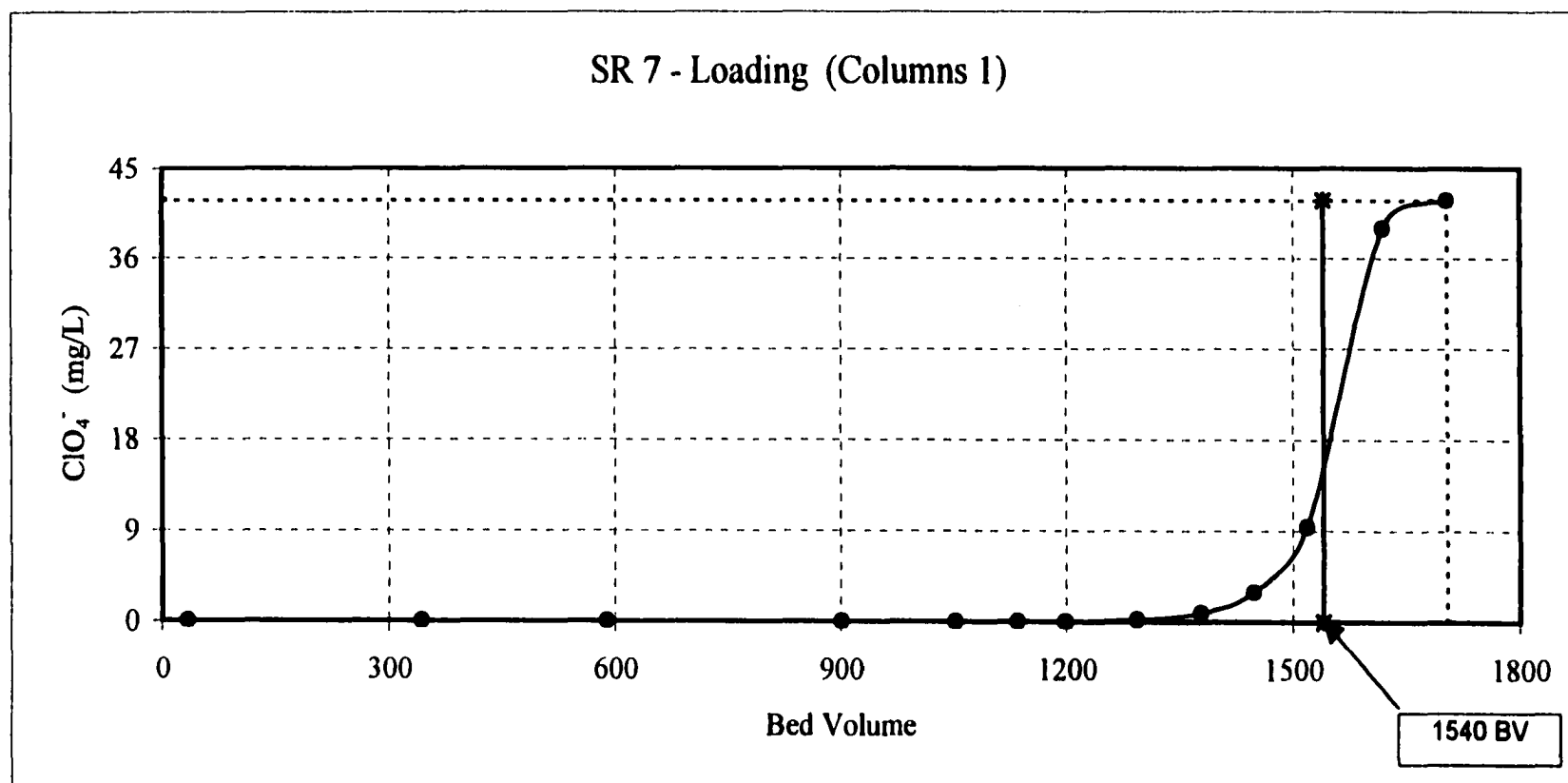
Therefore, ClO₄⁻ mass = 840 * 0.7 = 588 mg

Total perchlorate mass in the vials = 117.30 mg
ClO₄⁻ mass in the spent regeneration solution = 588.00 mg

Total ClO₄⁻ recovered (mg) = 705.30

Continued

B.Total Amount of Perchlorate Exchanged with the Resins:



$$\text{Perchlorate mass} = (1540 \text{ BV}) * 57.43 \text{ (mL/BV)} * (1\text{L} / 1000 \text{ mL}) * (40 \text{ mg/L}) = 3537.69 \text{ mg}$$

$$\text{Regeneration Efficiency} = [(705.3) / (3537.688)] * 100 = \boxed{19.9 \%}$$

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Publications:

Batista, Jacimaria R., F. X. McGarvey, and A. R. Vieira. 2000. The Removal of Perchlorate from Waters Using Ion-Exchange Resins, Chapter 13 In Perchlorate in the Environment, edited by Edward T. Urbansky, Plenum, pp. 135-145.

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Thesis Title: The Removal Of Perchlorate From Waters Using Ion-Exchange Resins.

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