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Low-Pressure Reverse Osmosis Membrane Treatment of Landfill Leachate

by
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ABSTRACT

The fear that contaminated leachate could escape from the Trail Road Municipal Landfill Site, and the need for a cost-effective on-site treatment alternative, has led to an evaluation of the options for treating the leachate. One treatment option being examined is the use of low-pressure reverse osmosis (RO), which is becoming increasingly attractive with the development of new technology. The purpose of this study is to evaluate the technical feasibility of this treatment process for synthetic and real landfill leachate.

Membrane 'coupon' experiments were conducted to study three types of low-pressure membranes (supplied by Hydranautics, Fluid Systems, and Saehan Industries), to determine the membrane with the highest permeate flux and rejection capabilities, to conduct statistical analysis on the testing apparatus and to test how the selected membrane was able to cope with different concentrations of synthetic leachate at different operating pressures. Under low-pressure conditions [100 - 200 psi (689 - 1378 kN/m^2)], the Hydranautics' membrane was selected as the most appropriate low-pressure RO membrane for the treatment of landfill leachate. A feed of 5000 mg/l NaCl made up with RO water gave removal efficiencies greater than 97% at permeate flowrates ranging from 27.0 to 53.0 l/m^2/hr. The Hydranautics' membrane achieved consistently high removal rates for total organic carbon (TOC) (>84%), for NH_3 (>83%) and Cl^- (>81%) using feeds of various synthetic leachate concentrations. For operating pressures between 150 and 225 psi (1034 and 1550 kN/m^2), the product permeate fluxes were in the range of 7.7

to 31.7 l/m^2/hr; at lower operating pressures [75 - 150 psi (517 - 1034 kN/m^2)], the product flux was in the range of 1.9 to 9.5 l/m^2/hr.

Membrane 'coupon' experiments were conducted on the Hydranautics' membrane with actual Trail Road leachate to determine the effect of leachate concentration and operating pressure on the product flux and on the TOC, NH_3, and the Cl^- removal efficiencies. The 'coupon' experiments achieved TOC and Cl^- removal efficiencies greater than 96% and NH_3 removal efficiencies greater than 88%. For operating pressures in the range of 150 - 240 psi (1034 - 1654 kN/m^2), the product flux was in the range of 26.0 to 54.0 l/m^2/hr.

Tests on Trail Road leachate samples were conducted with a lab-scale Hydranautics' spiral-wound membrane at operating pressures of 40, 50, and 60 psi (276, 345, and 413 kN/m^2). The Hydranautics' spiral-wound configuration produced low removal rates and permeate fluxes for highly concentrated leachate. The range of removal rates for TOC and Cl^- were 73 to 96% and 27 to 93%, respectively. Product flux was in the range of 0.6 and 5.5 l/m^2/hr.

It is recommended that a pilot-scale membrane test, using a spiral-wound membrane capable of withstanding higher operating pressures [>60 psi (413 kN/m^2)], should be conducted at the Trail Road Landfill Site using real leachate.

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List of Abbreviations

ANOVA	Analysis of Variance
AOX	Adsorbable Organic Halogens
BAC	Biologically Active Carbon
BOD	Biochemical Oxygen Demand, mg O_2/l
BOD_5	Five-day Biochemical Oxygen Demand, mg O_2/l
CA	Cellulose Acetate
COD	Chemical Oxygen Demand, mg O_2/l
HELP	Hydrologic Evaluation of Landfill Profile
MBR	Membrane Bioreactor
MF	Microfiltration
NF	Nanofiltration
NRCC	National Research Council Canada
PAC	Powder Activated Carbon
PR	Product Rate, l/m^2/hr
PWP	Pure Water Permeate, l/m^2/hr
PWP_f	Final Pure Water Permeate, l/m^2/hr
PWP_i	Initial Pure Water Permeate, l/m^2/hr
R^2	Coefficient of Correlation
RO	Reverse Osmosis
SDI	Salt Density Index
SS	Suspended Solids, mg/l
TDS	Total Dissolved Solids, mg/l
TOC	Total Organic Carbon, mg/l
TSS	Total Suspended Solids, mg/l
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
WBM	Water Balance Model

List of Variables

ΔP	Transmembrane Pressure Drop, $kg/m/s^2$
ΔS	Change in Storage, mm
a	Temperature Correction Factor, (-)
A	Volume of FAS required for blank, ml
B	Volume of FAS required for sample, ml
B_S	Coefficient of solute permeability, LT^{-1}
C_f	Concentration of Solute in the Feed, mg/l
C_p	Concentration of Solute in the Permeate, mg/l
C_{PWP}	Concentration of Solute in the Pure Water Permeate, mg/l
C_{RO}	Concentration of Solute in the RO Water, mg/l
C_S	Concentration of solute, ML^{-3}
D_S	Solute diffusivity, L^2T^{-1}
E(Y)	Expected Response Variable
ET	Evapotranspiration, mm
f	Degrees of Freedom
F_{lof}	Lack-of-fit test Statistic
F_{reg}	Regression Test Statistic
GI	Groundwater Intrusion, mm
J_S	Solute flux, $ML^{-2}T^{-1}$
J_V	Membrane Flux, $l/m^2/hr$
k	Number of Factors being studied
K_S	Distribution constant for concentrations on both sides of membrane, (-)
M	Concentration of FAS, mg/l
P	Precipitation, mm
PERC	Percolation at the bottom of the Landfill, mm
RF	Runoff, mm
R	Resistance Term
R_A	Adsorptive Resistance

R_m	Membrane Resistance
S	Membrane Separation Efficiency, %
SS	Sum of Squares
t	Time, s
T	Operating Temperature, C
x_1	Corrected Operating Pressure
x_2	Corrected TOC concentration
x_3	Corrected NH^+_4 concentration
x_4	Corrected Cl^- concentration
y	Observed Value

Greek Symbols

β_{ij}	Model Parameters
δ_M	Membrane Wall Thickness, length
μ	permeate viscosity, kg/m/s
π	Osmotic Pressure, psi
ρ	Density, kg/m^3
σ	Reflection Coefficient, (-)

Chapter 1 - Introduction

Storage in a landfill site is the cheapest method of solid waste disposal. As a result, it is currently the primary means of disposing of solid waste (McBean *et al.*, 1995), and it will continue to be so. However, the issues surrounding solid-waste management are becoming increasingly important because, despite the environmental improvements of landfill sites, landfill leachate continues to have a detrimental impact on the surrounding ecosystem. (Landfill leachate is rainwater and groundwater that percolates through the solid waste and picks up soluble components in the process; unless properly collected and treated, it seeps from the bottom and sides of the landfill into the groundwater.) Proper collection and treatment of landfill leachate is therefore essential if contamination of surrounding surface and groundwater is to be minimized. Groundwater contamination is a serious problem because groundwater is the source of drinking water for many communities; once contaminated it is a long term problem and costly to purify it.

The Trail Road Landfill site is located in the Regional Municipality of Ottawa Carleton, Nepean, Ontario, Canada. The entire site exists on a 200 ha area of which 135 ha are a buffer zone surrounding the site. Approximately one third of the waste collected in the Ottawa-Carleton region is disposed of at the Trail Road Site. In 1995, this amounted to 175,000 tonnes of municipal solid waste from the Regional Municipality of Ottawa Carleton (RMOC, 1995).

There are currently four stages at the site, two of which are capped. The two capped stages do not have an engineered landfill liner or collection system. The third stage is currently an active filling area, which was engineered with a synthetic liner and a leachate collection and recirculation system. The leachate collected at the Trail Road Landfill Site is either recycled back into the active face or is transported in a tanker truck to the Robert O. Pickard Environmental Centre (ROPEC) sewage treatment plant (approximately 40 km). The cost of trucking and the potential for groundwater contamination of the recycled leachate have resulted in the evaluation of alternative technologies for on-site treatment. The project described in the following investigates the potential use of low-pressure RO membrane technology for the treatment of landfill leachate generated at the Trail Road Landfill Site.

The study involved the following four stages:

1) Characterize and select a membrane from three ultra-low pressure RO membranes using a feed solution of sodium chloride.

2) Use the selected membrane to determine the separation and permeation rates using a synthetic leachate as a feed solution.

3) Use different concentrations of real leachate to determine the separation and permeation rates at different operating pressures.

4) Use a membrane with a spiral-wound configuration to determine the separation and permeation rates using a real leachate at different operating pressures.

The results of this project would provide preliminary information to be used to determine the feasibility of low-pressure reverse osmosis for the treatment of landfill leachate.

Layout of the Thesis

Chapter 2 presents a literature review; it discusses aspects concerning both landfill leachate and membrane treatment technology. The factors that affect landfill leachate flowrate and composition, particularly the Trail Road Municipal Landfill leachate, are presented. Membrane technologies, classification and applications in landfill leachate treatment are also discussed.

Chapter 3 presents the first paper of the thesis; it gives the results and discussion for the first two experiments of the project:

1) the selection of the appropriate membrane type, and
2) the coupon tests with synthetic leachate.

Chapter 4 presents the second paper of the thesis; it gives the results and discussion for the third and fourth experiments of the project:

3) the coupon tests with Trail Road Landfill leachate, and
4) the spiral-wound tests using Trail Road Landfill leachate .

Chapter 5 gives the overall conclusions and recommendations for the project, while Chapter 6 gives the list of references.

Chapter 2 - Literature Review

2.1 Landfill Leachate

Landfill leachate is characterized by its generation rate and composition, which are both affected by the age of the landfill site. The following sections discuss the composition of the leachate and its generation rates.

2.1.1 Leachate Flowrate

Leachate is formed when the waste moisture content exceeds its field capacity (El-Fadel *et al.*, 1997). (The field capacity is the maximum amount of moisture that can be retained in a porous medium without producing downward percolation.) Water entering a landfill site is trapped within interstitial spaces or pores; until the field capacity is exceeded, no leachate is produced. Consequently, when water is first introduced into a new landfill, there is a delay before leachate is produced. Fungaroli and Steiner (1979) estimated that for the first year of landfill site operation, water infiltration into the site does not result in any significant leachate production. But after 3 years of operation, it was found that the leachate generation rates agreed with estimates derived from a water-balance model, where allowance is made for the travel time of the water through the site.

The flowrate of leachate is influenced by several factors: rainfall, snowmelt, groundwater intrusion, the initial moisture content of the refuse, recirculation of leachate, and refuse decomposition (El-Fadel *et al.* 1997; Lema *et al.* 1988). Limiting the amount of liquid entering the landfill site reduces the generation of leachate. Therefore, to reduce the volume of leachate generated, a low permeability cap could be used to reduce the volume of water entering the landfill. (Pavelka *et al.* 1993).

The generation and distribution of leachate within a landfill site is also influenced by the age of the waste, its pretreatment and compaction, and the size and density of the constituent particles (El-Fadel *et al.* 1997; Lema *et al.* 1988).

Leachate Generation Models

The water balance model (WBM) is a commonly used means to estimate the volume of leachate generated from a landfill site (El-Fadel *et al.*, 1997). It is expressed as follows.

$$PERC = P - ET - RF + GI - \Delta S \qquad \text{Eq. 1}$$

Where: PERC is the percolation at the bottom of the landfill, mm,
P is the precipitation, mm,
ET is the evapotranspiration, mm,
RF is the runoff, mm,
GI is the groundwater intrusion, mm, and
ΔS is the change in storage, mm.

The WBM states that water which passes through the landfill cover and beyond the depth influenced by evapotranspiration will exit the landfill as leachate. This is only valid once the landfill site has reached its field capacity for holding water (El-Fadel *et al.*, 1997). Figure 1 illustrates the general representation of the model.

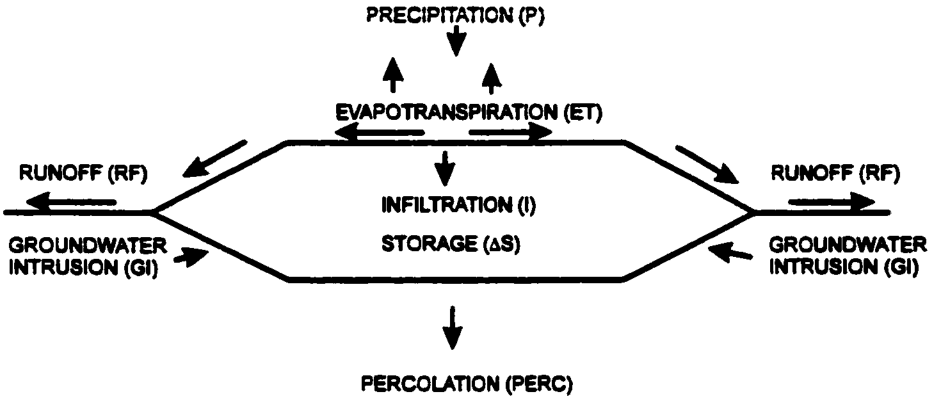

Figure 1: Water Balance Model (El-Fadel *et al.*, 1997)

There is uncertainty associated with estimating the variables of this model because they are either weather variables, which are difficult to predict, or dependent parameters (such as runoff coefficients, the degree of waste compaction, or the moisture content) whose values are not known with great accuracy.

The concept underlying Eq. 1 was used by the United States Environmental Protection Agency (USEPA) and the Department of Defense in the United States in the development of the Hydrologic Evaluation of Landfill Profile (HELP) model. This model simulates hydrologic processes for a landfill by performing daily, sequential water budget analyses using a quasi-two-dimensional approach. The HELP model incorporates lateral drainage, snowmelt and freezing. According to El-Fadel *et al.* (1997), the most significant improvement over the WBM model is the HELP model's ability to calculate a flow rate through the waste so that one can estimate the time for the leachate's appearance.

Trail Road Landfill Site

Two studies were conducted at the Trail Road Landfill, Nepean, ON, by Golder Associates (1990 and 1993) using the HELP model. Dillon (1994) regards this as the most suitable approach for predicting the hydrologic performance of a particular landfill configuration in terms of flow through the waste and leachate production. Using climatic data for Syracuse, NY, adjusted to Ottawa, ON, many scenarios were modeled, including several landfill configurations (to account for site growth) that overcome the inherent limitations that the model is static and unable to handle changes in the landfill configuration.

A preliminary study by Golder Associates in 1990 (Golder Associates, 1990), considered the waste to be placed at field capacity. This led the study to over-predict of the volume of leachate in the early stages of landfill operation (Dillon, 1994).

A second study, by Golder Associates in 1993 (Golder Associates, 1993), compared predictions of the model, using an adjustment factor, with actual leachate pumping data. The initial water content of the waste was varied in a range below the field capacity. The best agreement with reality was obtained when the initial water content of the waste was 40% of the field capacity, which implies that significant storage capacity for water/leachate is present within the waste (Dillon, 1994).

Dillon's report (1994) stated that the HELP model predicted that the leachate generation rate for the Trail Road Landfill Site would be 50 mm/yr per unit area of landfill for the early years of the landfill and 150 to 200 mm/yr per unit area of landfill in the later years of landfill operation. However, the volume of leachate generated at the Trail Road Landfill site varies from season to season (Dillon, 1994), as Figure 2 shows; the leachate pumping rates for 1997 at the Trail Road Landfill Site had their lowest flows in January and February and their highest flows between March and May.

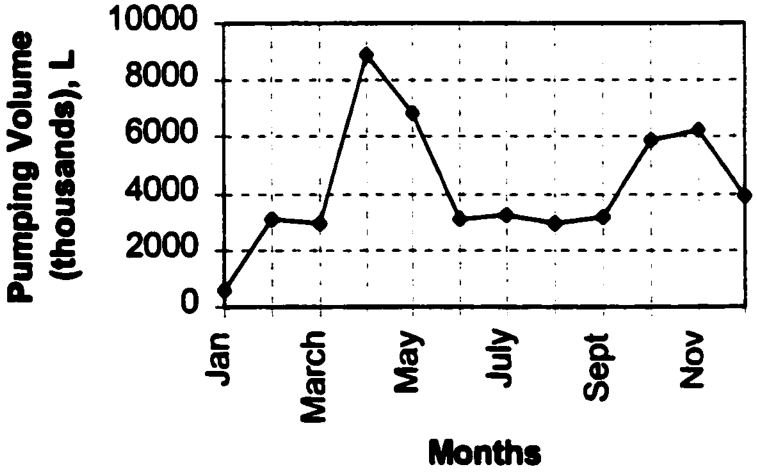

Figure 2: Leachate Pumping Rates (1997) Trail Road Landfill Site (Watson, 1998)

2.1.2 Leachate Characteristics and Constituents

Leachate composition varies from a manageable biodegradable waste source to an extremely hazardous waste. It does, however, have certain consistent characteristics. It is generally anoxic, has a high biochemical oxygen demand (BOD), and contains high concentrations of organic carbon, nitrogen, chloride, iron, manganese, and phenols (Staubitz *et al.*, 1991).

The age of the landfill affects the strength and biodegradability of its leachate. Therefore, the composition of a leachate depends both on the source of the waste and on how long it has been in the site. Furthermore, the age of a landfill site also affects the solid waste stabilization and so the composition of the leachate (Chian and DeWalle, 1976). Chian and DeWalle (1976) recommend using ratios of different parameters to characterize leachate since the concentration of different pollutants show a considerable day-to-day variation.

The ratio of BOD to chemical oxygen demand (COD) of landfills tends to decrease as the age of the landfill increases. This reflects the more oxidized state of the organic carbon, which is less readily available as an energy source for microbial growth. The resulting leachate is more difficult to treat by biological means (Chian and DeWalle, 1976). Figure 3 illustrates a typical leachate BOD/COD variation with time.

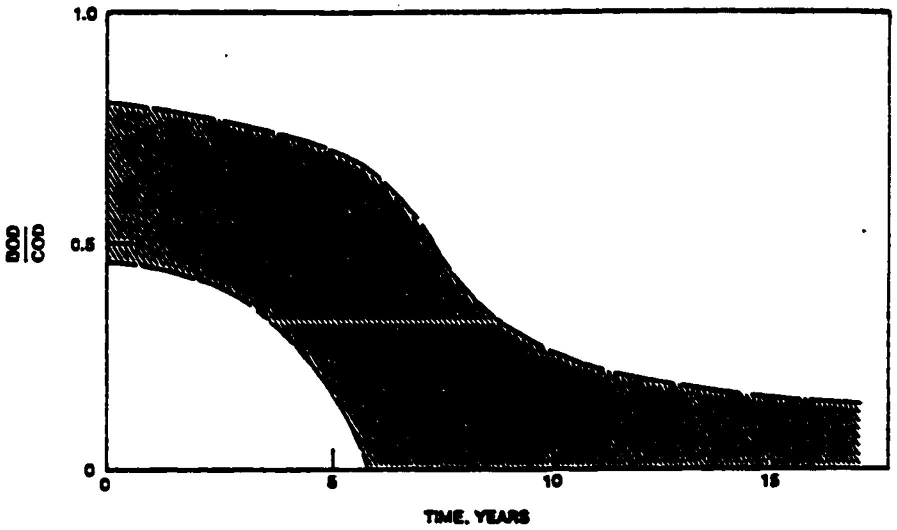

Figure 3: BOD/COD ratio versus Time (Chian and Dewalle, 1976)

The operational practices of a landfill also affect the characteristics of the leachate (Bilstad and Madland, 1992). Recycling of leachate to the landfill, over time, increases the inorganic content of the leachate relative to that of the organic, making it less suitable for biological treatment. Improvements in the sealing techniques at the landfill boundaries lead to increases in the leachate concentrations, reducing the amount of water infiltration into the landfill.

Ross (1990) studied the change with time of certain characteristics of a leachate from a landfill used for the co-disposal of toxic material with municipal refuse. His results are shown in Table 1 with respect to total dissolved solids (TDS), COD and ammonia nitrogen:

Table 1: Leachate Characteristics over Time

Parameter		**Stabilization Time (months)**				
		5	**12**	**21**	**29**	**42**
TDS	**mg/l**	33 750	39 450	31 980	16 480	10 133
COD	**mg/l**	38 100	56 373	49 000	19 300	2 000
ammonia N	**mg/l**	197	1 483	1 340	1 140	1 340

adapted from Ross (1990)

Table 1 shows how the leachate from a given landfill site varies with time. All three parameters considered, TDS, COD and ammonia N, initially increase in concentration from month 5 to month 12 but then decrease.

The composition of the leachate varies from landfill to landfill. Kettern (1992) characterized the leachate from four different landfills: two domestic waste landfills (A, W), one sewage sludge landfill (E), and one special waste landfill (N). Table 2 shows how the leachate concentrations change with the source of the waste.

Table 2: Characteristics of Leachate from four Landfills

Landfill	**BOD_5** **mg/l**	**COD** **mg/l**	**NH_4-N** **mg/l**
A	239	2341	1082
E	2696	4885	433
W	181	1511	694
N	10550	22508	7411

adapted from Kettern (1992)

The leachate from the special waste landfill has concentrations of 10,550 mg/l and 22,508 mg/l for BOD_5 and COD, respectively. Even the two domestic waste landfills (A and W) produce leachate with different concentrations; A is twice as strong as W. Unfortunately, Kettem (1992) fails to indicate the age of the four landfills, which could have a significant impact on the strength of the leachate.

Pavelka *et al.* (1993) evaluated leachate data from 18 commercial hazardous waste landfills to determine the overall leachate composition and the parameters that affect leachate generation and characteristics. These parameters included chemical properties, whether co-disposal of hazardous and municipal solid wastes was used, climatic conditions, and the age of the waste in the landfills.

The conclusions from the work reviewed in this section are that the characteristics and flowrate of a leachate are highly variable, from site to site, waste to waste, and season to season. This variability makes it crucial for all leachate treatment techniques to be tested at the laboratory scale. The variability in flowrate and composition makes it impossible to determine a standard treatment process, since it will be different for each site.

Trail Road Landfill Site

Dillon (1994) found that BOD and COD concentrations of the leachate generated at the Trail Road Landfill Site are scattered but the BOD/COD ratio follows a trend: it lies generally in the range of 0.5 - 0.75, as shown by Figure 4 (Dillon, 1994). This trend was used by Dillon (1994), in conjunction with Chian's long-term BOD to COD trend, to predict BOD and COD concentrations of the Trail Road Landfill leachate.

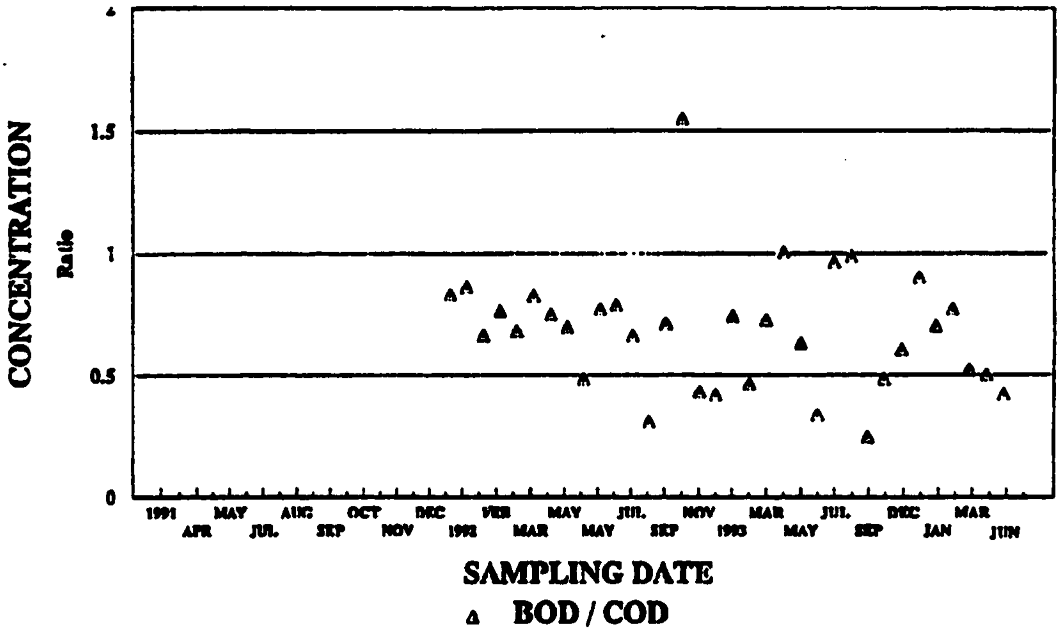

Figure 4: BOD/COD ratio versus Time for Trail Road Landfill Site (Dillon, 1994)

Currently, leachate at the Trail Road landfill site is collected and re-injected into the site or transported to the ROPEC treatment centre. Table 3 lists the typical leachate characteristics for the period of 21/07/93 to 14/07/94 (Lentz, 1996). Trail Road leachate is highly variable in both quantity and quality (Table 3).

Table 3: Trail Road Landfill Leachate Chemical Data

Parameter	Value, mg/l *	Parameter	Value, mg/l *
Conductivity, µmho/cm	1120 - 14100	**Ca**	119 - 12700
pH	6.50 - 7.90	**SO_4**	<2 - 390.00
Hardness ($CaCO_3$)	446 - 33009	**Al**	0.034 - 0.87
Suspended Solids	40 - 440	**Ba**	0.28 - 0.82
COD	2300 - 15000	**B**	0.17 - 8.8
TOC	59 - 5800	**Cr**	<0.002 - 0.22
Mg	36.2 - 391.0	**Cu**	<0.002 - 0.42
Na	95 - 1580	**Fe**	0.48 - 68
K	6 - 764	**Pb**	0.0001 - 0.035
Cl	61 - 1750	**Ni**	0.16 - 0.43
F	0.1 - 0.8	**Zn**	0.002 - 6.5

* unless otherwise specified, units are mg/l

2.1.3 Leachate Treatment Processes

The above sections describe some of the factors affecting the volume and the characteristics of the leachate. These characteristics are dependent on several factors: the age of the waste, its type, and the infiltration rate. Such dependence of the leachate makes it difficult to treat but there has been extensive research into different leachate treatment methods, and some are outlined in the following paragraphs.

Both aerobic and anaerobic biological treatment processes have been tested for use as treatment of landfill leachate (Collivignarelli *et al.*, 1993; Shams-Khorzani *et al.*, 1994). Collivignarelli *et al.* (1993) found that although anaerobic biological treatment reduces the organic portion of the leachate, it did not reduce the organic loading to levels that are suitable for direct discharge. Both Collivignarelli *et al.*(1993) and Shams-Khorzani *et al.* (1994) found that biological treatment processes are only useful for so-called 'young' leachates. Lentz (1996) conducted a study to determine the feasibility of treating the landfill leachate generated at the Trail Road Landfill Site using upflow anaerobic sludge blanket sequencing batch reactors. She tested different concentrations of leachate, but did not change the flowrate. This technology did not reduce the levels of sulphide, chloride and BOD concentrations sufficiently for sewer disposal, and given that changes in leachate flowrate make the treatment even more difficult, this process is clearly not suitable for the treatment of the leachate generated at the Trail Road Landfill site. In general biological reactors require high capital cost and the wastewater requires further treatment before land disposal or discharge into a waterway.

The present study examines the feasibility of using low-pressure reverse osmosis to treat the landfill leachate from the Trail Road landfill site. The effects of operating pressure and leachate concentration on the removal efficiencies of ammonia nitrogen, chloride and TOC for a selected low-pressure RO membrane were determined.

2.2 Membrane Technology

Membranes as filters are classified according to the size of particles that are removed during filtration in addition to the configuration of the membrane. The following section examines classes of membrane filters, different membrane configurations, and membrane materials.

2.2.1 Classes of Membrane Filtration

Filtration processes are classified according to the size of particles that are removed from the feed stream (Figure 5). Five different processes are discussed in this paper: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), RO, and low-pressure RO. All forms of filtration discussed below are methods used in cross-flow filters (Figure 6); the distinguishing characteristic for each process is the size of particles that the membrane removes. For cross-flow filtration the liquid flows across the membrane surface, rather than through the depth of the filter, minimizing the accumulation of material on the filter (Porter, 1990). There are three liquid streams for these filters: the feed, the retentate and the permeate. The feed is the wastewater being treated, the retentate is the concentrated stream that does not pass through the membrane, and the permeate is the treated effluent.

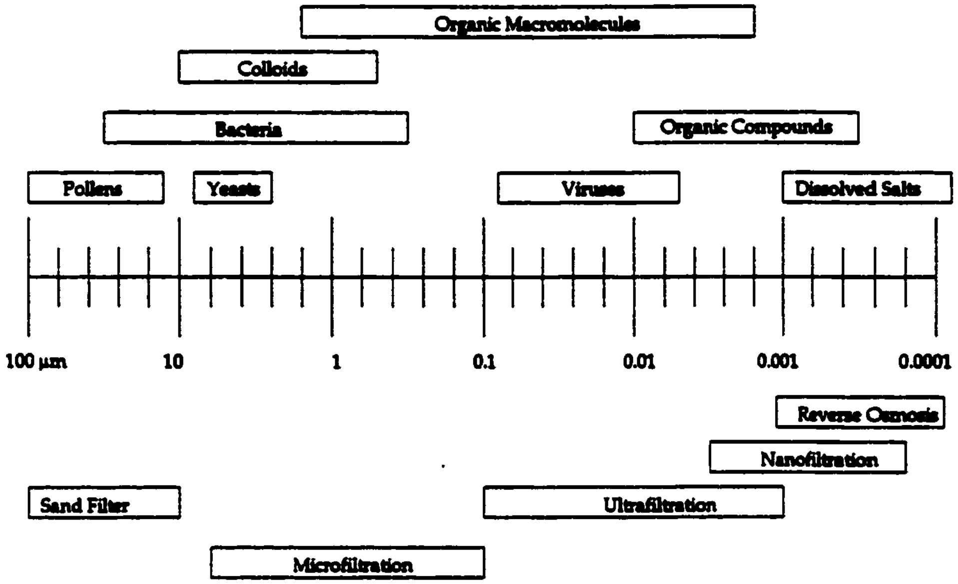

Figure 5: Membrane Process Particle Size Ranges (Droste, 1997)

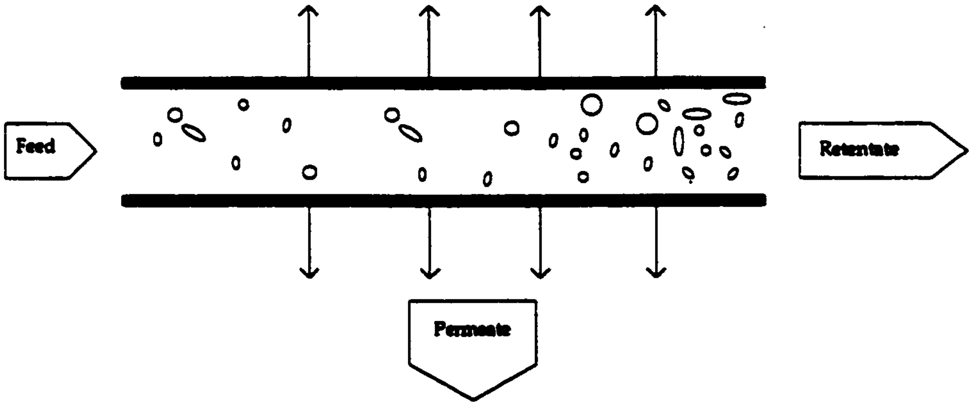

Figure 6: Cross-Flow Filtration (Porter, 1990).

Removal efficiency depends on the filtration process selected, and the choice between the different membrane processes is determined by the difference of pressure applied to the membrane (Gaeta, 1995). The smaller the particles required to be removed by the membrane, the higher the operating costs. Choice of the membrane process is thus a trade-off between removal efficiency and operating costs.

The following sections discuss the different filter classifications.

Microfiltration

MF is a low-pressure membrane process that removes suspended solids in the range 0.10 μm to 10 μm from a liquid stream. It is used to remove suspended matter and microorganisms, while it passes water, salts and select macromolecules. MF is often used as the process to remove solids after chemical precipitation of toxic metals (Krug and McDougall, 1989).

Ultrafiltration

UF is a process that uses a low-pressure membrane to separate species of high molecular weight from a feed stream. UF separates small colloids and large molecules from water and other liquids, and it removes particles in the 0.002 to 0.1 μm range (Krug and McDougall, 1989 and Gaeta, 1995). Nonionic matter is retained by the UF unit, but most ionic matter usually passes, depending on the molecular weight cutoff of the filter. UF is commonly used for the concentration of wastewaters containing emulsified oils or large molecular weight organic contaminants. The earliest application of UF was the recovery and concentration of protein from cheese whey (Caetano, 1995). UF membranes are very sensitive to fouling and to concentration polarization (Gaeta, 1995), which is the reduction in the flux through the membrane caused by an increase in the concentration of the solute at the membrane's surface.

Nanofiltration

NF falls between RO and UF on the filtration/separation spectrum. This process can pass more water at lower pressure than RO, and it removes particles in the 300 to 1,000 molecular weight range but rejects sulphate salts, while passing chloride salts. NF may be used for the selective removal of hardness ions like calcium and magnesium.

Reverse Osmosis

RO is a high-pressure membrane process for separating low molecular weight species from a feed stream. It is accomplished by applying a pressure (over and above the solution osmotic pressure) to a concentrated solution, thereby forcing pure water to flow across a semipermeable membrane to the dilute side. The process is so-called because the pressure forces the water to flow from the concentrated solution to the dilute solution. The pressure required to achieve a reverse effect depends on the concentration of salts in the original solution and on the amount of water that must be removed. Typical operating pressures range between 200 and 1000 psi (1378 and 6890 kN/m^2). RO removes ionized salts, colloids, and organic molecules down to a molecular weight of 100. RO has been used for the desalination of water since the 1960s (Caetano, 1995).

Low-pressure Reverse Osmosis

The principles of low-pressure RO are the same as RO, but the definition of low-pressure RO varies. Ujang and Anderson (1996) define an operating pressure below 100 psi (689 kN/m^2) as low-pressure RO, whereas Hao *et al.* (1996) use the wider range of 70-200 psi (483 - 1378 kN/m^2). The advantage of low-pressure RO membranes is that they require only a fraction of the operating pressure to achieve a pure water product, thus reducing operating costs.

2.2.2 Membrane Materials

For pressure-driven membrane processes, the flux of the permeate is inversely proportional to the thickness of the membrane (Aptel and Buckley, 1996). It was the development of the class of anisotropic membranes that led to the breakthrough in industrial applications. Membranes of this class consist of a very thin top layer supported by a thicker more porous sublayer. The top layer acts as the selective barrier, whereas the sublayer is only present for support. As anisotropic membranes are surface filters, they are more resistant to fouling than conventional filters, which act as depth filters and retain particles within the internal structure. Surface filters retain the particles at the top of the filter where they are removed by the shear forces applied by the feed solution (Porter, 1990). There are two types of anisotropic membranes: asymmetric and composite, and are dealt with separately below.

Asymmetric Membranes

An asymmetric membrane consists of a very thin (0.1 to 1 µm) selective skin barrier on a porous supporting layer (100 to 200 µm) (Porter, 1990). In the late 1950s cellulose acetate (CA) membranes were first manufactured and they are still used commercially today. CA membranes can withstand continuous exposure to low concentrations of residual chlorine (0.1 to 0.5 mg/l at 25°C) (Taylor and Jacobs, 1996), but they do have several disadvantages because they are subject to biological attack and to hydrolysis at temperatures above 30°C. Figure 7 illustrates a typical asymmetric membrane.

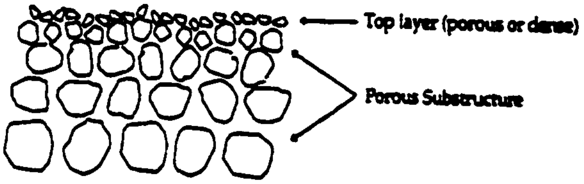

Figure 7: Schematic Drawing of an Asymmetric Membrane (Aptel and Buckley, 1996)

Thin-Film-Composite Reverse Osmosis Membranes

Thin-film-composite membranes, which are anisotropic with a top layer and a sublayer made of different materials, are generally more expensive to manufacture than asymmetric ones. The top layer is extremely thin and provides the area for mass transfer, and the sublayer is usually only for support. Figure 8 illustrates a typical composite membrane.

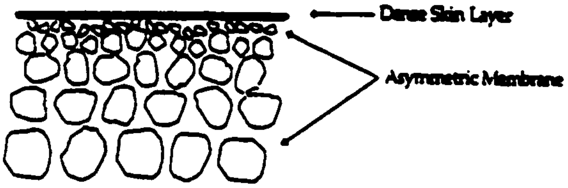

Figure 8: Schematic Drawing of a Composite Membrane (Aptel and Buckley, 1996)

Composite membranes differ from those of asymmetric reverse osmosis in their preparation. Composite membranes are prepared in two steps: casting of the microporous support, and deposition of the barrier layer on the surface of this support. There are advantages to this method of preparation. As mentioned above, asymmetric membranes have a selective barrier and support of the same material, whereas in composite membranes, different polymers can be used for the barrier and the support layer. This allows polymers to be used with the desired selectivity for the barrier, although they may make poor supports.

2.2.3 Membrane Configurations

Membranes are available in different configurations for each filtration process. The required configuration depends on the wastewater being treated, the restrictions on operating cost, and the area available for the filter unit.

Tubular

Tubular membranes, which were the earliest design of industrial scale UF equipment using synthetic membranes, have the least densely packed configuration and have relatively large open channels. Their internal diameters range from 12.5 to 25 mm and their lengths from 0.5 to 1.5 m (Cheryan, 1986). Tubular modules have a low area-to-volume ratio, and so need a lot of space (Cheryan, 1986). Their large openings allows them to handle feed streams with a high concentration of large particles with minimum blocking. Their rugged design makes them acceptable in many industrial applications, and they are especially useful in wastewater treatment where there is a high concentration of suspended solids (Gaeta, 1995). Figure 9 shows a typical tubular membrane module.

Spiral-wound

Spiral-wound membranes have the most densely packed configuration. They are essentially flat sheets arranged in parallel to form a narrow slit for fluid flow. The whole assembly is rolled spirally around a central channel. The height of the feed channel is controlled by the thickness of the spacer in the channel. Spacers of 0.76 and 1.1 mm are the most common. An advantage of the narrow channel is that it allows more of the membrane area to be packed into a given pressure vessel. The feed is pumped lengthwise along the unit, while the permeate is forced through the membrane sheets into the permeate channel and spirals towards the perforated centre collection tube.

Spiral-wound filters may foul if the feed source has a high level of suspended solids because they tend to plug the narrow spacer layer. So often a pretreatment process is required to remove particles that would cause clogging. Figure 10 shows a typical spiral-wound membrane configuration.

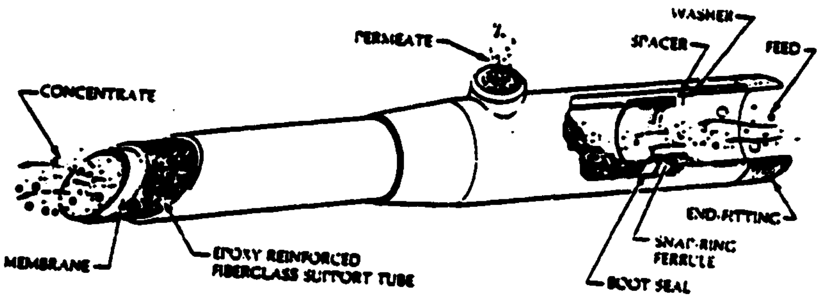

Figure 9: Tubular Membrane Module Configuration (Cheryan, 1986)

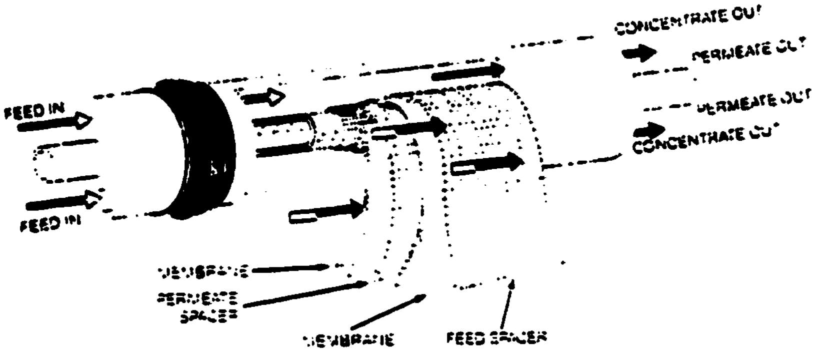

Figure 10: Spiral-wound Membrane Configuration (Cheryan, 1986)

Hollow-fiber

Hollow-fiber membranes are formed from fibers 0.1 to 1.5 mm long with a hole inside (Matsuura, 1994). These fibers are self-supporting structures. The feed is supplied to either the inside or the outside of the fiber. Figure 11 shows a bundle of fibers mounted in a pressure vessel. According to Matsuura (1994), the attractive feature of a hollow-fiber module is its the large ratio of membrane surface area to module space. The size of the hollow-fiber module is therefore smaller than other modules for a given treatment performance capacity. The unattractive feature of this membrane configuration is its inability to be regenerated and its sensitivity to fouling.

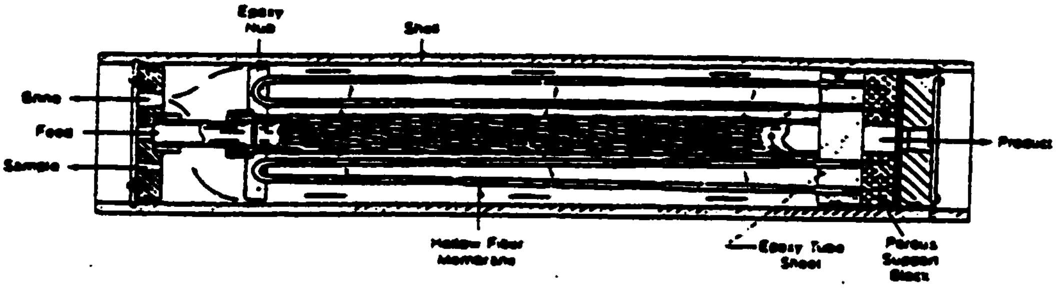

Figure 11: Hollow-fiber Membrane Configuration (Matsuura, 1994)

Plate and Frame

Plate-and-frame membranes use the simple flat-sheet configuration. They are cast on fine "scrim" with a drainage grid between the scrim and the plate. Several plates are stacked together such that the permeate collects in the drainage grid. Disc and tube membranes developed by ROCHEM are a common type of plate-and-frame configuration used for the treatment of landfill leachate (Peters, 1991). According to Brock (1983), the plate-and-frame configuration is expensive and skilled labour is needed to service it. Figure 12 shows a plate-and-frame system.

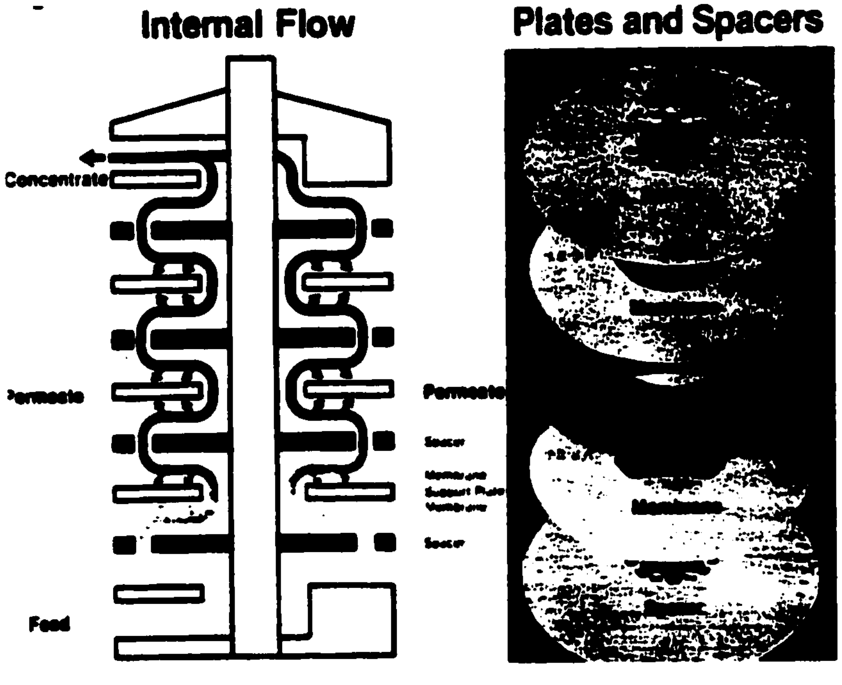

Figure 12: Typical Plate-and-Frame Configuration

2.2.4 Membrane Performance

Permeate and Solute Fluxes

Dal-Cin *et al.* (1996) developed a system of equations to describe the permeate flux. Their model describes transport across the membrane as:

$$J_v = \frac{\Delta P}{\mu R}, \qquad \text{Eq. 2}$$

where J_v is the membrane flux and ΔP is the pressure drop across the membrane, μ is the fluid viscosity and R is the resistance term. Flux decline due to membrane fouling is determined with the following:

$$J_v = \frac{\Delta P - \sigma\pi}{\mu(R_m + R_A)}, \qquad \text{Eq. 3}$$

where σ is the reflection coefficient,

π is the osmotic pressure,

R_A is the hydraulic resistance due to adsorptive fouling, and

R_m is the hydraulic resistance due to the membrane.

The solute flux (J_s) in the absence of fouling is directly proportional to the concentration gradient across the membrane. It was developed by Slater *et al.* (1983), thus:

$$J_S = B_S \,\Delta\, C_S, \qquad \text{Eq. 4}$$

where ΔC_s is the difference in solute concentrations between the permeate and feed. B_s, which is a coefficient of permeability for solute species, combines the following constants:

$$B_s = \frac{D_s K_s}{\delta_M}, \qquad \text{Eq. 5}$$

where D_s is the solute diffusivity, δ_M is the membrane thickness, and K_s accounts for the distribution of concentrations on both sides of the membrane.

The separation efficiency (S) for the membrane is defined in terms of the solute rejection:

$$S = 1 - \frac{C_p}{C_f}, \qquad \text{Eq. 6}$$

where C_p is the concentration of solute in the permeate and C_f is the concentration of solute in the feed or concentrated solution.

Concentration Polarization

Concentration polarization is the reduction in the membrane flux caused by an increase in the concentration of the solute at the surface of the membrane. For RO and NF membranes, solutes and other species in the feed stream are transported toward the membrane surface by bulk convective flow at the same speed as that of the permeating solvent. The membrane is semipermeable; the solutes will be retained at its interface. The cross-flow velocity in the boundary region is laminar and the backtransport of the solute into the bulk stream can only occur by diffusion. The concentration of solute at the membrane must be much higher than that in the bulk for the backdiffusion of the solute to balance the convective flow of solute toward the membrane surface. Concentration polarization may cause the retention of solute to decrease as pressure increases. This occurs when the concentration of the solute at the surface of the membrane has increased over that of the bulk stream. Concentration at the surface will increase with pressure and result in a decrease in solute retention. Colloidal matter may form a cake that reduces permeate flux (Fig. 13).

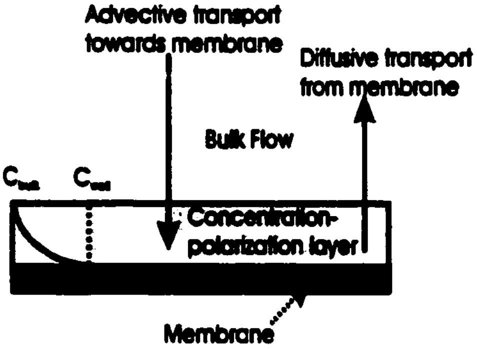

Figure 13: Concentration Polarization (Weisner and Aptel, 1996)

2.2 Applications of Membranes for Treatment of Landfill Leachate

The roles of MF, UF, NF and RO for the treatment of landfill leachate are discussed in the following section.

2.3.1 Microfiltration

Visvanathan *et al.* (1994) treated landfill leachate by cross-flow MF and ozonation. The leachate was first treated with powder-activated carbon (PAC) and then ozonated. A single-channel tubular MF ceramic membrane was used for this study. The leachate had a low BOD_5/COD (0.05) ratio, indicating that it had low biodegradability and that a physical/chemical treatment process was therefore appropriate (Visvanathan *et al.*, 1994). The leachate contained significant amounts of colloidal matter and dissolved solids. Its total solids were 12,500 mg/l and suspended solids were 588 mg/l. The addition of PAC increased the membrane flux, and when no PAC was used prior to filtering the leachate, the membrane would clog. A steady permeate flux of 160 $l/m^2/hr$ was maintained when applying 20 g/L of PAC. This demonstrates the importance of pretreating a leachate to avoid fouling the membrane.

Visvanathan *et al.* (1994) concluded that MF only removes suspended particles but does not remove sufficient colloidal solids to be considered an effective treatment process; it does, however, have a role as pretreatment for RO.

2.3.2 Microfiltration with Reverse Osmosis

Krug and McDougall (1989) did a bench-scale study to test the feasibility of using MF in combination with RO to treat landfill leachate. The experiment consisted of a membrane test unit with a half-inch tubular membrane for the MF unit and two spiral-wound membranes for the RO unit. Since spiral-wound membranes were used for the RO, the MF process needed a high removal efficiency to avoid fouling. The researchers tested four different chemical pretreatment methods:

- 1st test - caustic soda was added to the raw leachate to a pH of 10,
- 2nd test - the pH of the leachate was adjusted to 10 using lime,

- 3rd test - the pH was adjusted to 10 with lime and 20 g/L of PAC, and
- 4th test - the pH was adjusted to 10 using lime and soda ash.

Krug and McDougall (1989) concluded that the flux obtained depended on the chemical used in the pretreatment process. Solids formed with caustic soda had a greater tendency to foul the MF membrane and therefore had the lowest flux. The results for the 3rd test showed that the addition of PAC increased the permeate flux, although the flux of the lime, and the lime plus powdered activated carbon, are lower than would be expected for a MF membrane, but no abnormal levels of fouling occurred (Krug and McDougall, 1989). The best pretreatment method was the second test, where lime adjusted the pH to 10.

Krug and McDougall (1989) concluded that the precipitation/MF step could remove suspended solids (SS), metals and hardness from the leachate, and that the RO step removed virtually all the remaining organics and dissolved solids present from the first stage.

Zenon Environmental (1990) conducted field tests to treat landfill leachate from the Muskoka lakes sanitary landfill, which generated 2.4 x 10^7 l/d of leachate (McBride *et al.*, 1988). They pretreated the leachate with lime, based on the results of Krug and McDougall (1989), and followed with MF to remove the large particles before passing the leachate through a RO unit. They used a tubular MF membrane combined with a spiral-wound RO unit. The Muskoka Lakes landfill leachate had a relatively low biodegradability since it was aerated in two settling ponds prior to membrane treatment. The initial characteristics of the leachate are given in Table 4.

Table 4: Initial Leachate Characteristics from Krug and McDougall (1989)

Parameter	Concentration (mg/l)
TSS	203
BOD	280
COD	510
TOC	180
BOD/COD	0.54

The MF unit showed stable flux rates ranging from 92 to 132 l/m^2/hr using leachate pretreated with lime or lime in combination with soda ash. Inorganic parameters were reduced from 50 to 99.9% by the precipitation/MF process. The pH of the permeate from the MF unit was adjusted to 6.7 and the RO unit achieved a stable flux of 32 l/m^2/hr at a volume reduction of 80%.

Both Zenon (1990) and Krug and McDougall (1989) successfully used spiral-wound membranes, whereas traditionally only tubular membranes were thought appropriate for treating wastewaters with a high concentration of suspended solids. However, this work showed that, with an appropriate method of pretreatment, spiral-wound membranes can be used.

2.3.3 Ultrafiltration

Slater *et al.* (1985) used UF to characterize a landfill leachate by molecular weight distribution. Their objective was not to treat the leachate but rather to demonstrate how UF could be used to separate compounds from it based on molecular size. Yao *et al.* (1993) similarly characterized Kraft-pulp-mill effluent.

Isaacs *et al.* (1992) used UF to treat leachate from a non-hazardous and municipal solid waste landfill. Their objective was to reduce the oil content and SS of the leachate. The initial SS concentration was between 400 and 900 mg/l and had to be reduced to less than 100 mg/l. The leachate had an average COD concentration of 6000 mg/l. Since the only concern was the removal of oil and SS, Isaacs *et al.* (1992) chose UF as the appropriate treatment. They used a tubular Koch UF membrane system and compared the treatability of raw and alum-pretreated leachate. They achieved a 30 to 40% reduction in COD with the UF membrane. The membrane flux for treating the raw leachate was between 63 and 88 $l/m^2/h$. The concentration ratio was high, 15 to 1, resulting in 6.7% of the feed becoming a concentrate of oily solids that required disposal. They did not have any problems with fouling of the membrane, and concluded that UF of either raw leachate or alum-pretreated leachate could achieve a SS concentration of 20 mg/l.

Pirbazari *et al.* (1996) used a hybrid method of UF and biologically active carbon (UF-BAC) to treat two types of landfill leachates. The leachate was treated in a bioadsorberreactor combination with a PAC slurry. In this method a biofilm forms on the surface of the PAC and biodegrades the organic material. The reduction in the flux is controlled by two factors: a turbulent flow regime in the membrane unit, and the use of the PAC particles. Pirbazari *et al.* (1996) used tubular, cross-flow anisotropic membranes in the UF unit and found that the permeate flux was reduced almost to zero when no PAC was added, which is consistent with the findings of Visvanathan *et al.* (1994). Pirbazari *et al.* (1996) also found that a PAC concentration of only 1% was required to control the permeate flux. After 30 hours, the fraction of the initial permeate flux of the first leachate was held constant at approximately 35% of the initial flux (8.3 $l/m^2/hr$). The flux for the second leachate was higher; it was held constant at 85% of the original flux (13 $l/m^2/hr$). These flux values are lower than those for other UF processes. TOC removal of the pretreated leachate was approximately 95-98% effective. The leachate was pretreated using coagulation/flocculation for leachate I and air oxidation for leachate II.

The conclusion from the above is that UF is not often used as a stand-alone treatment process. It will remove the larger particles but will not remove a high percentage of the COD. Thus UF is often used as the initial step in a two-stage process, combined with RO.

2.3.4 Nanofiltration

Linde *et al.* (1995) compared the result of treating a salt solution and a landfill leachate by NF. The leachate, which was from a waste cell consisting of mostly ash, contained a high salt content (55 g chloride/l). Two types of tubular NF membranes were used (AFC30 and a newly developed membrane AFC40). They are both thin-film composite membranes with negatively charged groups. Linde *et al.* (1995) found that the retention of sulphate salts was significantly higher than the retention of chloride salts. They also found that the retention of the multivalent cations was about 3 times higher than the retention of the monovalent cations in solutions with a high concentration of monovalent anions. For the landfill leachate with a high salt content most of the heavy metals and multivalent cations, were rejected while the monovalent cations passed through the membrane. The retention of cadmium, zinc, lead and chromium was higher than 70%, but the retention of potassium and sodium was less than 10%. This study demonstrated that if chlorides are not of concern in the effluent, NF can be used as the treatment process in place of RO. NF has the benefit that it requires a lower operating pressure and therefore will have a lower operating cost.

Rautenbach and Linn (1996) combined high-pressure RO with NF to achieve zero discharge for a leachate that had a serious risk of fouling or scaling. They used 3 stages: RO (6078 kN/m^2), NF, and high pressure RO (12,156 - 20,260 kN/m^2) to achieve water recovery rates of 97%, based on an energy input of 8.5 kWh/m^3.

The conclusion from the work reviewed above is that NF is an appropriate technology when the removal of chlorides is not a concern. However, chloride is a concern at the Trail Road Landfill Site and so RO has to be considered in the treatment option.

2.3.5 Membrane Bioreactor (MBR) combined with RO

Two studies were conducted at the Amouville-Les-Mantes municipal leachate treatment plant in France. This facility, which combines MBR, UF, and RO, produces an average of 3000 m^3 of treated leachate per year (Touve *et al.*, 1993). Touve *et al.* (1993) did a pilot-scale study and found that ammonia and SS were completely removed in the MBR steps, and that the salts, metals and COD were removed in the RO step. Fouling was reduced by using the MBR-RO combination, which gave an average flux of 20 $l/m^2/hr$ that was kept constant for 4 days without any chemical cleaning.

Courant *et al.* (1992) had previously found that the combination of RO and MBR was the only process capable of producing a high quality effluent. They maintained excellent nitrification (>99%) in their MBR and removed 40% of their COD throughout their 135-day experiment. The permeate from the MBR passed through the RO unit to achieve a removal of 97.7% for COD.

Weber and Holz (1991) concluded that biological treatment alone of raw leachate yields unsatisfactory results. Their experiment combined a two-stage RO process: a 1st stage of tubular membranes, then a 2nd stage of spiral-wound membranes with biological pretreatment. Treatment of the raw leachate using the activated sludge process reduced the TOC and the adsorbable organic halogens (AOX). Ammonia was reduced by 10%, but this is not sufficient since ammonia will affect the rejection in RO. Weber and Holz

(1991) concluded that advanced biological pretreatment of leachate would be required, including nitrification and denitrification and final purification by RO. Biological pretreatment diminishes the conductivity of the leachate, and so the greater the pretreatment the higher the allowable concentration factor. Since the biological pretreatment of raw leachate enhances the effectivity of RO, the membrane process should only be operated as the final step of a multi-stage treatment plant.

Kettern (1992) determined that RO combined with primary biological leachate treatment can accept higher rates than a leachate treatment plant taking raw leachate. The membrane area needed for treatment can be reduced substantially.

Mayr *et al.* (1995) tested biomass separation using a biological nitrification/denitrification step followed by MF. They passed permeate from the microfilter through an RO unit and found that the permeate from the microfilter, prior to the RO unit, had a removal efficiency higher than 95% for ammonium and higher than 85% for COD, while the RO step removed any impurities that remained after MF. The leachate in the experiments had high initial concentrations of ammonium and COD: 6.145 kg/m^3 and 30.26 kg/m^3, respectively. The second leachate that Mayr *et al.* (1995) tested had lower initial concentrations of COD and ammonium, and so additional carbon sources were required to remove the nitrogen.

2.3.6 Sand Filter and Reverse Osmosis

Stevens and Walrand-Görlier (1995) describe the treatment of landfill leachate by a combination of Rochem DT RO module with a sand filter for pretreatment. The permeability for the membranes varied from 40.25 to 75.9 $l/m^2/hr{\cdot}kN/m^2$. The value for the landfill leachate was 46.6 $l/m^2/hr{\cdot}kN/m^2$, indicating that fouling did occur. They do not say how to deal with the fouling.

2.3.7 Reverse Osmosis

Friedrich and Standish (1998) describe a pilot-scale RO plant designed to treat 170 m^3/d of raw leachate. It operated for about one month. This pilot-system used 10 disk-tube RO modules at a maximum operating pressure of 870 psi (5994 kN/m^2). Average rejections for COD and NH_3 were 99.24 and 99.16%, respectively. The results of the pilot study show that it is feasible to design, construct and operate a full-scale RO system. Kinman, *et al.* (1985) explored the fouling of RO membranes by various pollutants. They applied the silt-density index (SDI) to landfill leachate to determine the relationship between specific ions or compounds in the leachate and the fouling of the membrane. The SDI test evaluates the rate of plugging of a membrane filter at a pressure of 30 psig (207 kN/m^2). Each experiment used a cellulose acetate membrane and coagulation/settling as pretreatment. The RO system was a spiral-wound module operated at 190 psig (1309 kN/m^2) for the tests, except when the membrane was flushed.

Three strengths of leachate were tested at different: 3, 5 and 10%. The SDI produced no useful predictive results, and in most cases the membrane fouled before the test was finished. The tests used spiral-wound membranes which, due to their smaller channels, plug more easily than tubular ones. The only pretreatment used was coagulation and settling.

Kinman and Nutini (1991) studied the feasibility of using RO to treat landfill leachate. Theirs was a pilot-scale project where the leachate was pumped through a 10 μm prefilter before passing through the RO unit. (The RO unit had a 5 μm prefilter mounted in front of the membrane.) This system operated at a pressure of 250 psi (1723 kN/m^2). The results showed that the treatment of landfill leachate by RO is feasible since it reduced by 97% the levels of total solids and organics, although the authors do not specify what flux gave this removal efficiency. Fouling, which occurred at higher operating pressures, resulting in a slight decrease in permeate flux, was circumvented by operating at lower pressures [200-250 psi (1378-1723 kN/m^2)]. This in turn produced a concentrate flux which provided sufficient self-cleaning of the membrane surface.

Collivignarelli *et al.* (1993) discussed the feasibility of applying RO to treat landfill leachate. They recommend using it as part of a two-step system or alternatively to place it upstream of a biological unit.

From the above it can be seen that RO is a potential technology for the treatment of landfill leachate and it is capable of reducing pollutants to acceptable limits. Unfortunately, high operating pressures are required for an RO and this dramatically increases the costs of treatment. New, low-pressure RO membranes are being developed that offer removal efficiencies similar to those of a conventional RO process but at a fraction of the operating pressure, thereby making it a more accessible treatment process. The following section discusses recent studies in the field of low-pressure RO.

2.3.8 Low-pressure Reverse Osmosis

Low-pressure RO uses operating pressures less than 200 psi (1378 kN/m^2) (Ujang and Anderson, 1996). Recent research by Hofman *et al.* (1997) shows that this is an effective process for direct treatment of surface water and the removal of pesticides and organic micropollutants. The operating pressure of their tests is not known but their membranes had rejection rates for dissolved salts comparable to conventional composite polyamide RO membranes, with feed pressure of 30 - 40% less. Low-pressure RO has also been used in industrial applications. It has been used successfully to remove Zn^{2+} and Cu^{2+} at operating pressures less than 100 psi (689 kN/m^2) (Ujang and Anderson, 1996).

Low-pressure RO is a promising process; the lower operating pressures will reduce the cost of the treatment process making it suitable for many more applications.

2.4 This project

Low-pressure RO was used to treat landfill leachate from the Trail Road Landfill Site. The aim was to see if this is a practical method to apply in this context. The work was divided into four phases:

1. the selection of a suitable membrane material using 5000 ppm NaCl as a test solution,
2. the testing of the membrane using synthetic leachate at different operating pressures,
3. the testing of the membrane using real leachate at different operating pressures, and
4. the testing of spiral-wound membrane configuration with real leachate.

Chapter 3 - Membrane Selection and Removal Efficiency for Various Concentrations of Synthetic Leachate

3.1 Introduction

In 1997, 51,000,000 L of landfill leachate were trucked from the Trail Road Municipal Landfill Site for disposal at the local Wastewater Treatment plant. The fear that contaminated leachate could escape from the Landfill Site, and the need for a cost-effective on-site treatment alternative, has lead to an evaluation of the options for treating the leachate. One treatment option being examined is the use of low-pressure RO, which is becoming increasingly attractive with the development of new technology. Until recently, RO was too expensive to be considered an alternative, but lower operating pressures have decreased the cost associated with this technology. Recent research into ultra-low and low-pressure RO shows that it is an effective direct treatment process for the removal of pesticides and organic micropollutants in surface water (Hofman *et al.* 1997). Low-pressure RO has also been used industrially to remove Zn^{2+} and Cu^{2+}, using operating pressures less than 100 psi (689 kN/m^2) (Ujang and Anderson, 1996). The application of low-pressure RO membranes to leachate is now being examined because the operating costs of these membranes continue to fall.

Membranes for low-pressure RO are available commercially from several suppliers, and three were chosen for this project: Hydranautics, Fluid Systems and Saehan Industries.

The purposes of this project were to characterize select low-pressure membranes, to determine the membrane with the highest permeate flux and rejection capabilities, to conduct a statistical analysis of the testing apparatus and, finally, to test the ability of the selected membrane to cope with different concentrations of synthetic leachate at different operating pressures.

3.2 Material and Methods

3.2.1 Analytical Methods

Measurements of the conductivity, TOC, ammonia, and chloride concentrations were made. Conductivity was measured with a YSI Scientific Model 32 conductance meter, and the TOC concentration with a TOC - 5000 high temperature Shimadzu TOC Analyser. To determine the ammonia nitrogen and chloride concentrations, an ammonia electrode and a combination Cl^- 96-17 Orion specific ion electrodes were used, respectively. The concentrations of the ammonia nitrogen and the chloride ions were determined from the instrumental readings as millivolts and then compared to calibration curves that were generated from known concentrations of solutions in separate experiments.

3.2.2 Testing Apparatus

The membrane selection tests and the synthetic leachate experiments were conducted using a so-called "coupon membrane testing unit", which was developed at the National Research Council of Canada (NRCC) and has been used for numerous membrane experiments (Dal-Cin *et al.*, 1995). It comprises 12 cells in each of which a coupon (sample of membrane) can be subjected simultaneously to the same experimental conditions (Fig. 14). Each cell has an active membrane area of 14.5 cm^2 and is mounted upside down to prevent suspended matter from settling on the membrane surface (Fig.15).

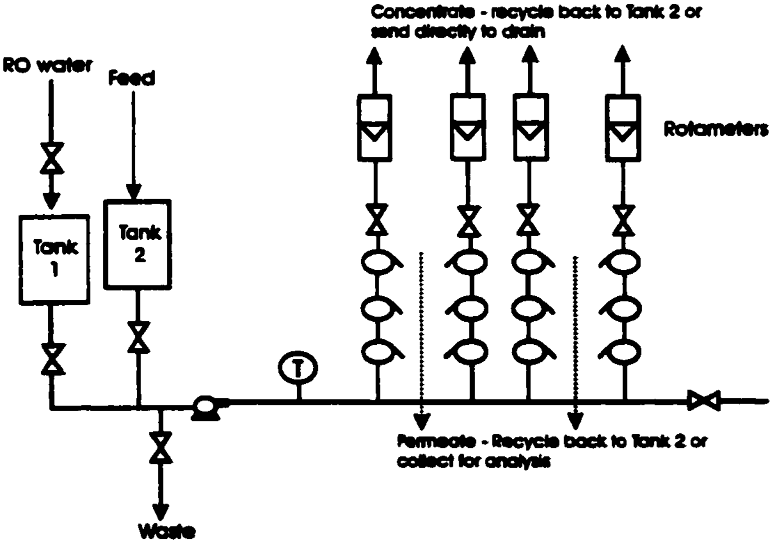

Figure 14: Coupon Membrane Testing Apparatus

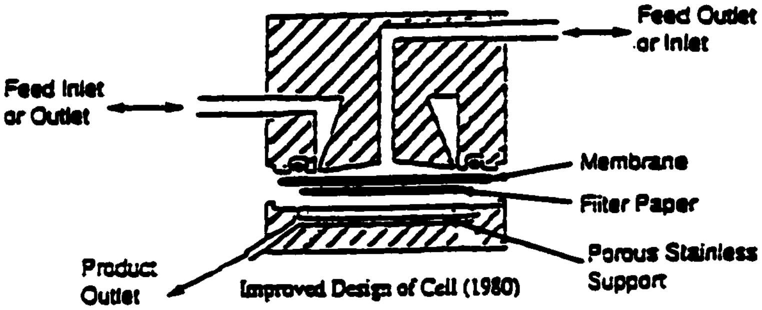

Figure 15: Test Cell

In Fig. 14, the feed from Tank 1 is RO water that passes through the membranes to measure the rate at which pure water can permeate. Tank 2 contains the feed solution. The twelve cells are located in 4 rows of 3 cells, which configuration reduces the pressure loss across the membranes. The flow through each row is controlled by a rotameter, and the permeate is either recycled to the feed tank or is collected at each cell as a sample. The concentrate is either recycled to the feed tank or is sent directly to the drain. The operating pressure for each experiment was adjusted by controlling the flow through each row of cells. During the experiment, the four rotameters are adjusted by trial and error until all flowrates are equal and the desired operating pressure is obtained. Then samples of feed, permeate, pure water permeate and RO water can all be taken on line.

The tests alternated between those using pure RO water and those using product, and the product rate was determined as the permeation rate through the membrane when a test solution (i.e., leachate or water containing 5000 mg/l NaCl) is used instead of pure water (Tweddle *et al.*, 1990).

3.2.3 Experimental Protocols

Membrane Selection

Three types of low-pressure membranes (supplied by Hydranautics, Fluid Systems and Saehan Industries) were studied to determine which was the most suitable. The membrane supplied by Hydranautics was a low-pressure polyamide (5 cm by 30 cm spiral-wound type 2012-UST-ESPA); that from Fluid Systems was an ultra-low pressure model 4921, and that from Saehan Industries was identified only as an 'ultra-low pressure RO' membrane. Samples, or coupons, were cut from each type of membrane and were compared based on product flux and removal efficiency, measured as conductivity, for a feed containing 5000 mg/l NaCl made up with RO water.

The fluxes were determined using Equations 8 and 9 from the mass collected in a given time (approximately 15 minutes). These equations are commonly used in the membrane industry:

$$Flux(l / m^2 / hr) = \frac{Mass * 3600 * a}{1.45E^{-3} * t * \rho}, \qquad \text{Eq. 7}$$

where: *Mass* is the mass of permeate collected, g,

t is the collection time, s,

ρ is the liquid density @ 5°C, kg/m^3, and

a is the temperature correction factor given in Eq. 9.

Thus:

$$a = \frac{10^{1.002*\left(1.3272*(20-T)-0.00105*(T-20)^2 \middle/ (T+105)\right.}}{0.8904}, \qquad \text{Eq. 8}$$

where T is the operating temperature, °C.

The removal efficiency of the membrane is determined by:

$$\%removal = \frac{F_{initial} - RO - (P - PWP)}{F_{initial} - RO} * 100\%, \qquad \text{Eq. 9}$$

where $F_{initial}$ is the concentration or conductivity of the feed,

P is the concentration or conductivity of the permeate,

RO is the concentration or conductivity of the RO water, and

PWP is the concentration or the conductivity of the pure water permeate.

The membranes from Saehan Ind., Hydranautic, and Fluid System were placed in test cells 1 through 4, 5 through 8, and 9 through 12, respectively, and characterized at three low operating pressures: 100, 150 and 200 psi (689, 1034 and 1378 kN/m^2).

The experimental procedure was the following:

1. RO water was run through the system for an hour at the specified operating pressure,
2. then samples of permeate were collected for each test cell (the sampling time varied depending on the volume of water permeating),
3. then the product was run through the system for an hour at the specified operating pressure,
4. then samples of the permeate were collected for each test cell (the time depending on the volume of the product permeating),
5. then feed samples were collected,
6. then finally RO water was run through the system for an hour to clean the membranes.

The pure water permeate flux was determined from the mass of water collected in step 2, and the product rate from the mass of permeate collected in Step 4.

Statistical Variability

The run-to-run variability and cell-to-cell variability of the results were determined from the coupon testing apparatus. The run-to-run variability is the difference between the average results of all twelve cells for ostensibly identical experimental runs, while cell-to-cell variability is the difference between the results for each cell for a specific run. Coupon membranes from Hydranautics were loaded into twelve cells, then four identical experiments were done using a feed of 5000 mg/l NaCl at an operating pressure of 150 psi (1034 kN/m^2). This was done to compare the pure water permeate flowrate, the permeate flowrate, and the removal efficiency for each cell.

Tests using a Feed of Synthetic Leachate

Tests with a feed of synthetic leachate were done to observe the effect of key parameters on the product rate and removal efficiency. The synthetic leachate was created using ammonium acetate, sodium chloride and ammonia chloride. It is important to note that colloidal material, SS and aromatic hydrocarbons were not included in the synthetic leachate. A so-called "4-factor fractional experimental composite design" (described in Appendix B) was used to study the effects of operating pressure, TOC, NH_3 and Cl^- concentrations on the ratio of pure water permeate to product flux, and on the removal efficiencies of TOC, NH_3, and Cl^-. The chosen parameters for the synthetic leachate are summarized in Table 5. Acetic acid was used as the carbon source. The operating pressures ranged from 75 to 225 psi (517 to 1550 kN/m^2) and are based partly on the limits recommended by the manufacturer, and partly on the results from the initial membrane characterization study. The TOC, NH_3, and Cl^- concentrations chosen for the synthetic leachate are based on the ranges reported by Dillon (1994) for the Trail Road Landfill leachate.

Table 5: Range of Parameter Concentrations for Synthetic Leachate

Parameter	Testing Range
Operating Pressure	75 - 225 psi
TOC	1300 - 3400 mg/l
NH_3	320 - 2500 mg/l
Cl^-	700 - 3400 mg/l

The TOC, NH_3 and Cl^- concentrations and their coded values for all of the synthetic leachate feeds are given in Table 6, where the coded values are derived from Equations 10 to 13. To calculate the coded parameters a range is selected and the higher number is +1 and the lower number is -1. For operating pressure, 689 kN/m^2 was selected as +1 and 1378 kN/m^2 as -1. For the four coding equations the +1 and -1 values were selected arbitrarily. The parameters are coded so that their influence can be compared based solely on the magnitude of the coefficient.

$$x_1 = \frac{oper.press.(kN/m^2) - {(689+1378)}/{2}}{{(1378-689)}/{2}} \qquad \text{Eq. 10}$$

$$x_2 = \frac{TOC(mg/L) - {(3292+1279)}/{2}}{{(3292-1279)}/{2}} \qquad \text{Eq. 11}$$

$$x_3 = \frac{NH_3(mg/L) - {(2523+486)}/{2}}{{(2523-486)}/{2}} \qquad \text{Eq. 12}$$

$$x_4 = \frac{Cl^-(mg/L) - {(2000+1000)}/{2}}{{(2000-1000)}/{2}} \qquad \text{Eq. 13}$$

The experiments on the Hydranautics' membrane were run at 5 levels of each of the 4 factors studied: operating pressure, TOC, NH_3, and Cl^-.

The experiment was operated in the range of 29 to 34°C. Difficulty was experienced in controlling the operating temperature because it tended to increase at higher pressures. The temperature correction factor (Eq. 8) was used to account for this variation.

Table 6: Summary of Experimental Design for the Low-Pressure RO Synthetic Leachate Experiments

					Coded Values			
Leachate Sample	TOC mg/l	NH_3 mg/l	Cl^- mg/l	Operating Pressure, kN/m^2	Operating Pressure	TOC	NH_3	Cl^-
1	1398	486	934	792	-0.700	-0.882	-1.000	-1.132
2	1586	504	2359	1412	1.100	-0.695	-0.982	1.718
3	2893	-	1708	758	-0.800	0.604	-	0.416
4	2954	1365	1213	1344	0.900	0.664	-0.137	-0.574
5	1356	754	1644	723	-0.900	-0.923	-0.737	-0.574
6	1279	1818	953	1378	1.0	-1.0	0.308	-1.094
7	2839	1062	809	758	-0.8	0.55	-0.434	-1.094
8	3292	2523	2037	1344	0.9	1.0	1.0	1.074
9	2339	780	1585	517	-1.5	0.53	-0.711	0.17
10	2259	858	3403	1550	1.5	-0.26	-0.63	3.806
11	1445	892	1043	1034	0	-0.835	-0.601	-0.914
12	3366	778	1259	1034	0	1.074	0.713	-0.482
13	2038	326	1382	1034	0	-0.246	-1.157	-0.236
14	2399	902	1335	1102	0.2	0.113	-0.592	-0.33
15	2515	804	701	1034	0	0.228	-0.688	-1.598
16	2124	677	1824	999	-0.1	-0.16	-0.822	0.648
17	2326	853	1294	1034	0	0.04	-0.64	-0.412
18	2209	993	1359	1034	0	-0.076	-0.502	-0.282
19	2130	569	1275	1034	0	-0.154	-0.919	-0.45
20	2133	614	1259	1034	0	-0.152	-0.874	-0.482

Commercial least-squares analysis software (STATISTICA 4.5) was used to develop empirical models to describe the effects of operating pressure, TOC, ammonia and chloride concentrations on the response variables.

3.3 Results and Discussion

3.3.1 Membrane Selection

Using conductivity measurements, membranes types were compared on the basis of their permeate flux and removal efficiency, using a feed solution with a NaCl concentration of 5000 mg/l. The results are summarized in Table 7. The low standard deviations for the PWP, PR and the percent recovery indicate the consistency of the experimental results. This good reproducibility of the tests justifies a strong confidence in the results. Results in Table 7 are the average of four test cells for each membrane type.

Table 7: Summary of Membrane Characterization Results

Membrane Type	Oper. Press. psi (KN/m^2)	Pure Water Permeate l/m^2/hr	Std. Dev.	Product Rate l/m^2/hr	Std. Dev.	% Recovery	Std. Dev.
Saehan	100 (689)	0	0	0	0	0	0
Hydranautic	100 (689)	47.6	1.93	26.7	1.42	97.3	0.4
Fluid Systems	100 (689)	31.8	4.70	21.1	2.81	50.7	4.1
Saehan	150 (1034)	33.5	2.46	17.7	1.48	90.3	2.3
Hydranautic	150 (1034)	71.0	4.15	31.9	1.62	97.5	0.4
Fluid Systems	150 (1034)	34.1	4.18	22.8	2.39	53.2	4.1
Saehan	200 (1378)	41.3	2.75	28.8	2.28	93.0	2.14
Hydranautic	200 (1378)	86.0	4.78	52.6	3.17	98.0	0.09
Fluid Systems	200 (1378)	41.9	4.33	33.2	3.12	57.0	5.8

Figure 16 shows the average permeate flux for each membrane type while Figure 17 shows the removal efficiencies of the membranes at the three different operating pressures: 100, 150 and 200 psi (689, 1034 and 1378 kN/m^2).

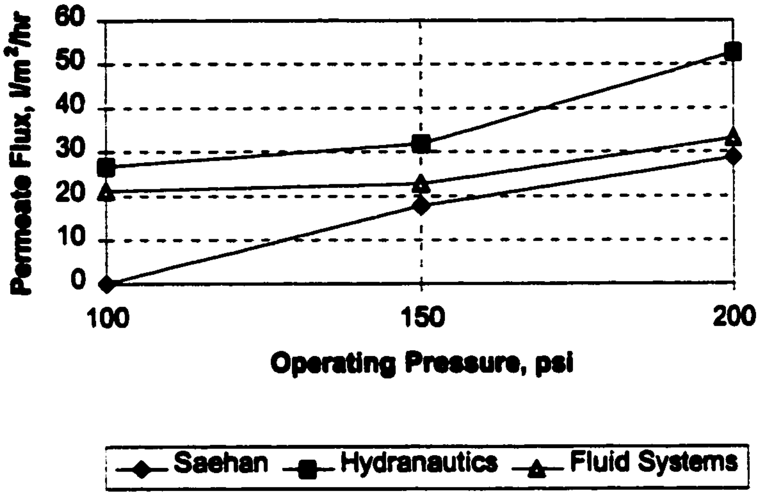

Figure 16: Product Permeate Flux resulting from a feed of 5000 mg/l NaCl

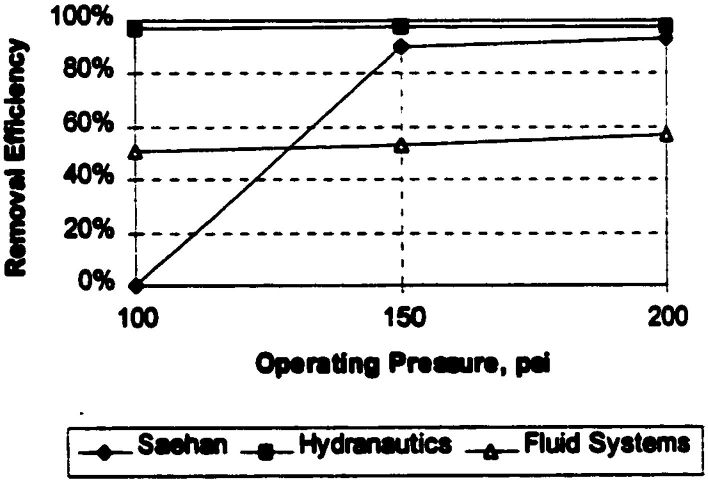

Figure 17: Removal Efficiency for a feed of 5000 mg/l NaCl

Figure 16 shows that the membrane from Hydranautics has a 1.3 to 1.6 times higher permeate flux rate than the other two. Figure 17 shows that the average removal efficiencies for the Hydranautics' membrane consistently achieves removal rates above 97%, whereas the Fluid System membrane has low removal efficiencies (51 to 57%), The Saehan Industries' membrane did not produce any permeate flow at the operating pressure of 100 psi (689 kN/m^2) although it did have high removal efficiencies at higher operating pressures (90 to 93%). It was unexpected that the Saehan did not produce any product flux at 100 psi, but four samples of the membrane were tested and the results are considered valid. Since low-pressure membrane application is the object of this project, the Saehan Industries' membrane was therefore not considered suitable for the remainder of the project.

The Trail Road Landfill site is concerned with reducing the concentration of the permeate and maximizing the amount of permeate produced. Hydranautics' membrane was selected as the membrane for future study.

Run-to-Run Variability

Run-to-run variability shows how reliable it is to use identical test runs as replicates for data analysis. The results of the run-to-run variability are shown in Table 8. Their averages and standard deviations were determined from four identical experimental runs. The standard deviations range from 0.61 to 2.17 for the pure water and product fluxes, and from 0.10 to 1.63% for the percent removal efficiency. These low standard deviations show that it is safe to use as replicates different experimental runs with identical conditions. The removal efficiencies show a seven times higher standard deviation for test cell 4 than for the average of the remaining eleven cells. This was not considered to affect the rest of the study, and this cell was still considered as a replicate for the rest of the experiment, since the standard deviation for the product rate and permeate rate fell well within the range of the other 11 cells.

Table 8: Summary of Results – Run-to-Run Variability

	Pure water permeate	**Standard Deviation**	**Product Rate**	**Standard Deviation**	**Removal Efficiency**	**Standard Deviation**
Test Cell	**g/hr**	**g/hr**	**g/hr**	**g/hr**	**%**	**%**
1	59.8	1.78	36.4	0.86	97	0.18
2	54.5	1.46	33.0	0.92	97	0.20
3	64.1	1.75	39.5	1.04	94	0.35
4	52.7	1.73	31.0	0.66	97	1.63
5	55.4	1.59	33.4	0.74	97	0.10
6	54.4	1.70	32.2	0.61	98	0.19
7	60.7	1.69	37.2	1.06	96	0.17
8	62.6	2.17	37.6	0.88	97	0.20
9	59.5	1.91	36.0	0.83	95	0.28
10	59.7	1.49	37.9	1.24	92	0.27
11	59.2	1.92	35.9	0.93	93	0.23
12	58.2	1.33	36.8	1.00	93	0.21

Cell-to-Cell Variability

The cell-to-cell variability shows how reliable it is within an experimental run to use individual cells as replicates. Table 9 shows the results. The standard deviation of the flux ranges from 2.4 to 3.7, and that of the percent removal ranges from 2.02 to 2.07%.

These values are approximately twice as high as the run-to-run variability, but are still small enough that each test cell can be used as a replicate.

Table 9: Summary of Results – Cell-to-Cell Variability

	Pure water permeate	Standard Deviation	Product Rate	Standard Deviation	Percent Removal	Standard Deviation
Run	**g/hr**	**g/hr**	**g/hr**	**g/hr**	**%**	**%**
1	57.2	3.6	36.5	2.7	96	2.07
2	59.4	3.5	34.6	2.4	95	2.02
3	60.2	3.7	35.0	2.5	95	2.15
4	56.8	3.3	36.1	2.6	96	2.02

3.3.2 Tests using a Feed of Synthetic Leachate

On the basis of the first part of the experiments, the Hydranautics' membrane was selected as the most suitable membrane for the treatment of landfill leachate. Once the membrane was characterized, it was tested with feeds of synthetic leachate at different operating pressures. The NRCC coupon apparatus of Fig. 14 was used for these experiments, loaded with new Hydranautics' membranes. This allowed for twelve replicates throughout the experiment.

The experimental setup was based on a 4^{3-1} central composite design (Table 6), which enables the generation of equations to describe how TOC, NH_3 and Cl^- concentrations affect the percent removal for each parameter, in addition to their effect on the permeate flux. Equations 11 to 14 can be used to convert from coded to actual parameter values.

Table 10, which summarizes the coupon results of the synthetic leachate experiment with the low-pressure Hydranautics' membrane, shows that the Hydranautics' membrane consistently results in high removal rates for all three of the parameters that were examined (>84% for TOC, >83% for NH_3, and >78% Cl^-). At operating pressures equal to or greater than 150 psi (1034 kN/m^2), product fluxes were in the range 7.7 to 31.7 l/m^2/hr and for operating pressures lower than 150 psi (1034 kN/m^2), the product fluxes were in the range of 1.9 to 9.5 l/m^2/hr.

Close inspection of the results given in Table 10 shows that the operating pressure affects the product rate. To see whether this rate depends also on the concentrations of TOC, NH_3 and Cl^-, a least-squares analysis was made in which the data collected from the coupon experiments was used to develop empirical models that describe the influence and interrelationship of TOC, NH_3 and Cl^- on permeate flow in the experimental system. The technique involves the estimation of the model parameters for second-order models of the form.

$$E(Y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4. \qquad \text{Eq. 14}$$

Here: E(Y) is the expected value of the response variable,
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_{11}, \beta_{22}, \beta_{33}, \beta_{44}, \beta_{12}, \beta_{13}, \beta_{14}, \beta_{23}, \beta_{24}, \beta_{34}$
are the model parameters,
x_1 is the coded operating pressure,
x_2 is the coded TOC concentration,

x_3 is the coded NH_3 concentration, and
x_4 is the coded Cl^- concentration.

The development of the four models is given in Appendix B. Table 11 is a summary of the model parameters and the Analysis-of-Variance (ANOVA) results. 95% confidence intervals are included for each parameter.

Table 10: Summary of Synthetic Leachate Low Pressure RO Experimental Results

Run	**Operating Pressure**	**Temp. °C**	**PWP** $l/m^2/hr$	**PR** $l/m^2/hr$	**PR/PWP %**	**% rejection**		
						TOC	**NH_3**	**Cl^-**
1	115	30	26.9	9.5	35	94	94	95
2	205	33	48.2	31.7	66	96	94	97
3	110	29	19.9	2.1	11	84	-	78
4	195	32	43.9	8.4	19	94	99	94
5	105	29	18.9	6.4	34	89	85	87
6	200	33	42.2	27.7	66	94	96	95
7	110	29	21.8	3.9	18	88	87	82
8	195	32	41.2	7.7	19	95	97	93
9	75	28	15.9	1.9	12	84	83	81
10	225	33	49.0	24.9	51	95	95	98
11	150	32	32.6	19.2	59	95	94	94
12	150	30	32.5	8.5	26	94	93	90
13	150	30	31.5	12.8	40	96	91	94
14	160	32	32.8	12.6	38	94	91	92
15	150	32	32.8	13.2	40	95	93	93
16	145	31	27.8	8.1	29	94	90	91
17	150	31	30.6	12.4	41	94	94	92
18	150	30	30.1	12.7	42	95	94	93
19	150	31	29.7	11.1	37	95	92	93
20	150	32	34.7	10.8	31	95	93	92

Table 11: ANOVA Results for Synthetic Leachate Experiments

Parameter	PR/PWP	TOC removal %	NH_3 removal %	Cl^- removal %
β_0	0.345±0.031	91.08±0.98	91.76±0.81	86.27±1.31
β_1	0.115±0.043	6.47±0.96	5.48±1.24	10.83±1.73
β_2	-0.175±0.053			
β_3		-4.72±1.20		-9.80±2.40
β_4		-2.31±0.59		
β_{11}				
β_{22}				
β_{33}				-3.62±2.83
β_{44}				
β_{12}	-0.074±0.070			
β_{13}		4.19±1.42		6.01±2.66
β_{14}				
β_{23}				3.35±1.90
β_{24}				
β_{34}			2.20±1.06	1.66±0.96
R^2	0.858	0.958	0.845	0.963
F_{reg}	22.67	64.23	35.15	44.91
$F_{.05,v1,v2}$	3.06	2.96	3.24	2.91
F_{lof}	2.22	3.62	3.43	6.16
$F_{.05,v1,v2}$	8.74	8.76	8.72	8.81

The following equations are the final models describing the four parameters.

$$PR/PWP = 0.346 + 0.115x_1 - 0.175x_2 - 0.07x_1x_2, \qquad \text{Eq. 15}$$

$$\%TOCrejection = 91.08 + 6.47x_1 - 4.72x_3 - 2.31x_4 + 4.19x_1x_3, \qquad \text{Eq. 16}$$

$$\%NH3rejection = 91.76 + 5.48x_1 + 2.20x_3x_4, \text{ and} \qquad \text{Eq. 17}$$

$$\%Cl^-_{rejection} = 86.27 + 10.83x_1 - 9.80x_3 - 3.62x_3^2 + 6.01x_1x_3 + 3.35x_2x_3 + 1.66x_3x_4 \qquad \text{Eq. 18}$$

Where x_1 is the coded operating pressure,
x_2 is the coded TOC concentration,
x_3 is the coded NH_3 concentration, and
x_4 is the coded Cl^- concentration.

Coded variables were used to make it easier to compare the influence of the operating variables (Eq. 10 to 13).

All models have high coefficient of correlation (R^2) values (0.85 to 0.96), which shows that a large part of the variance in the data was accounted for in the final models. Equation 15 shows that the ratio of pure water permeate rate to permeate rate is affected by the applied operating pressure (x_1) as well as the TOC concentration (x_2). The operating pressure was expected to have a significant effect on the permeate rate since it is usually a governing factor for membrane permeate rates (Table 10). TOC concentration was also expected to have an effect since acetic acid (measured as TOC) is a larger molecule than NH_3 and Cl^-, and this will reduce the flux at higher concentrations. Equations 16, 17 and 18 show that the operating pressure (x_1) is a significant factor in determining removal efficiencies. The ammonia concentration (x_3) is the only parameter, other than the operating pressure (x_1), that influences the three removal efficiencies. This could be a result of the positive charge on the NH_3 molecule.

The difference between the observed and the predicted values of the response is called the residuals. They show a normal distribution with constant variance, for all the response variables (Appendix B). The normal probability plot for the residuals of Equation 15 (PR/PWP) is linear. Figure 18 shows that the values of the residuals do not follow any significant trend, which indicates that there is a constant variance. The equal scatter of the residuals about the x-axis (seen in Figure 19) shows that the variance is independent of the PR/PWP ratio.

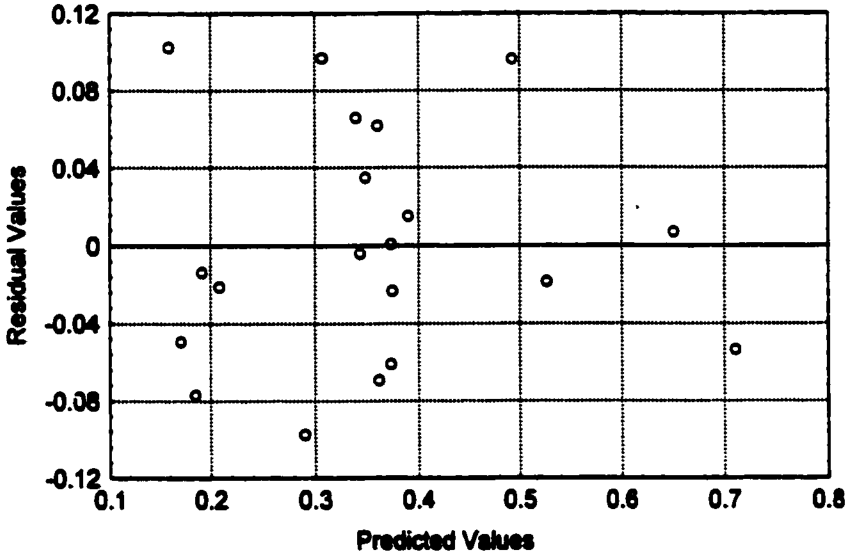

Figure 18: Residual Values versus Predicted Values for the Synthetic Leachate Coupon Experiment (line shows a residual of zero)

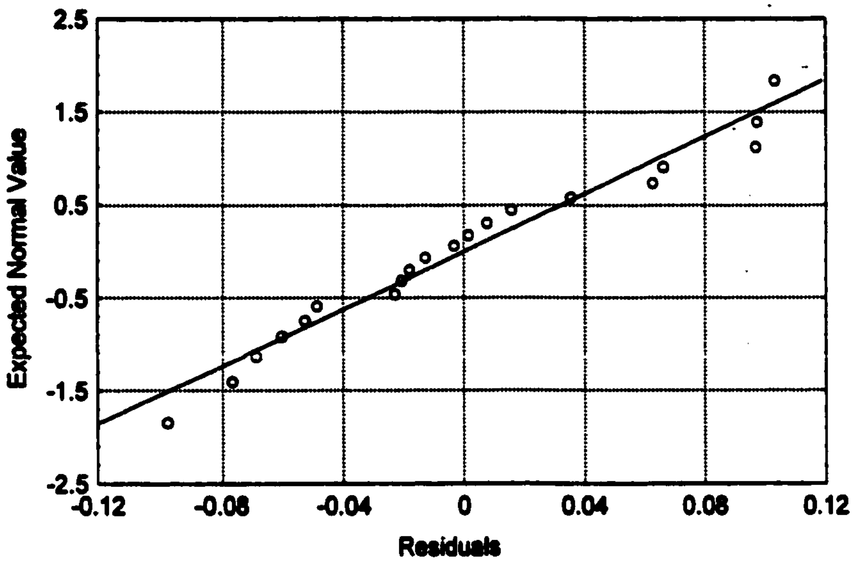

Figure 19: Expected Normal Value versus Residual Value for the Synthetic Leachate Coupon Experiment (line shows linear relationship between expected normal value versus residual values)

3.4 Conclusions

The Hydranautics' membrane was selected as the most appropriate membrane for the treatment of landfill leachate like that generated at the Trail Road Landfill Site. A feed of 5000 mg/l NaCl made up with RO water gave removal efficiencies greater than 97% at permeate flowrates ranging from 27.0 to 53.0 l/m^2/hr for operating pressures in the range of 100 to 200 psi (689 to 1379 kN/m^2). The Hydranautic membrane achieved consistently high removal rates for TOC (>84%), NH_3 (>83%) and Cl^- (>78%) using feeds of various synthetic leachate concentrations. Results from the central composite experimental design showed that the product flux is dependent on the operating pressure and on the TOC concentration. For operating pressures greater than 150 psi (1034 kN/m^2), the product permeate fluxes were in the range of 7.7 to 31.7 l/m^2/hr; at lower operating pressures [<150 psi (1034 kN/m^2)], the product flux was in the range of 1.9 to 9.5 l/m^2/hr. Based on these results, the Hydranautics' membrane shows a potential for use as a low-pressure membrane for the treatment of landfill leachate. The next step in the project was to test the Hydranautics' membrane with a feed of real leachate.

Chapter 4 - Low-Pressure Reverse Osmosis for the Treatment of Landfill Leachate

4.1 Introduction

Approximately one third of the waste collected in the Ottawa-Carleton Region is buried at the Trail Road Landfill site, which comprises 200 ha, including a 135-ha buffer zone. It is located in the Regional Municipality of Ottawa-Carleton, Nepean, Ontario. The fear that contaminated leachate may escape the site has prompted studies of the best way to treat the leachate.

The site is currently divided into four areas, or stages. Two of them are capped, although neither has an engineered landfill liner or collection system; a third is currently an active filling area. The fourth stage is left for future use. The active stage was constructed with a synthetic liner and leachate collection system. The collected leachate is either recycled into the active site or is transported by tanker truck to the sewage treatment plant. Neither is a fully satisfactory method because on the one hand there is potential for groundwater contamination by the leachate; on the other hand, trucking is expensive.

One treatment option being examined is the treatment of the leachate at the site is by low-pressure RO. Low-pressure RO is effective for direct treatment of surface water and the removal of pesticides and organic micropollutants (Hofman *et al.*, 1997); it has also been used successfully in industrial applications to remove Zn^+ and Cu^{2+} at pressures less than 100 psi (689 kN/m^2) (Ujang and Anderson, 1996).

Here are described further low-pressure RO experiments done using a Hydranautics' polyamide module of type 2012-UST-ESPA to remove TOC, NH_3 and Cl^-. The tests first used feeds of synthetic leachate of various concentrations and achieved removal rates of >84% for TOC, >83% for NH_3 and >78% for Cl^-. The product rates ranged from 7.7 to 31.7 l/m^2/hr at operating pressures equal to and greater than 150 psi (1034 kN/m^2), and ranged from 1.9 to 9.5 l/m^2/hr at operating pressures below 150 psi (1034 kN/m^2). The removal efficiencies remained high at the lower operating pressures. The following paper shows the results of using real leachate with a coupon-testing apparatus and a lab-scale spiral-wound membrane testing module.

4.2 Material and Methods

4.2.1 Analytical Methods

Measurements were made of the conductivity, the TOC, ammonia, and the chloride concentrations. These methods are discussed in Section 3.2.1 COD and pH were measured in accordance with Standard Methods 18th Edition (Greenberg *et al.*, 1992).

4.2.2 Testing Apparatus

The real leachate coupon tests were conducted using a so-called "coupon membrane testing unit", which was developed at National Research Council of Canada (NRCC). Details of the coupon apparatus are discussed in Section 3.2.2.

The spiral-wound membrane configuration, shown in Figure 20, was used for the experiment. The spiral-wound membrane is a 5 cm by 30 cm (2" x 12") membrane with an active membrane area of 0.45 m^2 (4.8 ft^2). The leachate was prefiltered through a 0.1 μm polypropylene filter to remove any suspended solids that might clog the membrane.

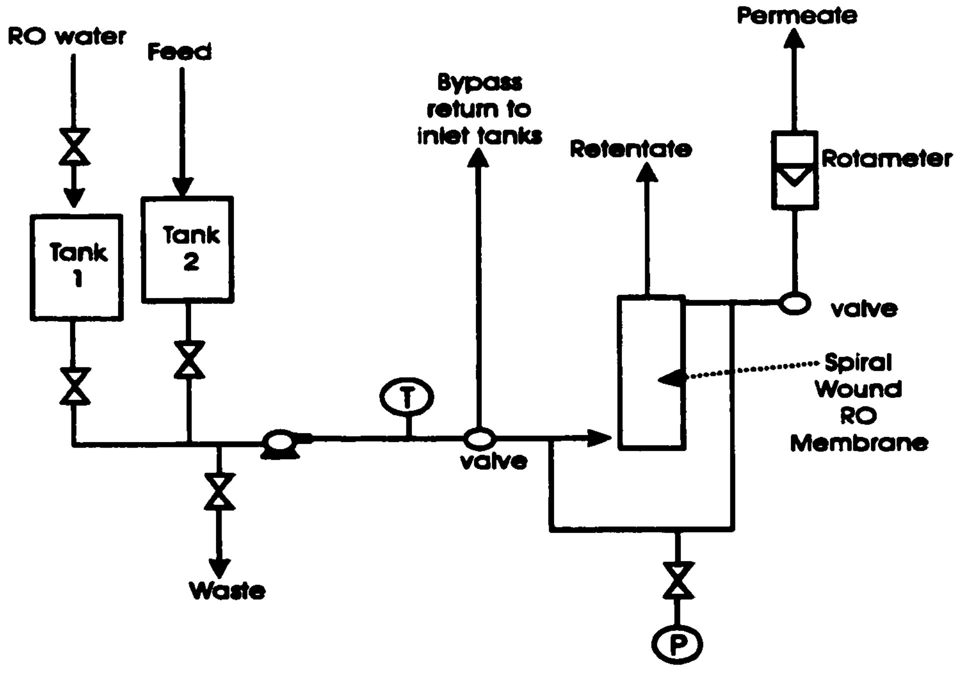

Figure 20: Sketch of the Spiral-wound Experimental Apparatus

4.2.3 Landfill Leachate

Samples of landfill leachate were collected from the Trail Road Landfill Site in November 1997. The leachate was frozen until used for testing. Once the samples were thawed, they were stored at 4°C to minimize biodegradation. Table 12 shows the characteristics of the leachate.

Table 12: Trail Road Landfill Leachate Characteristics

Parameter	Concentration Range
TOC	107 – 250 mg/l
pH	6.8 – 8.52
NH_3	236 – 1081 mg/l
COD	293 – 613 mg/l
Cl^-	449 – 1450 mg/l

These concentration ranges are lower than was predicted by Dillon (1994).

4.2.4 Experimental Protocols

Coupon Tests

'Coupon' samples from Hydranautics were loaded into the coupon membrane testing apparatus and tested with a feed of landfill leachate to determine the effect of leachate concentration and operating pressure on the product flux and on the TOC, NH_3, and Cl^- removal efficiencies. Details of the experimental protocol for the coupon tests are listed in Section 3.2.3. The Trail Road Landfill leachate was diluted with RO water to give leachate samples of different concentrations. These concentrations were tested with the coupon apparatus using a range of operating pressures from 100 to 240 psi (689 - 1654 kN/m^2).

A least-squares analysis was performed on the results using STATISICA Release 4.5 to develop an empirical model to describe the effect of operating pressure and leachate concentration on the ratio of product rate to pure water permeate rate.

Thirteen runs were made with the NRCC coupon apparatus using real leachate. The test conditions are listed in Table 13.

Table 13: Real Leachate Experimental Set-up

Run Number	**Operating Pressure psi (kN/m^2)**	**TOC mg/l**	**NH_3 mg/l**	**Cl^- mg/l**
1	150 (1034)	41	113	296
2	200 (1378)	58	132	272
3	150 (1034)	103	255	393
4	200 (1378)	107	236	449
5	125 (861)	142	335	570
6	240 (1654)	163	392	593
7	175 (1206)	71	187	180
8	180 (1240)	202	458	1049
9	175 (1206)	200	495	1365
10	175 (1206)	250	602	1332
11	100 (689)	236	1081	1450
12	100 (689)	109	210	514
13	175 (1206)	113	424	1034

Spiral-Wound Tests

Tests on 3 leachate samples were made with the lab-scale spiral-wound apparatus at operating pressures of 40, 50 and 60 psi (276, 345 and 413 kN/m^2). (These operating pressures are lower than those done with the coupon apparatus due to limitations in the equipment.) These tests were done to see whether the Hydranautics' membrane behaved as well in the spiral configuration as it did in the coupon tests. The concentrations of the feed used in these tests are given in Table 14. The experiment determined the removal efficiencies for both TOC and Cl$^-$, and the fluxes for both the product and the pure water permeates.

Table 14: Average Feed Concentrations for Spiral-Wound Tests

Leachate Sample	**Cl$^-$ mg/l**	**TOC mg/l**
1	207	165
2	2154	1646
3	2416	1628

Sample 1 is a dilute leachate with approximately 1/10th the chloride and TOC concentration of Samples 2 and 3. By testing various concentrations of leachate the effect of concentration on membrane performance can be determined.

4.3 Results and Discussion

4.3.1 Coupon Tests

Table 15 shows the pure water permeate rates, product rates and removal efficiencies for the thirteen experimental runs with real leachate.

Table 15: Summary of Results for Coupon Tests when using a Feed of Real Leachate

						Removal Efficiencies		
Run	**Operating Pressure**	**Temp.**	**PWP**	**PR**	**PR/PWP**	**TOC**	**NH_3**	**Cl^-**
Number	**psi (kN/m^2)**	**°C**	**$l/m^2/hr$**	**$l/m^2/hr$**	**%**	**%**	**%**	**%**
1	150 (1034)	30	32.4	30.7	95	97	88	98
2	200 (1378)	29	44.8	45.2	-	96	90	99
3	150 (1034)	28	34.1	27.8	81	98	91	96
4	200 (1378)	31	48.2	38.1	79	97	91	99
5	125 (861)	30	29.7	21.5	73	97	90	97
6	240 (1654)	30	58.4	54.0	93	97	90	98
7	175 (1206)	32	42.8	-	-	97	90	99
8	180 (1240)	31	45.7	30.8	67	97	92	99
9	175 (1206)	30	40.4	31.5	78	97	91	97
10	175 (1206)	30	42.8	25.9	60	97	91	98
11	100 (689)	29	22.7	13.7	60	97	96	96
12	100 (689)	30	22.1	17.4	79	97	90	97
13	175 (1206)	30	42.5	30.0	71	97	92	98

At operating pressures > 150 psi (1034 kN/m^2) the product fluxes are in the range of 25.9 to 54.0 l/m^2/hr. At lower operating pressures [<125 psi (861 kN/m^2)] the product fluxes decrease to the range of 13.7 to 21.5 l/m^2/hr. At these lower pressures, the product fluxes have decreased but the removal efficiencies have remained constant: TOC removal efficiencies are in the range of 96 to 98%, Cl^- removal efficiencies are in the range of 96 to 99%, and NH_3 removal efficiencies in the range of 88 to 96%. The ratio of product flux to pure water flux range from 0.60 to 0.95 over the entire range of operating pressures.

Three samples of permeate were tested for COD, Table 16 shows the results.

Table 16: COD for Permeate and Feed for Real Leachate Coupon Tests

	Feed	**Permeate**
Leachate Sample	**COD mg/l**	**COD mg/l**
3	293	10
5	413	12
8	613	8

It is interesting to compare the results for real leachate to those of the synthetic leachate tests (Section 3.3.2). First, note that the average influent concentrations of TOC, NH_3 and Cl^- are higher for the synthetic leachate than for the real leachate (Table 17). Second, note that when compared to the synthetic leachate results (Section 3.3.2), the range of the PR/PWP ratio for real leachate is higher than that of synthetic one (0.6 - 0.95 compared to 0.11 - 0.66).

Table 17: Average Influent Concentrations: Real and Synthetic Leachate

Parameter	Synthetic Leachate	Real Leachate
TOC, mg/l	2255	138
NH_3, mg/l	924	378
Cl^-, mg/l	1435	731

Third, Table 18 shows that the product permeate rate for the real leachate is higher than that of synthetic leachates over a range of operating pressures. (This is due to the lower TOC, NH_3 and Cl^- concentrations.)

Table 18: Product Permeate Rates for Real and Synthetic Leachates

Leachate Type	Product Permeate Rate (l/m²/hr)	
	< 150 psi (1034 kN/m²)	≥150 psi (1034 kN/m²)
Real Leachate	13.76 - 21.5	25.9 - 54.0
Synthetic Leachate	1.9 - 9.5	8.5 - 31.7

And fourth, note that the removal efficiency rates for TOC, NH_3 and Cl^- for the feed of real leachate are again higher than those of the synthetic leachate (Table 19).

Table 19: Removal Efficiency for Feeds of Real and Synthetic Leachate

Parameter	Removal Efficiency	
	Real Leachate	Synthetic Leachate
TOC	>96%	>84%
NH_3	>88%	>83%
Cl^-	>96%	>78%

For the synthetic leachate tests (Section 3.3.2) Equation 15 shows how the operating pressure and the TOC concentration affect the product rate. For the real leachate, Figure 21 shows for the coupon tests that only the operating pressure effects the product flux. Equation 15 has a high coefficient of correlation value, R^2, (0.88), illustrating that leachate concentration has little effect on the product permeate rate.

$$PR = 0.25x - 11.17, \qquad \text{Eq. 15}$$

where: PR is the product rate, $l/m^2/hr$ and
x is the operating pressure, psi.

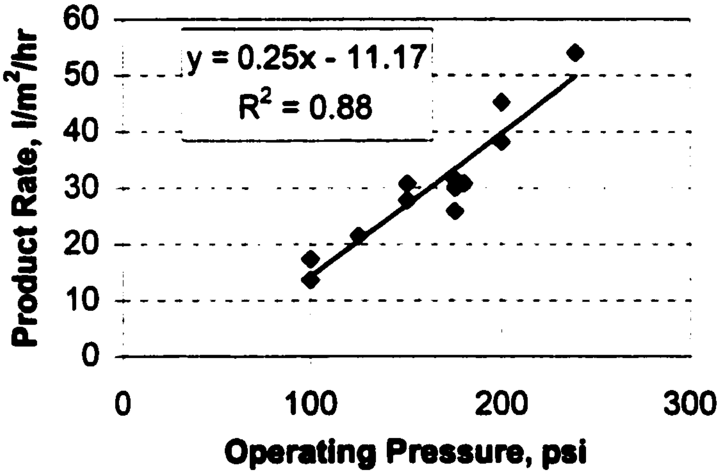

Figure 21: Data points show the measured Product Rate versus Operating Pressure for the Real Leachate Feed. The solid line shows a least-squares fit to these data.

This linear relationship seen in Figure 21 (between operating pressure and permeate flux) does not apply to the synthetic leachate coupon tests. Figure 22 shows the low R^2 (0.56) for the graph of product rate versus operating pressure. This indicates that at higher levels the concentration of the leachate affects the product permeate flux whereas, at lower concentrations only the operating pressure affects the product flux. It is predicted that if the real leachate concentrations were as high as described by Dillon (1994), the linear relationship between operating pressure and product flux would no longer hold.

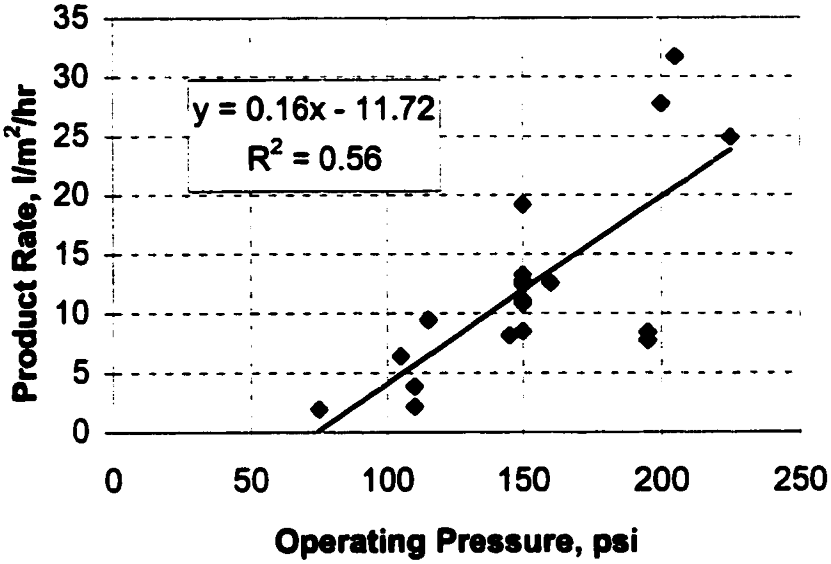

Figure 22: Data points show the measured Product Rate versus Operating Pressure for the Synthetic Leachate Feed. The solid line shows a least-squares fit to these data.

4.3.2 Spiral-wound Tests

Only three runs using the spiral-wound configuration were made, since these experiments were a preliminary investigation into the feasibility of this membrane configuration for the treatment of landfill leachate. Three operating pressures were tested, based on the recommended range by the manufacturer [40, 50 and 60 psi. (276, 345 and 413 kN/m²)]. The parameters TOC and Cl^-, were analyzed at this stage. Four replicates were taken for each product flux. There was one sampling port during each experimental run, so four consecutive samples were taken during each run. Table 20 and Table 21 summarize the run conditions and the results for the spiral-wound tests, respectively.

Table 20: Summary of Run Conditions for Spiral-wound Tests

Leachate Sample	P_{inlet} psi	Temp. °C	Cl^- mg/l	TOC mg/l	Cross Flow Velocity gal/min
1	40	18	207	165	0.32
2	49	15	2416	1646	0.28
3	60	22	2154	1628	0.35

Table 21: Summary of Results for Spiral-wound Tests

Leachate Sample	PWP $l/m^2/hr$	PR $l/m^2/hr$	Cl^- removal %	TOC removal %	PR/PWP %
1	10.9	5.50	93	96	51.0
2	10.3	0.60	27	73	5.0
3	17.9	0.90	51	78	5.1

Sample 1, which was tested at the lowest pressure, shows the most promising results. The PR/PWP ratio of 51%, and the removal efficiencies greater than 93%, show that this membrane configuration and type could be used for the treatment of landfill leachate. Although the PR/PWP ratio for sample 1 is high, the pure water permeate flux and product flux are low (10.9 and 5.50 $l/m^2/hr$, respectively). The difference between the highly concentrated leachate results (Samples 2 and 3) and the low concentration result (Sample 1) indicates that leachate concentration affects the performance of the membrane. Since tests 2 and 3 were done at higher operating pressures than test 1, they would be expected to show higher fluxes. The pure water permeate flux for test 3 is higher than for tests 1 and 2, but the product flux for tests 2 and 3 is an order of magnitude lower than that for test 1. Consequently, this shows how the leachate concentration effects the product permeate rate.

For this spiral-wound membrane to be used as treatment for the Trail Road Landfill leachate the product fluxes would have to increase. Even at the lowest leachate concentration (Sample 1), the product flux is too low (5.5 $l/m^2/hr$). Table 22 shows the membrane area required for the average, peak- and low-leachate flows for 1997 (Figure 2) from the Trail Road Landfill site based on product fluxes for the different operating pressures for the coupon and spiral-wound configurations.

Table 22: Membrane Surface Area Requirements for Coupon and Spiral-wound Tests at different Operating Pressures and Leachate Flowrates.

		Required Membrane Area		
	Flux ($l/m^2/hr$)	**Low Flow (4,302 l/hr)**	**Average Flow (4,942 l/hr)**	**Peak Flow (9,676 l/hr)**
Coupon (<1034 kN/m^2)	17.5	208 m^2	245 m^2	553 m^2
Coupon (>1034 kN/m^2)	32.5	112 m^2	152 m^2	298 m^2
Spiral-wound (276-413 kN/m^2)	2.3	1581 m^2	2149 m^2	4207 m^2
Spiral-wound (>413 kN/m^2)	**Future Research**	**Future Research**	**Future Research**	**Future Research**

The Hydranautics' module 2012-UST-ESPA is available in different sizes, the largest industrial size module is 3.05 m^2 (32.8 ft^2). Table 23 shows the number of 3.05 m^2

membranes modules that would be required based on the active-membrane surface areas given in Table 22.

Table 23: Summary of Membrane Module Requirements

	Required Number of Membrane Modules		
	Low Flow	**Average Flow**	**Peak Flow**
Coupon (<1034 kN/m^2)	68	93	181
Coupon (>1034 kN/m^2)	37	50	98
Spiral-wound (276-413 kN/m^2)	518	704	1379
Spiral-wound (>413 kN/m^2)	**Future Research**	**Future Research**	**Future Research**

Based on the permeate flux of 2.3 l/m^2/hr, and on the average of the three spiral-wound membrane tests, the number of membrane units that would be required is not feasible. However, the coupon tests, at higher operating pressures, do result in a feasible number of membrane units. To treat the average leachate flowrate, 50 membrane modules would be required. Since the results of the coupon tests show excellent removal efficiencies for all of the tests' parameters, this technology could be used to treat the landfill leachate at the Trail Road site, if the permeate flux could be kept at 32 l/m^2/hr.

4.4 Conclusions

Using Trail Road Leachate, the Hydranautics' membrane achieved TOC and Cl^- removal efficiencies greater than 96% and NH_3 removal efficiencies greater than 88%. For operating pressures greater than 150 psi (>1034 kN/m^2), the product flux was in the range of 26.0 to 54.0 l/m^2/hr. No adsorption fouling was observed with the Hydranautics' membrane. These results show that this membrane is capable of treating the Trail Road Landfill leachate.

The Hydranautics' spiral-wound membrane configuration produced low removal rates and product fluxes for highly concentrated leachate. Removal rates for TOC and Cl^- were greater than 73 and 27%, respectively. Product flux was greater than 0.6 l/m^2/hr. Results of the final phase of the project show that pretreatment must be considered for the use of a spiral-wound membrane configuration. The coupon tests show that high fluxes are possible at higher operating pressures [>150 psi (1034 kN/m^2)], but when the spiral-wound module was tested at lower operating pressures [<60 psi (413 kN/m^2)], the permeate fluxes were low (<5.5 l/m^2/hr). The coupon results show that this technology is feasible for treating the landfill leachate, however higher operating pressures need to be tested with the spiral-wound membrane configuration. The highly concentrated leachate produced a lower permeate flux (<1.0 l/m^2/hr) than the low concentration leachate (5.5 l/m^2/hr), which shows that the flux is also affected by the concentration of the leachate. Leachate pretreatment methods should therefore be investigated to increase the product flux.

Chapter 5 - Conclusions and Recommendations

The feasibility of using low-pressure RO as a treatment option for the Trail Road Municipal Landfill Leachate was determined through work that was divided into four phases:

1. the selection of a suitable membrane material using 5000 mg/l NaCl as a test solution,
2. the testing of the membrane using synthetic leachate at different operating pressures,
3. the testing of the membrane using real leachate at different operating pressures, and
4. the testing of spiral wound membrane configuration with real leachate.

Conclusions

1. The Hydranautics' 2012-UST-ESPA membrane was selected to be the most appropriate membrane for the treatment of landfill leachate based on the results of the membrane characterization tests for the Hydranautics', Fluid Systems' and Saehan Industries' membranes. The Hydranautics' membrane achieved removal rates greater than 97% at flows ranging from 27.0 l to 53.0 l/m^2/hr for operating pressures in the range of 100 to 200 psi (689 to 1378 kN/m^2).

2. The Hydranautics' membrane achieved consistently high removal rates for TOC (>84%), NH_3 (>83%) and Cl^- (>78%) using various synthetic leachate concentrations with the NRCC coupon-testing apparatus. Results from a central composite experimental design showed that the product flux is dependent on the operating pressure and on the TOC concentration. For operating pressures greater than 150 psi (1034 kN/m^2), the product fluxes were in the range of 7.7 to 31.7 $l/m^2/hr$. The tests with synthetic leachate showed the potential use of the Hydranautics' membrane in the treatment of the Trail Road Municipal Landfill leachate.

3. The Hydranautics' membrane achieved TOC and Cl^- removal efficiencies greater than 96% and NH_3 removal efficiencies greater than 88% with a feed of real leachate. For operating pressures greater than 150 psi (1034 kN/m^2), the product flux was in the range of 26.0 to 54.0 $l/m^2/hr$. No adsorption fouling was observed with the Hydranautics' membrane. All of which means that this membrane is potentially capable of treating the Trail Road Landfill leachate.

4. The configuration using the Hydranautics' spiral-wound membrane produced low removal rates and low product fluxes when the leachate was highly concentrated. Removal rates for TOC and Cl^- were greater than 73 and 27%, respectively. Product flux was greater than 0.6 $l/m^2/hr$. The coupon tests showed that high fluxes are possible at higher operating pressures [>150 psi (1034 kN/m^2)], but when the spiral-wound module was tested at lower operating pressures [<60 psi (413 kN/m^2)] the

permeate fluxes were low (<5.5 l/m²/hr). The coupon results show that this technology is feasible for treating the landfill leachate, but that higher operating pressures need to be tested with the spiral-wound membrane configuration. The highly concentrated leachate produced a lower permeate flux (<1.0 l/m²/hr) than the low-concentration leachate (5.5 l/m²/hr). This shows that the flux is also affected by the concentration of the leachate. Leachate pretreatment methods should therefore be investigated to increase the product flux.

Recommendations

The results of this project show that a spiral-wound membrane produces encouraging removal rates but the product flux is not high enough. It appears that the latter could be increased by raising the operating pressure. The recommendation is therefore that a pilot-scale membrane test, using a spiral-wound membrane capable of withstanding higher operating pressures than possible here, should be conducted at the Trail Road Site using real leachate.

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APPENDIX A: Raw Data

Membrane Characterization
Coupon Experiments with a Feed of Synthetic Leachate
Coupon Experiments with a Feed of Real Leachate
Spiral-wound Membrane Tests with a Feed of Real Leachate

Table 24: Membrane Characterization - Operating Pressure 100 psi

Cell	Coupon	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	Saehan	77.25	-	-	-	-	-
2	Saehan	77.39	-	-	-	-	-
3	Saehan	76.84	-	-	-	-	-
4	Saehan	77.44	-	-	-	-	-
5	Hydranautics	77.21	540	87.29	1380	91.73	29
6	Hydranautics	76.84	540	87.54	1380	92.03	28
7	Hydranautics	77.30	540	88.41	1380	93.78	20
8	Hydranautics	77.57	540	88.03	1380	93.38	30
9	Fluid System	77.20	540	84.74	1380	90.15	442
10	Fluid System	77.32	540	84.20	1380	90.15	433
11	Fluid System	77.18	540	85.37	1380	90.57	518
12	Fluid System	77.27	540	83.02	1380	87.11	471
RO							1
RO							1
Feed							936
Feed							947
PWP							2

Table 25: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	120	110	26	0.98
B	0.70	120	110		
C	0.68	120	100		
D	0.60	120	110		

Table 26: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	120	120	27	0.96
B	0.66	120	115		
C	0.68	120	115		
D	0.65	120	120		

Table 27: Membrane Characterization - Operating Pressure 150 psi

Cell	Coupon	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	Saehan	77.33	720	88.74	900	85.59	83
2	Saehan	77.17	720	87.43	900	84.60	96
3	Saehan	77.42	720	87.61	900	84.80	132
4	Saehan	77.13	720	86.80	900	83.89	84
5	Hydranautics	77.21	720	97.33	900	89.72	30
6	Hydranautics	76.92	720	99.34	900	90.34	27
7	Hydranautics	77.25	720	100.12	900	91.32	21
8	Hydranautics	77.47	720	100.16	900	91.26	29
9	Fluid System	76.63	720	88.16	900	86.77	445
10	Fluid System	77.46	720	88.27	900	87.27	437
11	Fluid System	79.46	720	90.73	900	89.84	528
12	Fluid System	77.37	720	86.04	900	85.51	468
RO							1
RO							1
Feed							975
Feed							1028
PWP							2

Table 28: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.70	160	150	28	0.94
B	0.65	160	150		
C	0.65	160	150		
D	0.65	160	150		

Table 29: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp.	Correction Factor
A	0.68	150	140	32	0.86
B	0.65	150	140		
C	0.64	150	140		
D	0.65	150	140		

Table 30: Membrane Characterization - Operating Pressure 200 psi

Cell	Coupon	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	Saehan	77.24	480	86.97	480	84.88	54.1
2	Saehan	77.37	480	86.28	480	84.18	71.6
3	Saehan	76.84	485	85.49	480	83.63	97.8
4	Saehan	77.43	480	85.83	480	83.75	54.0
5	Hydranautics	77.22	480	94.27	480	88.95	21.9
6	Hydranautics	76.84	480	95.77	480	89.72	20.1
7	Hydranautics	77.28	480	96.09	480		
8	Hydranautics	77.59	480	97	480	90.75	20.5
9	Fluid System	77.21	480	87.11	480	86.07	414
10	Fluid System	77.31	480	86.29	480	85.49	384
11	Fluid System	77.18	480	86.71	480	84.84	498
12	Fluid System	77.27	480	85.03	480	84.38	376
RO							1
RO							1
Feed							969
Feed							969
PWP							1

Table 31: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200	190	30	0.90
B	0.67	200	190		
C	0.66	200	190		
D	0.65	200	190		

Table 32: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200	190	32	0.86
B	0.65	200	190		
C	0.64	200	190		
D	0.67	200	190		

Table 33: Run-to-run and Cell-to-cell Variability - Run 1

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	77.32	840	92.11	900	87.86	27.0
2	77.16	840	90.89	900	86.89	28.6
3	77.4	840	93.38	901	88.90	52.5
4	77.1	840	90.06	900	86.12	26.8
5	77.19	840	91.02	900	86.95	30.6
6	76.9	840	90.35	900	86.20	23.4
7	77.23	840	92.48	898	88.15	39.0
8	77.45	840	93.01	900	88.43	29.8
9	76.61	840	91.47	900	87.11	51
10	77.1	840	92.22	900	88.34	82
11	79.41	840	94.19	900	89.98	67
12	77.36	840	92.05	900	88.12	69
RO						0
RO						0
Feed						971
Feed						971
PWP						3

Table 34: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	155	150	29	0.92
B	0.64	155	150		
C	0.64	155	150		
D	0.65	155	150		

Table 35: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	160	155	31	0.88
B	0.64	160	155		
C	0.65	160	155		
D	0.65	155	150		

Table 36: Run-to-run and Cell-to-cell Variability - Run 2

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	77.27	720	90.27	1020	88.81	27.9
2	77.35	720	89.19	1020	87.76	30.3
3	76.81	720	90.68	1020	89.20	54.4
4	77.4	720	88.95	1020	87.19	57.4
5	77.19	720	89.23	1020	87.75	30.0
6	76.82	720	88.723	1020	87.00	24.3
7	77.21	720	90.36	1020	88.94	39.4
8	77.56	720	91.26	1020	89.39	30.7
9	77.2	720	90.14	1020	88.51	53
10	77.25	720	90.2	1020	89.05	84
11	77.15	720	90.17	1020	88.44	68
12	77.31	720	89.84	1020	88.80	68
RO						0
RO						0
Feed						968
Feed						968
PWP						0

Table 37: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	160	155	28	0.94
B	0.65	160	155		
C	0.67	160	155		
D	0.64	160	155		

Table 38: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	165	160	31	0.88
B	0.65	165	160		
C	0.65	165	160		
D	0.64	165	160		

Table 39: Run-to-run and Cell-to-cell Variability - Run 3

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	77.32	600	88.82	1020	88.84	27.3
2	77.16	600	87.59	1020	87.60	29.2
3	77.4	600	89.72	1020	89.93	55.3
4	77.11	600	87.2	1020	86.99	26.2
5	77.2	600	87.84	1020	87.82	29.0
6	76.9	600	87.34	1020	87.16	24.3
7	77.24	600	88.9	1020	88.97	38.3
8	77.45	600	89.5	1020	89.42	30.3
9	76.62	600	88.09	1020	88.09	52
10	77.09	600	88.47	1020	89.13	81
11	79.41	600	90.73	1020	90.86	66
12	77.36	600	88.48	1020	89.09	68
RO						0
RO						0
Feed						918
Feed						918
PWP						1

Table 40: Pure Water Permeate Flow Conditions

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	160	155	30	0.9
B	0.66	160	155		
C	0.65	160	155		
D	0.63	160	155		

Table 41: Product Rate Flow Conditions

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150	145	31	0.88
B	0.65	150	145		
C	0.62	150	145		
D	0.66	150	145		

Table 42: Run-to-run and Cell-to-cell Variability - Run 4

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)	Conductivity
1	77.3	600	87.76	960	88.41	25.1
2	77.19	600	86.6	960	87.16	27.7
3	77.39	600	88.55	960	89.41	50.1
4	77.12	600	86.31	960	86.51	24.7
5	77.21	600	86.82	960	87.29	28.4
6	76.93	600	86.4	960	86.68	22.8
7	77.21	598	87.67	960	88.45	35.7
8	77.47	600	88.24	960	88.81	27.6
9	76.66	600	86.91	960	87.52	48
10	77.09	600	87.39	960	88.46	76
11	79.44	600	89.63	960	90.18	62
12	77.35	600	87.45	960	88.50	64
RO						1
RO						1
Feed						920
Feed						920
PWP						0

Table 43: Pure Water Permeate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	160	155	28	0.94
B	0.65	160	155		
C	0.64	160	155		
D	0.65	160	155		

Table 44: Product Rate Flow Conditions

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	160	155	30	0.9
B	0.65	160	155		
C	0.65	160	155		
D	0.64	160	155		

Table 45: Synthetic Leachate Coupon Tests - Test 1

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.21	780	86.93	6900	109.90
2	77.37	780	85.9	6900	106.61
3	76.85	780	86.96	6900	110.38
4	77.41	780	86.05	6900	105.70
5	77.23	780	86.21	6900	107.70
6	76.96	780	85.86	6900	106.03
7	77.28	779	87.09	6900	112.72
8	77.59	780	87.74	6900	111.87
9	77.19	780	86.84	6900	110.22
10	77.34	780	86.97	6900	114.09
11	77.2	780	86.85	6900	110.41
12	77.31	780	86.79	6900	111.98

Table 46: Synthetic Leachate Coupon Test Results - Test 1

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	74.97	70	0.0013	22.6	74.00	0.0011	40.2
2	75.03	68	0.0014	24.7	78.00	0.0009	33.5
3	107.50	57	0.0022	40.0	65.00	0.0017	60.5
4	74.46	69	0.0013	23.7	77.00	0.0010	35.0
5	78.55	65	0.0016	28.2	74.00	0.0011	40.2
6	71.18	69	0.0013	23.7	79.00	0.0009	32.0
7	79.30	65	0.0016	28.2	72.00	0.0012	44.0
8	68.66	69	0.0013	23.7	80.00	0.0009	30.5
9	99.35	60	0.0020	35.1	67.00	0.0016	55.3
10	135.40	50	0.0030	54.4	56.00	0.0026	91.2
11	113.90	55	0.0024	43.7	60.00	0.0021	76.0
12	122.80	54	0.0025	45.7	69.00	0.0014	50.4
RO	4.33	121	0.0001	2.4	184.00	0.0000	0.3
RO	4.33	121	0.0001	2.4	184.00	0.0000	0.3
Feed	1398	0	0.0270	486.0	5.00	0.0263	933.6
Feed	1398	0	0.0270	486.0	5.00	0.0263	933.6
PWP	4.85	119	0.0001	2.7	183.00	0.0000	0.3

Table 47: Pure Water Permeate Flow Conditions - Test 1

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	115	105	30	0.9
B	0.67	115	105		
C	0.65	115	105		
D	0.66	115	105		

Table 48: Product Rate Flow Conditions - Test 1

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	115	105	30	0.9
B	0.65	115	105		
C	0.64	115	105		
D	0.67	115	105		

Table 49: Synthetic Leachate Coupon Tests - Test 2

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.25	720	93.35	3120	126.58
2	77.35	720	91.63	3120	122.28
3	76.89	720	93.63	3120	126.20
4	77.39	720	91.84	3120	120.98
5	77.19	720	92.18	3120	124.44
6	76.82	720	91.74	3120	123.47
7	77.2	720	93.78	3120	130.57
8	77.56	720	94.37	3120	130.47
9	77.17	720	92.27	3120	127.47
10	77.24	720	92.09	3120	131.00
11	77.14	720	92.92	3120	126.35
12	77.29	720	93.04	3120	128.85

Table 50: Synthetic Leachate Coupon Test Results - Test 2

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	60.03	98.00	0.0010	17.9	69.00	0.0014	51.2
2	58.07	106.00	0.0008	13.8	72.00	0.0013	44.6
3	101.50	87.00	0.0014	25.5	55.00	0.0027	96.9
4	59.49	103.00	0.0008	15.2	75.00	0.0011	38.9
5	63.49	97.00	0.0010	18.5	71.00	0.0013	46.7
6	54.48	98.00	0.0010	17.9	75.00	0.0011	38.9
7	61.07	73.00	0.0022	39.9	69.00	0.0014	51.2
8	56.00	75.00	0.0021	37.4	77.00	0.0010	35.5
9	87.32	64.00	0.0030	53.3	60.00	0.0022	77.1
10	103.80	60.00	0.0034	60.5	51.00	0.0033	116.3
11	95.66	63.00	0.0031	55.0	56.00	0.0026	92.6
12	100.60	61.00	0.0033	58.7	54.00	0.0029	101.4
RO	4.01	133.00	0.0003	5.8	187.00	0.0000	0.2
RO	4.01	133.00	0.0003	5.8	187.00	0.0000	0.2
Feed	1586.00	-6.00	0.0280	504.1	-15.00	0.0665	2359
Feed	1586.00	-6.00	0.0280	504.1	-15.00	0.0665	2359
PWP	4.90	131.00	0.0003	6.2	184.00	0.0000	0.2

Table 51: Pure Water Permeate Flow Condition - Test 2

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	200	190	30	0.9
B	0.65	200	190		
C	0.65	200	190		
D	0.65	200	190		

Table 52: Product Rate Flow Conditions - Test 2

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	210	205	33	0.84
B	0.65	210	205		
C	0.68	210	205		
D	0.65	210	205		

Table 53: Synthetic Leachate Coupon Test - Test 3

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.3	1200	88.18	10500	88.93
2	77.21	1200	87.09	10500	85.50
3	77.39	1200	88.88	10500	88.57
4	77.1	1200	87.07	10500	85.16
5	77.18	1200	87.39	10500	85.95
6	76.89	1200	87.14	10500	84.69
7	77.45	1200	88.71	10500	89.58
8	77.35	1200	88.82	10500	87.15
9	76.61	1200	87.56	10500	88.38
10	77.09	1200	88	10500	94.72
11	79.4	1200	90.09	10500	93.20
12	77.15	1200	87.82	10500	92.64

Table 54: Synthetic Leachate Coupon Test Results - Test 3

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	390.50			0.00	28.00	0.0092	326.7
2	379.90			0.00	30.00	0.0084	298.7
3	600.20			0.00	20.00	0.0132	467.1
4	363.90			0.00	32.00	0.0077	273.2
5	405.90			0.00	30.00	0.0084	298.7
6	355.50			0.00	32.00	0.0077	273.2
7	419.00			0.00	26.00	0.0101	357.2
8	350.00			0.00	33.00	0.0074	261.2
9	500.40			0.00	24.00	0.0110	390.6
10	648.50			0.00	16.00	0.0158	558.6
11	550.60			0.00	20.00	0.0132	467.1
12	598.30			0.00	18.00	0.0144	510.8
RO	4.26			0.00	180.00	0.0000	0.3
RO	4.26			0.00	180.00	0.0000	0.3
Feed	2893.00			0.00	-9.00	0.0482	1707
Feed	2893.00			0.00	-9.00	0.0482	1707
PWP	7.00			0.00	181.00	0.0000	0.3

Table 55: Pure Water Permeate Flow Conditions - Test 3

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.68	110	105	26	0.98
B	0.65	110	105		
C	0.65	110	105		
D	0.65	110	105		

Table 56: Product Rate Flow Conditions - Test 3

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	110	105	29	0.92
B	0.67	110	105		
C	0.67	110	105		
D	0.65	110	105		

Table 57: Synthetic Leachate Coupon Test - Test 4

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.26	1140	100.07	3000	89.62
2	77.35	1140	97.83	3000	88.43
3	76.81	1140	100.96	3000	89.52
4	77.41	1140	98.12	3000	88.11
5	77.19	1140	98.51	3000	88.69
6	76.82	1140	98.27	3000	87.88
7	77.23	1140	101.19	3000	90.64
8	77.58	1140	101.44	3000	90.31
9	77.19	1140	100.14	3000	89.64
10	77.26	1140	100.21	3000	91.65
11	77.16	1140	99.61	3000	89.63
12	77.31	1140	99.98	3000	90.64

Table 58: Synthetic Leachate Coupon Test Results - Test 4

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	135.90	33.00	0.0013	23.7	109.00	0.0021	75.3
2	132.00	33.00	0.0013	23.7	113.00	0.0018	64.2
3	325.70	33.00	0.0013	23.7	99.00	0.0032	112.0
4	125.70	33.00	0.0013	23.7	113.00	0.0018	64.2
5	143.50	33.00	0.0013	23.7	115.00	0.0017	59.3
6	121.10	33.00	0.0013	23.7	130.00	0.0009	32.7
7	148.50	33.00	0.0013	23.7	122.00	0.0013	44.9
8	126.20	33.00	0.0013	23.7	128.00	0.0010	35.4
9	194.10	33.00	0.0013	23.7	111.00	0.0020	69.6
10	278.50	33.00	0.0013	23.7	100.00	0.0030	107.2
11	237.60	33.00	0.0013	23.7	104.00	0.0026	91.9
12	273.60	33.00	0.0013	23.7	110.00	0.0020	72.4
RO	4.40	58.00	0.0003	5.1	224.00	0.000	0.7
RO	4.00	58.00	0.0003	5.1	224.00	0.000	0.7
Feed	2954.00	-33.00	0.0759	1365	39.00	0.0342	1213
Feed	2954.00	-33.00	0.0759	1365	39.00	0.0342	1213
PWP	6.80	57.00	0.0003	5.44	214.00	0.0000	1.2

Table 59: Pure Water Permeate Flow Conditions - Test 4

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	200	190	30	0.9
B	0.65	200	190		
C	0.65	200	190		
D	0.64	200	190		

Table 60: Product Rate Flow Conditions - Test 4

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.68	190	185	34	0.82
B	0.65	190	185		
C	0.65	190	185		
D	0.65	190	185		

Table 61: Synthetic Leachate Coupon Test - Test 5

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.33	1020	85.29	4680	90.06
2	77.36	1020	84.72	4680	88.85
3	76.81	1020	85.34	4680	90.32
4	77.41	1020	84.91	4680	88.78
5	77.19	1020	84.83	4680	89.08
6	76.82	1020	84.55	4680	88.42
7	77.23	1020	85.7	4680	91.48
8	77.57	1020	85.16	4680	91.14
9	77.18	1020	85.37	4680	90.55
10	77.252	1020	85.48	4680	93.17
11	77.15	1020	85.13	4680	90.90
12	77.31	1020	85.39	4680	92.15

Table 62: Synthetic Leachate Coupon Test Results - Test 5

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	125.70	3.00	0.0062	110	49.00	0.0051	181
2	126.70	3.00	0.0062	110	51.00	0.0047	167
3	183.80	3.00	0.0062	110	39.00	0.0076	268
4	120.80	3.00	0.0062	110	55.00	0.0040	142
5	130.40	3.00	0.0062	110	52.00	0.0045	160
6	118.90	3.00	0.0062	110	55.00	0.0040	142
7	128.60	3.00	0.0062	110	49.00	0.0051	181
8	117.80	3.00	0.0062	110	54.00	0.0042	148
9	163.90	3.00	0.0062	110	43.00	0.0065	229
10	206.70	3.00	0.0062	110	32.00	0.0100	353
11	174.50	3.00	0.0062	110	38.00	0.0079	279
12	212.40	3.00	0.0062	110	35.00	0.0089	314
RO	3.98	123.00	0.0000	0.7	188.00	0.0000	0.7
RO	3.98	123.00	0.0000	0.7	188.00	0.0000	0.7
Feed	1356.00	-42.00	0.0419	754	-7.00	0.0464	1644
Feed	1356.00	-42.00	0.0419	754	-7.00	0.0464	1644
PWP	8.20	102.00	0.0001	1.6	175.00	0.0000	1.3

Table 63: Pure Water Permeate Flow Conditions - Test 5

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	100	95	26	0.98
B	0.68	100	95		
C	0.65	100	95		
D	0.64	100	95		

Table 64: Product Rate Flow Conditions - Test 5

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	110	100	29	0.92
B	0.65	110	100		
C	0.64	110	100		
D	0.68	110	100		

Table 65: Synthetic Leachate Coupon Test - Test 6

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.25	360	84.01	600	85.17
2	77.34	360	83.55	600	84.54
3	76.79	360	83.91	600	84.87
4	77.39	360	83.77	600	84.47
5	77.18	360	83.71	600	84.76
6	76.81	360	83.39	600	84.38
7	77.2	360	84.38	600	85.74
8	77.17	360	84.99	600	86.12
9	77.55	360	84.49	600	85.20
10	77.24	360	84.15	600	85.74
11	77.15	360	83.94	600	85.22
12	77.3	360	84.08	600	85.71

Table 66: Synthetic Leachate Coupon Test Results - Test 6

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	69.27	10.00	0.0052	92.7	94.00	0.0011	37.3
2	66.26	10.00	0.0052	92.7	97.00	0.0009	33.1
3	102.90	10.00	0.0052	92.7	87.00	0.0014	49.3
4	66.67	10.00	0.0052	92.7	97.00	0.0009	33.0
5	65.35	10.00	0.0052	92.7	96.00	0.0010	34.4
6	64.00	10.00	0.0052	92.7	98.00	0.0009	31.7
7	65.57	10.00	0.0052	92.7	94.00	0.0011	37.3
8	63.73	10.00	0.0052	92.7	98.00	0.0009	31.7
9							
10	100.10	10.00	0.0052	92.7	77.00	0.0021	73.6
11	94.58	10.00	0.0052	92.7	80.00	0.0018	65.3
12	92.14	10.00	0.0052	92.7	79.00	0.0019	67.9
RO	4.44	64.00	0.0004	7.5	194.00	0.0000	0.6
RO	4.44	64.00	0.0004	7.5	194.00	0.0000	0.6
Feed	1279.00	-54.00	0.101	1818	13.00	0.0269	952
Feed	1279.00	-54.00	0.101	1818	13.00	0.0269	952
PWP	6.65	49.00	0.0008	15.1	187.00	0.0000	0.9

Table 67: Pure Water Permeate Flow Conditions - Test 6

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200	195	30	0.9
B	0.65	200	195		
C	0.65	200	195		
D	0.65	200	195		

Table 68: Product Rate Flow Conditions - Test 6

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200	195	33	0.84
B	0.65	200	195		
C	0.68	200	195		
D	0.64	200	195		

Table 69: Synthetic Leachate Coupon Test - Test 7

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.29	840	84.91	5760	86.54
2	77.22	840	84.14	5760	85.49
3	77.39	840	85.42	5760	87.19
4	77.1	840	84.22	5760	85.35
5	77.18	840	84.39	5760	85.74
6	76.84	840	84.16	5760	85.03
7	77.44	840	85.46	5760	88.09
8	77.35	840	85.42	5760	87.07
9	76.6	840	84.22	5760	86.62
10	77.09	840	84.81	5760	90.12
11	79.39	840	86.84	5760	90.23
12	77.14	840	84.67	5760	89.09

Table 70: Synthetic Leachate Coupon Test - Test 7

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl^- mV	Cl^- M	Cl^- mg/l
1	278.40	-17.00	0.0082	147.2	59.00	0.0034	122
2	280.10	-17.00	0.0082	147.2	59.00	0.0034	122
3	433.10	-17.00	0.0082	147.2	50.00	0.0049	174
4	260.60	-17.00	0.0082	147.2	63.00	0.0029	104
5	286.80	-17.00	0.0082	147.2	60.00	0.0033	117
6	254.60	-17.00	0.0082	147.2	64.00	0.0028	100
7	315.20	-17.00	0.0082	147.2	55.00	0.0040	142
8	262.30	-17.00	0.0082	147.2	64.00	0.0028	100
9	368.60	-17.00	0.0082	147.2	52.00	0.0045	160
10	516.50	-17.00	0.0082	147.2	49.00	0.0051	181
11	428.50	-17.00	0.0082	147.2	46.00	0.0057	203
12	502.30	-17.00	0.0082	147.2	44.00	0.0062	220
RO	4.69	64.00	0.0001	1.9	198.00	0.0000	0.5
RO	4.69	64.00	0.0001	1.9	198.00	0.0000	0.5
Feed	2839.00	-54.00	0.0590	1061	11.00	0.0228	808
Feed	2839.00	-54.00	0.0590	1061	11.00	0.0228	808
PWP	7.02	49.00	0.0002	4.3	182.00	0.0000	0.9

Table 71: Pure Water Permeate Flow Condition - Test 7

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	110	105	26	0.98
B	0.66	110	105		
C	0.66	110	105		
D	0.65	110	105		

Table 72: Product Rate Flow Conditions - Test 7

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	110	105	29	0.92
B	0.68	110	105		
C	0.65	110	105		
D	0.6	110	105		

Table 73: Synthetic Leachate Coupon Test - Test 8

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.29	720	91.95	3000	89.62
2	77.24	720	90.5	3000	88.43
3	77.38	720	92.74	3000	89.52
4	77.14	720	90.49	3000	88.11
5	77.19	720	91.01	3000	88.69
6	76.89	720	90.79	3000	87.88
7	77.44	720	92.95	3000	90.64
8	77.35	720	92.83	3000	90.31
9	76.6	720	91.43	3000	89.64
10	77.11	720	92.08	3000	91.65
11	79.4	720	93.89	3000	89.63
12	77.14	720	91.72	3000	90.64

Table 74: Synthetic Leachate Coupon Test - Test 8

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	132.50	12.00	0.0048	86.1	66.00	0.0032	114
2	132.80	12.00	0.0048	86.1	70.00	0.0027	97.4
3	234.90	12.00	0.0048	86.1	55.00	0.0050	177
4	138.20	12.00	0.0048	86.1	68.00	0.0030	105
5	146.20	12.00	0.0048	86.1	67.00	0.0031	109
6	133.50	12.00	0.0048	86.1	71.00	0.0026	93.6
7	144.80	12.00	0.0048	86.1	66.00	0.0032	114
8	130.40	12.00	0.0048	86.1	73.00	0.0024	86.4
9	192.20	12.00	0.0048	86.1	58.00	0.0044	157
10	245.40	12.00	0.0048	86.1	47.00	0.0069	244
11	222.40	12.00	0.0048	86.1	53.00	0.0054	192
12	236.70	12.00	0.0048	86.1	52.00	0.0056	200
RO	5.15	112.00	0.0000	0.1	189.00	0.0000	0.83
RO	5.15	112.00	0.0000	0.1	189.00	0.0000	0.83
Feed	3292.00	-43.00	0.1402	2522	-6.00	0.0575	2036
Feed	3292.00	-43.00	0.1402	2522	-6.00	0.0575	2036
PWP	9.58	110.00	0.0000	0.2	154.00	0.0001	3.38

Table 75: Pure Water Permeate Flow Conditions - Test 8

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	190.0	185.0	32	0.86
B	0.66	190.0	185.0		
C	0.64	190.0	185.0		
D	0.65	190.0	185.0		

Table 76: Product Rate Flow Conditions - Test 8

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200.0	190.0	34	0.82
B	0.65	200.0	190.0		
C	0.66	200.0	190.0		
D	0.64	200.0	190.0		

Table 77: Synthetic Leachate Coupon Test - Test 9

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.31	1020	83.86	8940	83.77
2	77.22	1020	83.24	8940	83.00
3	77.39	1020	84.25	8940	84.75
4	77.11	1020	83.34	8940	83.03
5	77.2	1020	83.44	8940	83.16
6	76.89	1020	83.21	8940	82.33
7	77.44	1020	84.37	8940	85.38
8	77.35	1020	84.37	8940	84.79
9	76.6	1020	83.21	8940	84.70
10	77.09	1020	83.75	8940	90.74
11	79.4	1020	85.87	8940	86.11
12	77.15	1020	83.61	8940	87.12

Table 78: Synthetic Leachate Coupon Test - Test 9

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	315.80	-2.00	0.0075	134.60	44.00	0.0069	242.91
2	314.90	-2.00	0.0075	134.60	43.00	0.0071	253.30
3	461.10	-2.00	0.0075	134.60	34.00	0.0104	369.32
4	285.00	-2.00	0.0075	134.60	46.00	0.0063	223.38
5	327.90	-2.00	0.0075	134.60	42.00	0.0075	264.14
6	326.50	-2.00	0.0075	134.60	45.00	0.0066	232.94
7	375.00	-2.00	0.0075	134.60	38.00	0.0088	312.33
8	283.10	-2.00	0.0075	134.60	49.00	0.0056	196.99
9	388.90	-2.00	0.0075	134.60	38.00	0.0088	312.33
10	529.70	-2.00	0.0075	134.60	29.00	0.0128	455.40
11	464.20	-2.00	0.0075	134.60	33.00	0.0109	385.13
12	518.00	-2.00	0.0075	134.60	32.00	0.0113	401.61
RO	8.90	137.00	0.0000	0.18	183.00	0.0000	0.72
RO	8.90	138.00	0.0000	0.17	183.00	0.0000	0.72
Feed	2271.00	-39.00	0.0434	780.39	3.00	0.0382	1353.67
Feed	2406.00	-39.00	0.0434	780.39	-4.00	0.512	1815.06
PWP	10.04	113.00	0.0000	0.57	180.00	0.0000	0.81

Table 79: Pure Water Permeate Flow Conditions - Test 9

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	75.0	73.0	25	1
B	0.67	75.0	73.0		
C	0.65	75.0	73.0		
D	0.65	75.0	73.0		

Table 80: Product Rate Flow Conditions - Test 9

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.68	75.0	73.0	28	0.94
B	0.64	75.0	73.0		
C	0.65	75.0	73.0		
D	0.65	75.0	73.0		

Table 81: Synthetic Leachate Coupon Test - Test 10

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.24	240	82.94	1380	94.98
2	77.34	240	82.55	1380	93.46
3	76.79	240	82.72	1380	94.44
4	77.39	240	82.7	1380	93.12
5	77.2	240	82.67	1380	93.83
6	76.81	240	82.35	1380	93.51
7	77.2	240	83.14	1380	95.96
8	77.55	240	83.61	1380	96.32
9	77.18	240	82.91	1380	94.69
10	77.24	240	82.9	1380	96.13
11	77.15	240	82.71	1380	94.36
12	77.3	240	82.79	1380	95.37

Table 82: Synthetic Leachate Coupon Test - Test 10

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	100.10	20.00	0.0026	47.34	86.00	0.0012	41.80
2	107.60	20.00	0.0026	47.34	86.00	0.0012	41.80
3	171.60	20.00	0.0026	47.34	70.00	0.0023	81.72
4	105.10	20.00	0.0026	47.34	88.00	0.0011	38.44
5	107.30	20.00	0.0026	47.34	86.00	0.0013	41.80
6	98.12	20.00	0.0026	47.34	90.00	0.0010	35.35
7	105.20	20.00	0.0026	47.34	82.00	0.0014	49.43
8	101.40	20.00	0.0026	47.34	88.00	0.0011	38.44
9	138.50	20.00	0.0026	47.34	76.00	0.0018	63.55
10	172.60	20.00	0.0026	47.34	65.00	0.0028	100.76
11	153.60	20.00	0.0026	47.34	70.00	0.0023	81.72
12	158.90	20.00	0.0026	47.34	68.00	0.0025	88.86
RO	4.56	137.00	0.0000	0.18	202.00	0.0000	0.32
RO	4.56	137.00	0.0000	0.18	202.00	0.0000	0.32
Feed	2259.00	-41.00	0.0477	858.16	-19.00	0.096	3402.87
Feed	2259.00	-41.00	0.0477	858.16	-19.00	0.096	3402.87
PWP	9.07	95.00	0.0001	1.34	172.00	0.0000	1.14

Table 83: Pure Water Permeate Flow Conditions - Test 10

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	225.0	220.0	33	0.84
B	0.65	225.0	220.0		
C	0.62	225.0	220.0		
D	0.65	225.0	220.0		

Table 84: Product Rate Flow Conditions - Test 10

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	225.0	220.0	36	0.79
B	0.67	225.0	220.0		
C	0.64	225.0	220.0		
D	0.64	225.0	220.0		

Table 85: Synthetic Leachate Coupon Test - Test 11

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.3	300	81.7	1080	87.36
2	77.36	300	81.4	1080	86.67
3	76.8	300	81.39	1080	87.14
4	77.4	300	81.56	1080	86.51
5	77.18	300	81.43	1080	86.82
6	76.82	300	81.13	1080	86.51
7	77.21	300	81.84	1080	88.14
8	77.57	300	82.32	1080	88.43
9	77.17	300	81.65	1080	87.43
10	77.24	300	81.71	1080	88.14
11	77.15	300	81.5	1080	87.19
12	77.3	300	81.61	1080	87.75

Table 86: Synthetic Leachate Coupon Test - Test 11

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	60.15	20.00	3.2E-03	57.85	99.00	9.9E-04	35.07
2	62.57	20.00	3.2E-03	57.85	100.00	9.5E-04	33.73
3	93.36	20.00	3.2E-03	57.85	82.00	1.9E-03	68.05
4	63.79	20.00	3.2E-03	57.85	98.00	1.0E-03	36.46
5	66.32	20.00	3.2E-03	57.85	94.00	1.2E-03	42.62
6	65.91	20.00	3.2E-03	57.85	98.00	1.0E-03	36.46
7	61.45	20.00	3.2E-03	57.85	86.00	1.6E-03	58.22
8	61.85	20.00	3.2E-03	57.85	88.00	1.5E-03	53.85
9	82.89	20.00	3.2E-03	57.85	75.00	2.5E-03	89.41
10	93.35	20.00	3.2E-03	57.85	64.00	3.9E-03	137.31
11	86.46	20.00	3.2E-03	57.85	69.00	3.2E-03	112.99
12	87.52	20.00	3.2E-03	57.85	68.00	3.3E-03	117.48
RO	4.66	131.00	2.0E-05	0.37	206.00	1.5E-05	0.54
RO	4.66	131.00	2.0E-05	0.37	206.00	1.5E-05	0.54
Feed	1445.00	-40.00	5.0E-02	892.31	12.00	2.9E-02	1043.43
Feed	1445.00	-40.00	5.0E-02	892.31	12.00	2.9E-02	1043.43
PWP	7.00	92.00	1.2E-04	2.17	154.00	1.2E-04	4.11

Table 87: Pure Water Permeate Flow Conditions - Test 11

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.69	155.0	150.0	30	0.9
B	0.64	155.0	150.0		
C	0.64	155.0	150.0		
D	0.65	155.0	150.0		

Table 88: Product Rate Flow Conditions - Test 11

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	34	0.82
B	0.65	150.0	145.0		
C	0.62	150.0	145.0		
D	0.67	150.0	145.0		

Table 89: Synthetic Leachate Coupon Test - Test 12

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.27	360	82.31	2100	84.41
2	77.22	360	81.84	2100	84.45
3	77.39	360	82.63	2100	85.65
4	77.1	360	81.89	2100	85.11
5	77.17	360	82.03	2100	84.78
6	76.89	360	81.84	2100	84.32
7	77.44	360	82.73	2100	86.26
8	77.36	360	82.84	2100	85.94
9	76.61	360	81.76	2100	84.81
10	77.09	360	82.2	2100	86.61
11	79.4	360	84.41	2100	87.85
12	77.15	360	82.1	2100	85.98

Table 90: Synthetic Leachate Coupon Test - Test 12

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	157.60	21.00	3.1E-03	55.27	55.00	2.6E-03	90.47
2	167.20	21.00	3.1E-03	55.27	53.00	2.8E-03	97.81
3	302.40	21.00	3.1E-03	55.27	40.00	4.6E-03	162.40
4	168.50	21.00	3.1E-03	55.27	51.00	3.0E-03	105.75
5	165.70	21.00	3.1E-03	55.27	52.00	2.9E-03	101.70
6	149.90	21.00	3.1E-03	55.27	61.00	2.0E-03	71.60
7	176.70	21.00	3.1E-03	55.27	48.00	3.4E-03	118.87
8	154.30	21.00	3.1E-03	55.27	55.00	2.6E-03	90.47
9	224.60	21.00	3.1E-03	55.27	46.00	3.6E-03	128.51
10	317.50	21.00	3.1E-03	55.27	33.00	6.0E-03	213.37
11	270.70	21.00	3.1E-03	55.27	38.00	5.0E-03	175.57
12	291.50	21.00	3.1E-03	55.27	37.00	5.1E-03	182.55
RO	4.50	144.00	1.1E-05	0.20	178.00	2.1E-05	0.75
RO	4.50	144.00	1.1E-05	0.20	178.00	2.1E-05	0.75
Feed	3283.00	-37.00	4.3E-02	778.22	-12.00	3.5E-02	1234.02
Feed	3449.00	-37.00	4.3E-02	778.22	-13.00	3.6E-02	1283.10
PWP	10.74	115.00	4.2E-05	0.76	128.00	1.5E-04	5.25

Table 91: Pure Water Permeate Flow Conditions - Test 12

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	160.0	155.0	28	0.94
B	0.67	160.0	155.0		
C	0.67	160.0	155.0		
D	0.64	160.0	155.0		

Table 92: Product Rate Flow Conditions - Test 12

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	31	0.88
B	0.65	150.0	145.0		
C	0.7	150.0	145.0		
D	0.67	150.0	145.0		

Table 93: Synthetic Leachate Coupon Test - Test 13

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.26	600	85.37	2040	89.38
2	77.21	600	84.65	2040	88.30
3	77.39	600	88.73	2040	89.69
4	77.09	600	84.76	2040	88.01
5	77.19	600	84.97	2040	88.68
6	76.89	600	84.8	2040	88.32
7	77.35	600	85.9	2040	90.68
8	77.44	600	86.26	2040	90.51
9	76.6	600	84.8	2040	88.85
10	77.08	600	85.2	2040	90.57
11	79.4	600	87.36	2040	91.70
12	77.14	600	85.01	2040	89.89

Table 94: Synthetic Leachate Coupon Test - Test 13

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	77.43	43.00	1.7E-03	31.34	63.00	2.0E-03	69.53
2	77.76	43.00	1.7E-03	31.34	64.00	1.9E-03	66.78
3	137.10	43.00	1.7E-03	31.34	50.00	3.3E-03	117.57
4	76.73	43.00	1.7E-03	31.34	66.00	1.7E-03	61.60
5	80.07	43.00	1.7E-03	31.34	63.00	2.0E-03	69.53
6	74.61	43.00	1.7E-03	31.34	68.00	1.6E-03	56.81
7	81.43	43.00	1.7E-03	31.34	60.00	2.2E-03	78.49
8	70.10	43.00	1.7E-03	31.34	68.00	1.6E-03	56.81
9	108.40	43.00	1.7E-03	31.34	55.00	2.7E-03	96.06
10	140.60	43.00	1.7E-03	31.34	44.00	4.2E-03	149.81
11	123.00	43.00	1.7E-03	31.34	49.00	3.5E-03	122.41
12	125.20	43.00	1.7E-03	31.34	47.00	3.7E-03	132.71
RO	5.07	160.00	1.7E-05	0.30	180.00	1.7E-05	0.62
RO	5.07	160.00	1.7E-05	0.30	180.00	1.7E-05	0.62
Feed	2038.00	-16.00	1.8E-02	326.14	-11.00	3.9E-02	1382.15
Feed	2038.00	-16.00	1.8E-02	326.14	-11.00	3.9E-02	1382.15
PWP	9.53	133.00	4.9E-05	0.88	172.00	2.4E-05	0.85

Table 95: Pure Water Permeate Flow Conditions - Test 13

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	29	0.92
B	0.65	150.0	145.0		
C	0.66	150.0	145.0		
D	0.65	150.0	145.0		

Table 96: Product Rate Flow Conditions - Test 13

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	32	0.86
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.65	150.0	145.0		

Table 97: Synthetic Leachate Coupon Test - Test 14

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.27	360	82.44	2280	90.53
2	77.4	360	82.13	2280	89.43
3	77.22	360	82.58	2280	90.58
4	77.11	360	81.99	2280	89.04
5	77.19	360	82.21	2280	89.85
6	76.9	360	81.95	2280	89.43
7	77.45	360	82.1	2280	91.89
8	77.36	360	82.98	2280	91.95
9	76.61	360	81.83	2280	90.14
10	77.1	360	82.26	2280	92.03
11	79.41	360	84.49	2280	92.90
12	77.16	360	82.18	2280	91.17

Table 98: Synthetic Leachate Coupon Test - Test 14

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	116.90	17.00	4.6E-03	83.40	59.00	2.5E-03	86.99
2	123.60	17.00	4.6E-03	83.40	60.00	2.4E-03	83.66
3	187.60	17.00	4.6E-03	83.40	47.00	3.9E-03	138.91
4	123.80	17.00	4.6E-03	83.40	60.00	2.4E-03	83.66
5	129.30	17.00	4.6E-03	83.40	58.00	2.6E-03	90.45
6	117.80	17.00	4.6E-03	83.40	63.00	2.1E-03	74.43
7	132.40	17.00	4.6E-03	83.40	56.00	2.8E-03	97.79
8	117.00	17.00	4.6E-03	83.40	62.00	2.2E-03	77.39
9	161.60	17.00	4.6E-03	83.40	51.00	3.4E-03	118.84
10	201.00	17.00	4.6E-03	83.40	41.00	5.0E-03	175.53
11	185.40	17.00	4.6E-03	83.40	46.00	4.1E-03	144.43
12	185.60	17.00	4.6E-03	83.40	45.00	4.2E-03	150.17
RO	5.22	160.00	1.9E-05	0.34	179.00	2.3E-05	0.81
RO	5.00	160.00	1.9E-05	0.34	179.00	2.3E-05	0.81
Feed	2399.00	-45.00	5.0E-02	901.83	-10.00	3.6E-02	1282.79
Feed	2398.00	-45.00	5.0E-02	901.83	-12.00	3.9E-02	1386.86
PWP	13.97	128.00	6.5E-05	1.17	164.00	4.1E-05	1.45

Table 99: Pure Water Permeate Flow Conditions - Test 14

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	155.0	150.0	28	0.94
B	0.65	155.0	150.0		
C	0.65	155.0	150.0		
D	0.65	155.0	150.0		

Table 100: Product Rate Flow Conditions - Test 14

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	155.0	150.0	32	0.86
B	0.65	155.0	150.0		
C	0.64	155.0	150.0		
D	0.65	155.0	150.0		

Table 101: Synthetic Leachate Coupon Test - Test 15

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.29	420	83.84	2220	91.06
2	77.34	420	83.42	2220	90.00
3	76.8	420	83.65	2220	90.68
4	77.39	400	83.22	2220	89.89
5	77.18	417	83.54	2220	90.32
6	76.82	420	83.31	2220	89.85
7	78.67	450	86.18	2220	93.58
8	77.56	420	84.8	2220	92.58
9	77.19	420	83.85	2220	90.97
10	77.24	420	83.95	2220	92.32
11	77.15	420	83.72	2220	90.93
12	77.3	420	83.74	2220	91.60

Table 102: Synthetic Leachate Coupon Test - Test 15

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	115.20	25.00	3.4E-03	61.34	83.00	9.6E-04	34.12
2	115.50	25.00	3.4E-03	61.34	82.00	1.0E-03	35.47
3	169.90	25.00	3.4E-03	61.34	69.00	1.7E-03	58.90
4	117.30	25.00	3.4E-03	61.34	82.00	1.0E-03	35.47
5	119.20	25.00	3.4E-03	61.34	81.00	1.0E-03	36.88
6	108.60	25.00	3.4E-03	61.34	85.00	8.9E-04	31.56
7	123.90	25.00	3.4E-03	61.34	77.00	1.2E-03	43.11
8	107.60	25.00	3.4E-03	61.34	84.00	9.3E-04	32.81
9	148.70	25.00	3.4E-03	61.34	72.00	1.5E-03	52.39
10	190.60	25.00	3.4E-03	61.34	60.00	2.4E-03	83.66
11	167.70	25.00	3.4E-03	61.34	63.00	2.1E-03	74.43
12	168.50	25.00	3.4E-03	61.34	64.00	2.0E-03	71.58
RO	6.55	160.00	1.9E-05	0.34	176.00	2.6E-05	0.91
RO	7.00	160.00	1.9E-05	0.34	176.00	2.6E-05	0.91
Feed	2490.00	-42.00	4.5E-02	803.70	6.00	1.9E-02	687.32
Feed	2539.00	-42.00	4.5E-02	803.70	5.00	2.0E-02	714.65
PWP	21.39	127.00	6.8E-05	1.22	166.00	3.8E-05	1.34

Table 103: Pure Water Permeate Flow Conditions - Test 15

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.62	150.0	145.0	33	0.84
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.68	150.0	145.0		

Table 104: Product Rate Flow Conditions - Test 15

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	32	0.86
B	0.66	150.0	145.0		
C	0.64	150.0	145.0		
D	0.65	150.0	145.0		

Table 105: Synthetic Leachate Coupon Test - Test 16

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.3	540	84.21	2580	86.67
2	77.39	540	83.81	2580	85.97
3	77.21	540	84.38	2580	86.76
4	77.1	540	83.71	2580	85.67
5	77.18	540	83.94	2580	86.27
6	76.89	540	83.72	2580	85.70
7	77.43	540	84.76	2580	87.87
8	77.34	540	84.88	2580	87.59
9	76.6	540	86.65	2580	86.28
10	77.08	540	84.08	2580	88.23
11	79.39	540	86.25	2580	89.37
12	77.13	540	83.91	2580	87.50

Table 106: Synthetic Leachate Coupon Test - Test 16

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	116.60	22.00	3.8E-03	68.83	46.00	4.1E-03	144.43
2	118.00	22.00	3.8E-03	68.83	47.00	3.9E-03	138.91
3	177.70	22.00	3.8E-03	68.83	34.00	6.5E-03	230.63
4	116.20	22.00	3.8E-03	68.83	47.00	3.9E-03	138.91
5	124.60	22.00	3.8E-03	68.83	45.00	4.2E-03	150.17
6	109.90	22.00	3.8E-03	68.83	50.00	3.5E-03	123.57
7	125.10	22.00	3.8E-03	68.83	42.00	4.8E-03	168.81
8	108.00	22.00	3.8E-03	68.83	49.00	3.6E-03	128.48
9	147.70	22.00	3.8E-03	68.83	39.00	5.4E-03	189.77
10	192.70	22.00	3.8E-03	68.83	58.00	2.6E-03	90.45
11	172.00	22.00	3.8E-03	68.83	32.00	7.0E-03	249.33
12	177.30	22.00	3.8E-03	68.83	31.00	7.3E-03	259.25
RO	4.99	138.00	4.4E-05	0.80	178.00	2.4E-05	0.84
RO	4.99	138.00	4.4E-05	0.80	178.00	2.4E-05	0.84
Feed	2108.00	-36.00	3.5E-02	638.31	-18.00	4.9E-02	1752.50
Feed	2139.00	-39.00	4.0E-02	716.25	-20.00	5.3E-02	1894.66
PWP	12.96	99.00	2.0E-04	3.58	165.00	3.9E-05	1.39

Table 107: Pure Water Permeate Flow Conditions - Test 16

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	27	0.96
B	0.65	150.0	145.0		
C	0.64	150.0	145.0		
D	0.65	150.0	145.0		

Table 108: Product Rate Flow Conditions - Test 16

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	145.0	140.0	31	0.88
B	0.65	145.0	140.0		
C	0.65	145.0	140.0		
D	0.67	145.0	140.0		

Table 109: Synthetic Leachate Coupon Test - Test 17

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.35	480	83.43	1980	88.47
2	77.23	480	82.95	1980	87.42
3	77.39	480	83.87	1980	88.92
4	77.1	480	82.97	1980	87.24
5	77.19	480	83.15	1980	87.97
6	76.89	480	82.99	1980	87.45
7	77.44	480	83.97	1980	89.57
8	77.35	480	84.05	1980	89.42
9	76.61	480	82.96	1980	87.96
10	79.41	480	85.69	1985	92.03
11	77.1	480	83.24	1983	88.38
12	77.15	480	83.28	1980	89.06

Table 110: Synthetic Leachate Coupon Test - Test 17

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	106.50	22.00	2.9E-03	52.81	82.00	1.9E-03	68.05
2	109.40	22.00	2.9E-03	52.81	83.00	1.8E-03	65.45
3	182.20	22.00	2.9E-03	52.81	68.00	3.3E-03	117.48
4	101.60	22.00	2.9E-03	52.81	84.00	1.8E-03	62.95
5	108.70	22.00	2.9E-03	52.81	80.00	2.1E-03	73.57
6	105.20	22.00	2.9E-03	52.81	81.00	2.0E-03	70.76
7	115.00	22.00	2.9E-03	52.81	74.00	2.6E-03	92.97
8	104.70	22.00	2.9E-03	52.81	81.00	2.0E-03	70.76
9	154.00	22.00	2.9E-03	52.81	68.00	3.3E-03	117.48
10	202.80	22.00	2.9E-03	52.81	57.00	5.1E-03	180.42
11	174.60	22.00	2.9E-03	52.81	62.00	4.2E-03	148.45
12	189.80	22.00	2.9E-03	52.81	60.00	4.5E-03	160.50
RO	4.66	131.00	2.0E-05	0.37	192.00	2.6E-05	0.93
RO	4.66	131.00	2.0E-05	0.37	192.00	2.6E-05	0.93
Feed	2242.00	-39.00	4.7E-02	852.53	6.00	3.7E-02	1318.53
Feed	2409.00	-39.00	4.7E-02	852.53	7.00	3.6E-02	1268.09
PWP	6.87	93.00	1.2E-04	2.07	175.00	5.1E-05	1.81

Table 111: Pure Water Permeate Flow Conditions - Test 17

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	27	0.96
B	0.65	150.0	145.0		
C	0.68	150.0	145.0		
D	0.65	150.0	145.0		

Table 112: Product Rate Flow Conditions - Test 17

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	31	0.88
B	0.65	150.0	145.0		
C	0.66	150.0	145.0		
D	0.65	150.0	145.0		

Table 113: Synthetic Leachate Coupon Test - Test 18

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.25	780	87.62	2160	90.03
2	77.23	780	86.72	2160	88.81
3	77.39	780	88.08	2160	90.29
4	77.11	780	86.9	2160	88.58
5	77.19			2160	89.32
6	76.89	780	86.98	2160	88.94
7	77.34	780	88.22	2160	91.22
8	77.43	780	88.64	2160	91.13
9	76.6	780	87.08	2160	89.47
10	77.09	780	87.44	2160	91.38
11	79.4	780	89.61	2160	92.31
12	77.14	780	87.2	2160	90.62

Table 114: Synthetic Leachate Coupon Test - Test 18

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	115.30	24.00	3.5E-03	62.91	57.00	2.3E-03	83.10
2	115.70	24.00	3.5E-03	62.91	61.00	2.0E-03	70.50
3	181.40	24.00	3.5E-03	62.91	46.00	3.7E-03	130.60
4	110.70	24.00	3.5E-03	62.91	62.00	1.9E-03	67.66
5	118.80	24.00	3.5E-03	62.91	59.00	2.2E-03	76.54
6	108.50	24.00	3.5E-03	62.91	63.00	1.8E-03	64.94
7	114.90	24.00	3.5E-03	62.91	57.00	2.3E-03	83.10
8	104.90	24.00	3.5E-03	62.91	62.00	1.9E-03	67.66
9	148.20	24.00	3.5E-03	62.91	52.00	2.9E-03	102.05
10	182.10	24.00	3.5E-03	62.91	41.00	4.5E-03	160.39
11	160.70	24.00	3.5E-03	62.91	47.00	3.5E-03	125.34
12	168.40	24.00	3.5E-03	62.91	44.00	4.0E-03	141.78
RO	6.10	142.00	2.0E-05	0.36	173.00	2.0E-05	0.71
RO	6.10	142.00	2.0E-05	0.36	173.00	2.0E-05	0.71
Feed	2185.00	-39.00	5.5E-02	993.42	-11.00	3.8E-02	1359.41
Feed	2232.00	-39.00	5.5E-02	993.42	-11.00	3.8E-02	1359.41
PWP	16.13	128.00	3.7E-05	0.66	163.00	3.0E-05	1.07

Table 115: Pure Water Permeate Flow Conditions - Test 18

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	150.0	145.0	29	0.92
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.65	150.0	145.0		

Table 116: Product Rate Flow Conditions - Test 18

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	145.0	140.0	32	0.86
B	0.65	145.0	140.0		
C	0.65	145.0	140.0		
D	0.64	145.0	140.0		

Table 117: Synthetic Leachate Coupon Test - Test 19

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.29	420	82.87	2100	88.02
2	77.35	420	82.51	2100	87.21
3	76.79	420	82.64	2100	87.78
4	77.39	420	82.74	2100	87.05
5	77.17	420	82.65	2100	87.38
6	76.82	420	82.27	2100	86.89
7	77.19	420	83.12	2100	88.93
8	77.55	420	83.66	2100	88.81
9	77.17	420	82.85	2100	88.41
10	77.24	420	82.92	2100	89.23
11	77.14	420	82.66	2100	89.01
12	77.29	420	82.75	2100	88.63

Table 118: Synthetic Leachate Coupon Test - Test 19

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	97.07	33.00	2.6E-03	46.62	65.00	1.8E-03	64.14
2	100.00	33.00	2.6E-03	46.62	64.00	1.9E-03	66.78
3	156.60	33.00	2.6E-03	46.62	50.00	3.3E-03	117.57
4	100.20	33.00	2.6E-03	46.62	63.00	2.0E-03	69.53
5	101.90	33.00	2.6E-03	46.62	62.00	2.0E-03	72.40
6	91.55	33.00	2.6E-03	46.62	67.00	1.7E-03	59.16
7	103.80	33.00	2.6E-03	46.62	59.00	2.3E-03	81.73
8	94.47	33.00	2.6E-03	46.62	66.00	1.7E-03	61.60
9	124.70	33.00	2.6E-03	46.62	55.00	2.7E-03	96.06
10	166.20	33.00	2.6E-03	46.62	45.00	4.1E-03	143.88
11	145.60	33.00	2.6E-03	46.62	48.00	3.6E-03	127.46
12	152.70	33.00	2.6E-03	46.62	46.00	3.9E-03	138.19
RO	4.10	160.00	1.7E-05	0.30	180.00	1.7E-05	0.62
RO	4.10	160.00	1.7E-05	0.30	180.00	1.7E-05	0.62
Feed	2130.00	-30.00	3.2E-02	568.58	-9.00	3.6E-02	1274.87
Feed	2130.00	-30.00	3.2E-02	568.58	-9.00	3.6E-02	1274.87
PWP	8.48	121.00	7.9E-05	1.42	143.00	7.7E-05	2.75

Table 119: Pure Water Permeate Flow Conditions - Test 19

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	145.0	140.0	30	0.9
B	0.65	145.0	140.0		
C	0.65	145.0	140.0		
D	0.65	145.0	140.0		

Table 120: Product Rate Flow Conditions - Test 19

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.69	150.0	145.0	32	0.86
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.65	150.0	145.0		

Table 121: Synthetic Leachate Coupon Test - Test 20

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass	PR Sample Time (s)	PR Final Mass
1	77.26	360	82.75	1920	86.91
2	77.36	360	82.42	1920	86.17
3	76.8	360	82.49	1920	86.53
4	77.49	360	82.6	1920	86.14
5	77.14	360	82.57	1920	86.45
6	76.82	360	82.21	1920	86.06
7	78.67	360	84.5	1920	89.15
8	77.56	360	83.56	1920	88.03
9	77.17	360	82.69	1920	86.99
10	77.24	360	82.8	1920	88.08
11	77.15	360	85.58	1920	87.03
12	77.29	360	82.64	1920	87.53

Table 122: Synthetic Leachate Coupon Test - Test 20

Cell	TOC mg/l	NH_3 mV	NH_3 M	NH_3 mg/l	Cl- mV	Cl- M	Cl- mg/l
1	93.77	32.00	2.6E-03	46.88	63.00	2.1E-03	74.43
2	97.14	32.00	2.6E-03	46.88	64.00	2.0E-03	71.58
3	144.90	32.00	2.6E-03	46.88	51.00	3.4E-03	118.84
4	96.72	32.00	2.6E-03	46.88	53.00	3.1E-03	109.92
5	98.21	32.00	2.6E-03	46.88	53.00	3.1E-03	109.92
6	88.25	32.00	2.6E-03	46.88	67.00	1.8E-03	63.68
7	103.30	32.00	2.6E-03	46.88	59.00	2.5E-03	86.99
8	87.85	32.00	2.6E-03	46.88	64.00	2.0E-03	71.58
9	124.40	32.00	2.6E-03	46.88	58.00	2.6E-03	90.45
10	161.80	32.00	2.6E-03	46.88	43.00	4.6E-03	162.36
11	141.60	32.00	2.6E-03	46.88	49.00	3.6E-03	128.48
12	144.80	32.00	2.6E-03	46.88	51.00	3.4E-03	118.84
RO	5.90	138.00	4.4E-05	0.80	178.00	2.4E-05	0.84
RO	5.90	138.00	4.4E-05	0.80	178.00	2.4E-05	0.84
Feed	2125.00	-35.00	3.4E-02	614.26	-9.00	3.5E-02	1233.73
Feed	2141.00	-35.00	3.4E-02	614.26	-10.00	3.6E-02	1282.79
PWP	14.09	99.00	2.0E-04	3.58	161.00	4.6E-05	1.63

Table 123: Pure Water Permeate Flow Conditions - Test 20

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	31	0.88
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.64	150.0	145.0		

Table 124: Product Rate Flow Conditions - Test 20

	Flowrate	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150.0	145.0	32	0.86
B	0.65	150.0	145.0		
C	0.65	150.0	145.0		
D	0.65	150.0	145.0		

Table 125: Real Leachate Coupon Tests - Test 1

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.26	840	88.62	1380	95.75
2	77.36	840	88.43	1380	95.37
3	76.81	840	89.54	1380	97.35
4	77.40	840	87.89	1380	94.46
5	77.20	840	89.36	1380	97.21
6	76.82	840	87.25	1380	93.28
7	77.44	840	90.09	1380	98.20
8	77.57	840	89.14	1380	96.55
9	77.17	840	89.34	1380	96.93
10	77.25	840	90.02	1380	98.16
11	77.15	840	88.49	1380	95.56
12	77.31	840	89.08	1380	96.59

Table 126: Real Leachate Coupon Test Results - Test 1

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	0.54	56	15.4	170	4.5
2	0.49	56	15.4	163	6.0
3	0.53	56	15.4	149	10.8
4	0.48	56	15.4	170	4.5
5	0.40	56	15.4	169	4.7
6	0.52	56	15.4	159	7.1
7	0.44	56	15.4	161	6.5
8	0.49	56	15.4	158	7.4
9	0.44	56	15.4	156	8.1
10	0.39	56	15.4	166	5.3
11	0.43	56	15.4	168	4.9
12	0.39	56	15.4	164	5.8
RO	0.03	137	0.7	207	1.0
RO	0.03	138	0.6	207	1.0
Feed	40.94	5	112.6	70	295.7
Feed	40.96	5	112.6	70	295.7
PWP	0.08	113	1.7	212	0.8

Table 127: Pure Water Permeate Flow Conditions - Test 1

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	150	146	28	0.94
B	0.66	150	146		
C	0.64	150	146		
D	0.64	150	146		

Table 128: Product Rate Flow Conditions - Test 1

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	155	150	30	0.90
B	0.64	155	150		
C	0.65	155	150		
D	0.65	155	150		

Table 129: Real Leachate Coupon Tests - Test 2

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.25	420	84.89	1260	101.40
2	77.34	420	84.84	1260	100.99
3	76.79	420	85.46	1260	104.01
4	77.38	420	84.56	1260	99.76
5	77.18	420	85.49	1260	103.34
6	76.81	420	83.90	1260	99.02
7	77.43	420	85.87	1260	104.38
8	77.55	420	85.43	1260	102.41
9	77.17	420	85.33	1260	102.88
10	77.23	420	85.87	1260	104.88
11	77.14	420	84.85	1260	101.47
12	77.29	420	85.25	1260	102.83

Table 130: Real Leachate Coupon Test Results - Test 2

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	0.99	56	15.4	179	3.1
2	0.92	56	15.4	173	4.0
3	1.07	56	15.4	163	6.0
4	0.96	56	15.4	178	3.2
5	0.88	56	15.4	182	2.7
6	0.96	56	15.4	165	5.5
7	0.93	56	15.4	173	4.0
8	1.00	56	15.4	170	4.5
9	0.99	56	15.4	167	5.1
10	0.88	56	15.4	179	3.1
11	0.94	56	15.4	176	3.5
12	0.91	56	15.4	176	3.5
RO	0.46	137	0.7	224	0.5
RO	0.46	138	0.6	224	0.5
Feed	57.83	5	112.6	72	272
Feed	57.83	5	112.6	72	272
PWP	0.29	113	1.7	210	0.8

Table 131: Pure Water Permeate Flow Conditions - Test 2

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	200	195	27	0.96
B	0.65	200	195		
C	0.65	200	195		
D	0.65	200	195		

Table 132: Product Rate Flow Conditions - Test 2

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	200	195	29	0.92
B	0.65	200	195		
C	0.65	200	195		
D	0.66	200	195		

Table 133: Real Leachate Coupon Tests - Test 3

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.29	720	87.48	1680	96.73
2	77.39	720	87.36	1680	96.43
3	76.83	720	88.43	1680	98.81
4	77.43	720	86.94	1680	95.52
5	77.21	720	88.32	1680	98.54
6	76.85	720	86.34	1680	94.56
7	77.47	720	88.78	1680	99.20
8	77.60	720	88.13	1680	97.61
9	77.21	720	88.21	1680	97.84
10	77.27	720	88.79	1680	98.74
11	77.18	720	87.51	1680	96.81
12	77.34	720	87.90	1680	97.75

Table 134: Real Leachate Coupon Test Results - Test 3

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	1.38	43	25.6	109	14.8
2	1.44	43	25.6	103	18.2
3	1.60	43	25.6	93	25.8
4	2.25	43	25.6	105	17.0
5	1.42	43	25.6	108	15.3
6	1.59	43	25.6	102	18.9
7	1.47	43	25.6	103	18.2
8	1.47	43	25.6	106	16.4
9	1.49	43	25.6	100	20.2
10	1.38	43	25.6	108	15.3
11	1.32	43	25.6	114	12.4
12	1.38	43	25.6	109	14.8
RO	0.42	146	0.5	174	1.5
RO	0.42	139	0.6	174	1.5
Feed	102.9	-16	255	15	393
Feed	102.9	-16	255	15	393
PWP	0.76	113	1.7	167	2.0

Table 135: Pure Water Permeate Flow Conditions - Test 3

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	150	145	28	0.94
B	0.65	150	145		
C	0.65	150	145		
D	0.65	150	145		

Table 136: Product Rate Flow Conditions - Test 3

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	150	145	28	0.94
B	0.67	150	145		
C	0.67	150	145		
D	0.65	150	145		

Table 137: Real Leachate Coupon Tests - Test 4

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.30	420	86.26	1140	96.56
2	77.38	420	86.29	1140	96.33
3	77.22	420	87.53	1140	98.84
4	77.10	420	85.59	1140	95.06
5	77.18	420	87.10	1140	98.24
6	76.89	420	85.44	1140	94.63
7	77.48	420	87.66	1140	98.79
8	77.34	420	86.83	1140	97.10
9	76.60	420	86.49	1140	97.08
10	77.07	420	87.27	1140	98.38
11	79.40	420	88.83	1140	99.00
12	77.14	420	86.81	1140	97.48

Table 138: Real Leachate Coupon Test Results - Test 4

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	1.43	47	21.9	126	5.9
2	1.39	47	21.9	126	5.9
3	1.57	47	21.9	110	11.2
4	1.45	47	21.9	127	5.7
5	1.39	47	21.9	126	5.9
6	1.51	47	21.9	118	8.2
7	1.43	47	21.9	119	7.8
8	1.46	47	21.9	120	7.5
9	1.51	47	21.9	118	8.2
10	1.32	47	21.9	127	5.7
11	1.36	47	21.9	127	5.7
12	1.38	47	21.9	126	5.9
RO	0.41	146	0.5	187	0.5
RO	0.41	139	0.6	187	0.5
Feed	107	-14	236	17	450
Feed	107	-14	236	17	450
PWP	0.57	113	1.7	173	0.9

Table 139: Pure Water Permeate Flow Conditions - Test 4

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	205	200	32	0.86
B	0.68	205	200		
C	0.68	205	200		
D	0.63	205	200		

Table 140: Product Rate Flow Conditions - Test 4

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.64	200	195	31	0.88
B	0.66	200	195		
C	0.65	200	195		
D	0.64	200	195		

Table 141: Real Leachate Coupon Tests - Test 5

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.25	720	86.01	2340	99.11
2	77.37	720	86.03	2340	98.75
3	77.21	720	87.29	2340	101.64
4	77.10	720	85.32	2340	97.61
5	77.18	720	86.93	2340	101.93
6	76.88	720	85.13	2340	96.69
7	77.44	720	87.34	2340	101.94
8	77.34	720	86.52	2340	100.00
9	76.60	720	86.06	2340	99.66
10	77.08	720	86.88	2340	101.24
11	79.40	720	88.32	2340	101.30
12	77.14	720	86.41	2340	99.84

Table 142: Real Leachate Coupon Test Results - Test 5

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.02	35	34.9	103	14.8
2	2.08	35	34.9	93	22.0
3	2.37	35	34.9	83	32.7
4	2.01	35	34.9	99	17.3
5	1.89	35	34.9	98	18.0
6	2.14	35	34.9	92	22.9
7	2.06	35	34.9	92	22.9
8	2.01	35	34.9	96	19.5
9	2.00	35	34.9	93	22.0
10	1.85	35	34.9	102	15.4
11	1.87	35	34.9	104	14.2
12	1.89	35	34.9	100	16.7
RO	0.43	146	0.5	197	0.4
RO	0.43	139	0.6	197	0.4
Feed	141.6	-23	336	11	570
Feed	141.6	-23	336	11	570
PWP	0.55	113	1.7	164	1.3

Table 143: Pure Water Permeate Flow Conditions - Test 5

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	125	120	28	0.94
B	0.65	125	120		
C	0.63	125	120		
D	0.65	125	120		

Table 144: Product Rate Flow Conditions - Test 5

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	125	120	30	0.90
B	0.65	125	120		
C	0.65	125	120		
D	0.64	125	120		

Table 145: Real Leachate Coupon Tests - Test 6

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.26	600	93.00	1200	106.91
2	77.38	600	92.95	1200	106.79
3	77.21	600	95.08	1200	109.68
4	77.10	600	91.91	1200	104.72
5	77.18	600	94.57	1200	109.35
6	76.88	600	91.74	1200	104.53
7	77.43	600	95.05	1200	109.84
8	77.35	600	93.55	1200	107.26
9	76.59	600	93.56	1200	107.71
10	77.08	600	94.48	1200	108.48
11	79.40	600	95.50	1200	109.24
12	77.14	600	93.56	1200	108.03

Table 146: Real Leachate Coupon Test Results - Test 6

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.05	30	42.5	121	7.2
2	1.93	30	42.5	112	10.3
3	2.12	30	42.5	99	17.3
4	2.06	30	42.5	110	11.2
5	2.02	30	42.5	110	11.2
6	2.11	30	42.5	106	13.1
7	1.96	30	42.5	107	12.6
8	2.02	30	42.5	109	11.7
9	2.02	30	42.5	104	14.2
10	1.92	30	42.5	113	9.9
11	1.90	30	42.5	110	11.2
12	1.86	30	42.5	111	10.8
RO	0.42	146	0.5	181	0.7
RO	0.42	139	0.6	181	0.7
Feed	163	-27	392	10	594
Feed	163	-27	392	10	594
PWP	0.53	113	1.7	184	0.6

Table 147: Pure Water Permeate Flow Conditions - Test 6

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	230	225	30	0.90
B	0.65	230	225		
C	0.63	230	225		
D	0.65	230	225		

Table 148: Product Rate Flow Conditions - Test 6

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	250	245	30	0.90
B	0.64	250	245		
C	0.65	250	245		
D	0.67	250	245		

Table 149: Real Leachate Coupon Tests - Test 7

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.30	420	85.26		90.9
2	77.38	420	85.30		90.78
3	77.26	420	86.40		92.50
4	77.17	420	84.67		89.90
5	77.25	420	86.05		91.15
6	76.94	420	84.54		89.61
7	77.49	420	86.49		92.61
8	77.40	420	85.73		91.33
9	76.66	420	85.47		91.13
10	77.10	420	86.09		91.11
11	79.46	420	87.80		93.19
12	77.18	420	85.74		91.51

Table 150: Real Leachate Coupon Test Results - Test 7

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	1.16	49	20.2	149	2.4
2	1.16	49	20.2	148	2.5
3	1.16	49	20.2	142	3.1
4	1.37	49	20.2	148	2.5
5	1.16	49	20.2	151	2.2
6	1.16	49	20.2	138	3.7
7	1.27	49	20.2	148	2.5
8	1.17	49	20.2	147	2.6
9	1.16	49	20.2	144	2.9
10	1.07	49	20.2	148	2.5
11	1.09	49	20.2	140	3.4
12	1.01	49	20.2	140	3.4
RO	0.40	195	0.1	195	0.4
RO	0.40	195	0.1	195	0.4
Feed	70.53	-8	187	40	180
Feed	70.53	-8	187	40	180
PWP	0.62	113	1.7	196	0.4

Table 151: Pure Water Permeate Flow Conditions - Test 7

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	175	170	32	0.86
B	0.65	175	170		
C	0.64	175	170		
D	0.67	175	170		

Table 152: Product Rate Flow Conditions - Test 7

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	175	170	32	0.86
B	0.61	175	170		
C	0.66	175	170		
D	0.65	175	170		

Table 153: Real Leachate Coupon Tests - Test 8

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.26	360	84.34	1320	95.41
2	77.38	360	84.36	1320	95.19
3	77.21	360	85.23	1320	97.11
4	77.08	360	83.79	1320	94.12
5	77.18	360	85.01	1320	96.92
6	76.89	360	83.58	1320	93.59
7	77.43	360	85.31	1320	97.35
8	77.35	360	84.68	1320	95.93
9	76.59	360	84.28	1320	95.75
10	77.08	360	84.92	1320	96.76
11	79.40	360	86.67	1320	97.57
12	77.18	360	84.49	1320	96.20

Table 154: Real Leachate Coupon Test Results - Test 8

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.54	33	37.8	215	2.8
2	2.56	33	37.8	214	2.9
3	2.80	33	37.8	179	10.7
4	2.49	33	37.8	193	6.4
5	2.40	33	37.8	189	7.4
6	2.66	33	37.8	178	11.1
7	2.56	33	37.8	177	11.5
8	2.55	33	37.8	176	11.9
9	2.56	33	37.8	174	12.8
10	2.32	33	37.8	184	8.9
11	2.42	33	37.8	184	8.9
12	2.43	33	37.8	173	13.3
RO	0.39	195	0.1	227	1.8
RO	0.39	195	0.1	227	1.8
Feed	202	-31	458	55	1049
Feed	202	-31	458	55	1049
PWP	0.61	113	1.7	229	1.7

Table 155: Pure Water Permeate Flow Conditions - Test 8

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	180	175	30	0.90
B	0.65	180	175		
C	0.65	180	175		
D	0.65	180	175		

Table 156: Product Rate Flow Conditions - Test 8

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	180	175	31	0.88
B	0.65	180	175		
C	0.65	180	175		
D	0.65	180	175		

Table 157: Real Leachate Coupon Tests - Test 9

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.28	480	85.28	1140	93.03
2	77.41	480	85.27	1140	92.80
3	77.24	480	86.23	1140	94.37
4	77.12	480	84.68	1140	91.78
5	77.21	480	86.04	1140	94.20
6	76.91	480	84.50	1140	91.29
7	77.46	480	86.38	1140	94.71
8	77.36	480	85.70	1140	93.51
9	76.62	480	85.30	1140	93.20
10	77.09	480	85.94	1140	94.13
11	79.41	480	87.66	1140	95.18
12	77.16	480	85.56	1140	93.66

Table 158: Real Leachate Coupon Test Results - Test 9

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.08	27	47.7	184	34.4
2	2.14	27	47.7	184	34.4
3	2.35	27	47.7	168	60.6
4	2.07	27	47.7	179	41.5
5	2.02	27	47.7	179	41.5
6	2.33	27	47.7	179	41.5
7	2.19	27	47.7	179	41.5
8	2.19	27	47.7	179	41.5
9	2.14	27	47.7	179	41.5
10	1.94	27	47.7	179	41.5
11	1.99	27	47.7	179	41.5
12	2.02	27	47.7	179	41.5
RO	0.38	195	0.1	290	0.8
RO	0.38	195	0.1	290	0.8
Feed	200	-33	496	80	1365
Feed	200	-33	496	80	1365
PWP	0.57	113	1.7	293	0.7

Table 159: Pure Water Permeate Flow Conditions - Test 9

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.67	175	170	28	0.94
B	0.65	175	170		
C	0.64	175	170		
D	0.65	175	170		

Table 160: Product Rate Flow Conditions - Test 9

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	190	185	30	0.90
B	0.62	190	185		
C	0.68	190	185		
D	0.66	190	185		

Table 161: Real Leachate Coupon Tests - Test 10

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.26	540	86.83	1140	90.16
2	77.39	540	86.79	1140	90.03
3	77.22	540	87.97	1140	91.18
4	77.10	540	86.13	1140	89.20
5	77.19	540	87.76	1140	91.24
6	76.89	540	85.98	1140	88.62
7	77.44	540	88.10	1140	91.63
8	77.35	540	87.29	1140	90.64
9	76.60	540	86.98	1140	90.26
10	77.08	540	87.23	1140	91.00
11	79.41	540	89.31	1140	92.37
12	77.15	540	87.26	1140	90.74

Table 162: Real Leachate Coupon Test Results - Test 10

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.71	23	55.8	82	27.6
2	2.66	23	55.8	88	21.4
3	3.15	23	55.8	68	50.1
4	2.86	23	55.8	84	25.3
5	2.68	23	55.8	85	24.3
6	3.16	23	55.8	77	34.1
7	2.99	23	55.8	73	40.5
8	2.95	23	55.8	78	32.7
9	2.74	23	55.8	76	35.6
10	2.76	23	55.8	84	25.3
11	2.80	23	55.8	83	26.4
12	2.73	23	55.8	84	25.3
RO	0.4	195	0.1	170	0.6
RO	0.4	195	0.1	170	0.6
Feed	250	-38	602	-9	1332
Feed	250	-38	602	-9	1332
PWP	0.73	113	1.7	140	2.3

Table 163: Pure Water Permeate Flow Conditions - Test 10

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	175	170	28	0.94
B	0.65	175	170		
C	0.65	175	170		
D	0.66	175	170		

Table 164: Product Rate Flow Conditions - Test 10

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.63	175	170	30	0.90
B	0.65	175	170		
C	0.66	175	170		
D	0.66	175	170		

Table 165: Real Leachate Coupon Tests - Test 11

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.29	1440	91.15	4380	103.02
2	77.42	1440	91.02	4380	102.19
3	77.24	1440	92.76	4380	105.02
4	77.17	1440	90.21	4380	101.29
5	77.23	1440	92.55	4380	105.46
6	76.92	1440	89.84	4380	99.85
7	77.49	1440	82.87	4380	106.09
8	77.40	1440	91.77	4380	104.03
9	76.64	1440	91.53	4380	103.88
10	77.13	1440	92.32	4380	105.09
11	79.47	1440	93.52	4380	105.04
12	77.17	1440	91.63	4380	103.71

Table 166: Real Leachate Coupon Test Results - Test 11

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	3.28	26	49.6	69	48.0
2	3.41	26	49.6	68	50.1
3	4.01	26	49.6	54	91.0
4	3.42	26	49.6	70	46.0
5	3.28	26	49.6	68	40.1
6	3.74	26	49.6	62	64.7
7	3.73	26	49.6	64	59.4
8	3.55	26	49.6	67	52.3
9	3.50	26	49.6	65	56.9
10	3.21	26	49.6	73	40.5
11	3.19	26	49.6	74	38.8
12	3.29	26	49.6	72	42.2
RO	0.4	195	0.1	163	0.9
RO	0.4	195	0.1	163	0.9
Feed	236.4	-53	1081	-11	1450
Feed	236.4	-53	1081	-11	1450
PWP	1.23	113	1.7	165	0.8

Table 167: Pure Water Permeate Flow Conditions - Test 11

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	100	95	29	0.92
B	0.65	100	95		
C	0.65	100	95		
D	0.65	100	95		

Table 168: Product Rate Flow Conditions - Test 11

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	110	100	29	0.92
B	0.68	110	100		
C	0.64	110	100		
D	0.65	110	100		

Table 169: Real Leachate Coupon Tests - Test 12

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.26	2040	94.80	3480	103.94
2	77.39	2040	94.53	3480	103.13
3	77.21	2040	96.71	3480	106.09
4	77.10	2040	93.57	3480	102.02
5	77.18	2040	96.54	3480	106.32
6	76.89	2040	93.07	3480	100.34
7	77.44	2040	96.88	3480	106.87
8	77.35	2040	95.51	3480	104.64
9	76.61	2040	95.41	3480	104.75
10	77.09	2040	96.26	3480	106.02
11	79.40	2040	97.18	3480	105.92
12	77.15	2040	95.37	3480	104.71

Table 170: Real Leachate Coupon Test Results - Test 12

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	1.45	46	22.7	92	13.8
2	1.52	46	22.7	86	17.7
3	1.65	46	22.7	75	27.8
4	1.53	46	22.7	89	15.6
5	1.57	46	22.7	84	19.2
6	1.70	46	22.7	81	21.7
7	1.58	46	22.7	84	19.2
8	1.51	46	22.7	87	17.0
9	1.48	46	22.7	85	18.4
10	1.48	46	22.7	93	13.3
11	1.42	46	22.7	95	12.2
12	1.36	46	22.7	92	13.8
RO	0.39	195	0.1	159	0.9
RO	0.39	195	0.1	159	0.9
Feed	98.67	-11	210	4	514
Feed	98.67	-11	210	4	514
PWP	0.50	113	1.7	156	1.0

Table 171: Pure Water Permeate Flow Conditions - Test 12

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.68	100	95	25	1.00
B	0.68	100	95		
C	0.65	100	95		
D	0.65	100	95		

Table 172: Product Rate Flow Conditions - Test 12

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.68	110	100	30	0.90
B	0.68	110	100		
C	0.66	110	100		
D	0.63	110	100		

Table 173: Real Leachate Coupon Tests - Test 13

Cell	Initial Mass (g)	PWP Sample Time (s)	PWP Final Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.27	360	85.59	1440	96.24
2	77.39	360	83.60	1440	95.96
3	77.31	360	84.38	1440	97.70
4	77.11	360		1440	94.84
5	77.18	360	84.14	1440	97.84
6	76.96	360	82.88	1440	94.35
7	77.45	360	84.39	1440	98.20
8	77.42	360	83.89	1440	96.82
9	76.60	360	83.37	1440	96.65
10	77.12	360	83.98	1440	97.53
11	79.50	360	85.91	1440	98.52
12	77.15	360	83.70	1440	97.02

Table 174: Real Leachate Coupon Test Results - Test 13

Cell	TOC mg/l	NH_3 mV	NH_3 mg/l	Cl- mV	Cl- mg/l
1	2.46	35	34.9	76	26.7
2		35	34.9	78	24.6
3	2.25	35	34.9	65	41.9
4	2.27	35	34.9	78	24.6
5	2.34	35	34.9	78	24.6
6	2.35	35	34.9	74	29.0
7	2.36	35	34.9	74	29.0
8	2.01	35	34.9	75	27.8
9	2.22	35	34.9	74	29.0
10	2.45	35	34.9	83	20.0
11	2.05	35	34.9	82	20.8
12	2.04	35	34.9	83	20.0
RO	0.38	195	0.1	154	1.1
RO	0.38	195	0.1	154	1.1
Feed	177	-29	424	-13	1034
Feed	177	-29	424	-13	1034
PWP	0.65	113	1.7	147	1.4

Table 175: Pure Water Permeate Flow Conditions - Test 13

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.66	175	170	28	0.94
B	0.66	175	170		
C	0.65	175	170		
D	0.65	175	170		

Table 176: Product Rate Flow Conditions - Test 13

	Flowrate gal/min	Inlet Pressure psi	Outlet Pressure psi	Temp. C	Correction Factor
A	0.65	180	175	30	0.90
B	0.65	180	175		
C	0.68	180	175		
D	0.68	180	175		

Table 177: Spiral-wound Tests - Flow Results - Test 1

Sample	PWP Initial Mass (g)	PWP sample time (s)	PWP final Mass (g)	PR Initial Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	79.35	30	123.01	77.39	30	100.14
2				76.85	30	99.15
3				77.23	30	99.12
4				76.87	30	99.01

Table 178: Spiral-wound Tests - Concentration Results - Test 1

Sample	TOC mg/l	Cl^- mV	Cl^- mg/l
1	13.04	99	21
2	12.37	110	14
3	11.63	111	13
4	9.9	112	13
RO	3.5	179	1
Feed	165	39	207
PWP	4.8	183	1

Table 179: Spiral-wound Tests - Test Conditions - Test 1

	Temperature (C)	Temp Corr.	Inlet Pressure psi	Outlet Pressure psi
PWP	24	1.02	40	33
PR	15	1.28	40	32

Table 180: Spiral-wound Tests - Flow Results - Test 2

Sample	PWP Initial Mass (g)	PWP sample time (s)	PWP final Mass (g)	PR Initial Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.51	30	113.77	77.51	30	91.83
2	76.91	30	113.05	76.91	30	91.98
3	77.33	30	113.72	77.33	30	92.69
4	76.98	30	113.55	76.98	30	88.72

Table 181: Spiral-wound Tests - Concentration Results - Test 2

Sample	TOC mg/l	Cl^- mV	Cl^- mg/l
1	415	-15	1646
2	437	-14	1584
3	459	-14	1584
4	465	-12	1467
RO	0.069	175	1
Feed	1646	-22	2154
PWP	1.4	170	1

Table 182: Spiral-wound Tests - Test Conditions - Test 2

	Temperature (C)	Temp Corr.	Inlet Pressure psi	Outlet Pressure psi
PWP	24	1.02	49	42
PR	18	1.18	49	42

Table 183: Spiral-wound Tests - Flow Results - Test 3

Sample	PWP Initial Mass (g)	PWP sample time (s)	PWP final Mass (g)	PR Initial Mass (g)	PR Sample Time (s)	PR Final Mass (g)
1	77.51	10	97.79	77.51	120	89.09
2	76.91	10	97.69	76.91	120	89.84
3	77.33	10	98.35	77.33	120	93.11
4	76.98	10	98.89	76.98	120	89.8

Table 184: Spiral-wound Tests - Concentration Results - Test 3

Sample	TOC mg/l	Cl^- mV	Cl^- mg/l
1	349	-6	1165
2	346	-6	1165
3	357	-6	1165
4	360	-7	1211
RO	0.17	152	3
Feed	1628	-25	2416
PWP	1.65	137	5

Table 185: Spiral-wound Tests - Test Conditions - Test 3

	Temperature (C)	Temp Corr.	Inlet Pressure psi	Outlet Pressure psi
PWP	24	1.02	60	50
PR	22	1.07	60	50

APPENDIX B: Central Composite Experimental Design

Central Composite Experimental Design

Box and Wilson (1951) introduced the so-called Central Composite Design for second-order models. It is based on the general second-order expansion:

$$E(Y) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq i}^{k} \beta_{ij} x_i x_j , \qquad \text{Eq. 16}$$

where: E(Y) is the expected value of the response variable,

β_0, β_i, β_j are the model parameters,

x_i and x_j are the coded factors being studied, and

k is the number of factors being studied.

This design consists of a two-level factorial or fractional factorial design with the addition of axial and centre points. The axial points are situated in pairs (α coded units) along the axis of each each operating variable. The value of α and the number of centre point replicates varies according to the number of operating variables.

A central composite design was used for the coupon membrane tests made with a feed of synthetic leachate (Section 3.2.3). Four factors were used in the design: the operating pressure, and the TOC, NH_3 and Cl^- concentrations, but only a fractional factorial experiment was conducted. Box and Wilson (1951) recommend an α value of 2.0 and 9 centre points for a 3^{4-1}.

Analysis of Models

Using a least-squares analysis, four assumptions are made (Wadsworth, 1990):

1. The values of the operating variables are known exactly. (This means that any uncertainty associated with a value of an operating variable has much less effect on the response value than the uncertainty associated with a measured value of the response.)

2. The form of the model is appropriate. (That is, the expected value of the model is zero.)

3. The variance of the random-error term is constant over the region of the operating variables used to collect the data.

4. There is no systematic association of the random error for any one data point with the random error for any other data point.

An additional assumption, that the random errors are normally distributed, provides a basis for probability statements about model parameters, and for predictions and for hypothesis tests.

Model Lack-of-Fit Test

To determine the adequacy of a least-squares model, it is necessary to perform an analysis of the residuals from the model.

In the (ANOVA) analysis of the variance, the variation is separated into two components, regressional and residual. Thus:

$SS = SS_R + SS_E,$ Eq. 17

where: SS is the total sum of squares,

SS_R is the regression sum of squares, and

SS_E is the residual sum of squares.

Furthermore, the standard definitions apply:

$SS = \sum (y_i - \bar{y})^2$, Eq. 18

$SS_E = \sum (y_i - \hat{y})^2$, Eq. 19

$SS_R = SS - SS_E$, Eq. 20

where y_i is the observed value of the response variable at design point *i*,

$\bar{y}$ is the mean value of the observed responses, and

$\hat{y}$ is the predicted response variable at point *i*.

To test for lack of fit the residual sum of squares SS_E is divided into two components:

$SS_E = SS_{PE} + SS_{LOF}$, Eq. 21

where SS_{PE} is the sum of squares due to pure error, and

SS_{LOF} is the sum of squares due to lack of fit.

The pure-error sum of squares is calculated using the repeat observations of the centre point replicates and then pooling over the m levels of *x* (Montgomery and Peck, 1982). Thus:

$$SS_{PE} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2, \qquad \text{Eq. 22}$$

where m is the number of points were replicates were taken and n_i is the number of replicates taken at the point m. The degrees of freedom associated with the sum of squares of pure error, f_{PE}, is:

$$f_{PE} = \sum_{i=1}^{m} (n_i - 1). \qquad \text{Eq. 23}$$

The sum of squares for lack of fit, SS_{LOF}, and its corresponding degrees of freedom, f_{LOF}, are determined by subtracting the pure error from the residual values. The F_0 statistic, MS_{LOF}/MS_{PE}, provides the basis for the evaluation of lack of fit. The model fits if

$F_0 > F_{\alpha, fLOF, fPE}$

Table 186 shows the layout of the ANOVA test,

Table 186: ANOVA Test

Sources of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Regression	p	SS_R	$MS_R = SS_R/p$	MS_R/MS_E
Residual	N-p-1	SS_E	$MS_E = SS_E/(N-p-1)$	
Lack of Fit	f_{LOF}	SS_{LOF}	$MS_{LOF} = SS_{LOF}/f_{LOF}$	MS_{LOF}/MS_{PE}
Pure Error	f_{PE}	SS_{PE}	$MS_{PE}=SS_{PE}/f_{PE}$	
TOTAL	N-1	SS		

Another way to see whether a model fits experimental data is to use the coefficient of determination, R^2, which is defined by:

$$R^2 = \frac{SS_R}{S_{yy}} = 1 - \frac{SS_E}{S_{yy}} \qquad \text{Eq. 24}$$

R^2 is thus a measure of the reduction in the variability of y obtained by using the regressor variables $x_1, x_2, \ldots, x_k$ (Montgomery and Peck, 1982). A large R^2 does not necessarily imply that the regression model is good one. Adding a regressor to the model will always increase R^2, so it is crucial to perform a residual analysis to determine if the model is a good fit.

Residual Analysis

Residual e_i, where

$$e_i = y_i - \hat{y}_i \qquad \text{Eq. 25}$$

Any inadequacies in a model are exposed by plotting the residual values against those predicted by the model. Then any trends in the distribution of the residuals shows that the variance of the errors is not constant.

If the normal probability distribution plot for the residuals results in a straight line, then the distribution is normal. If the residuals are not normally distributed, then there is a problem with the model.

Parameter Confidence Intervals

To construct confidence intervals for the regression coefficients β_j, the errors are assumed to be normally and independently distributed with a mean equal to zero and a variance of σ^2. Equation 26 shows the 100(1-α) confidence interval for β_j,,

$$\hat{\beta}_j - t_{\alpha/2,n-p}\sqrt{\sigma^2 C_{jj}} \le \beta \le \hat{\beta}_j + t_{\alpha/2,n-p}\sqrt{\sigma^2 C_{jj}} \qquad \text{Eq. 26}$$

where $\hat{\beta}_j$ is the regression coefficient,

C_{jj} is the jth diagonal element of the $(X'X)^{-1}$ matrix, and

σ^2 is the variance.

The variance can be estimated from the pure-error variance or, if there is no lack of fit, by $SS_R/(N-p-1)$.

Model Analysis – Synthetic Leachate Feed

$PR/PWP = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2$

Table 187: Parameter Estimates for Ratio of Product Rate to Pure Water Permeate Rate

	β_0	β_1	β_2	β_{12}
Estimate	0.34519	0.1149	-0.175	-0.0738
Std. Err.	0.01483	0.020156	0.02494	0.03281
t(16)	23.348	5.703	-7.0143	-2.249
p-level	0.0000	0.0000	0.0000	0.03897
Variance Explained = 85.804%			R = 0.92631	

Table 188: ANOVA Table for Ratio of Product Rate to Pure Water Permeate Rate

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	$F_{.05,v1,v2}$
Regression	4	0.42131	0.10533	22.67	3.06
Residual	15	0.06969	0.004646		
(Lack of Fit)	12	0.06265	0.005214	2.2187	8.74
(Pure Error)	3	0.00704	0.00235		
TOTAL	19	0.491			

Table 189: Correlation Matrix of Parameter Estimates for Ratio of Product Rate to Pure Water Permeate Rate

	β_0	β_1	β_2	β_{12}
β_0	1.000000	-.060357	.075561	-.039723
β_1	-.060357	1.000000	-.047789	.135231
β_2	.075561	-.047789	1.000000	-.182381
β_{12}	-.039723	.135231	-.182381	1.000000

Table 190: Pure Error Variance for Ratio of Product Rate to Pure Water Permeate Flux

For Replicate Set	
Mean	0.3789
sum of residuals squared	0.00704
degrees of freedom	3
pure error variance	0.00235

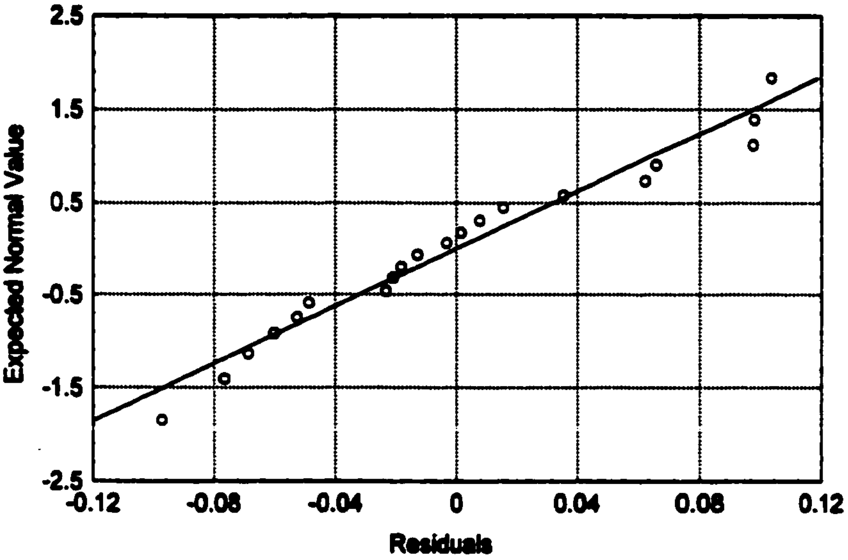

Figure 23: Expected Normal Value versus Residual for PR/PWP model

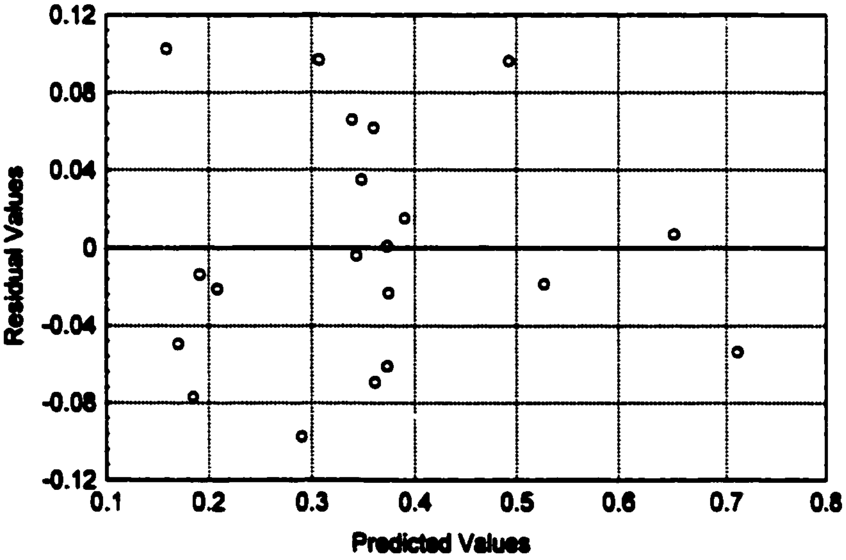

Figure 24: Residual versus Predicted Value, PR/PWP model

TOC Removal Efficiency = $\beta_0 + \beta_1 x_1 + \beta_3 x_3 + \beta_{13} x_1 x_3 + \beta_{11} x_1^2$

Table 191: Parameter Estimates for TOC removal efficiency

	β_0	β_1	β_3	β_{13}	β_{11}
Estimate	91.0761	6.47354	-4.72001	4.191314	-2.31460
Std.Err.	.4495	.45199	.56134	.667121	.27839
t(15)	202.5946	14.32218	-8.40854	6.282690	-8.31438
p-level	.0000	.00000	.00000	.000015	.00000

Variance Explained = 95.823% R = 0.97889

Table 192: ANOVA Table for TOC removal Efficiency

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	$F_{.05,v1,v2}$
Regression	5	245.306	49.0612	64.233	2.96
Residual	14	10.694	0.7638		
(Lack of Fit)	11	9.944	0.904	3.616	8.76
(Pure Error)	3	0.75	0.25		
TOTAL	19	256			

Table 193: Correlation Matrix of Parameter Estimates for TOC Removal Efficiency

	β_0	β_1	β_3	β_{13}	β_{11}
β_0	1.000000	-.595745	.840456	-.634392	-.431953
β_1	-.595745	1.000000	-.675618	.803672	-.025166
β_3	.840456	-.675618	1.000000	-.683762	-.134670
β_{13}	-.634392	.803672	-.683762	1.000000	.018759
β_{11}	-.431953	-.025166	-.134670	.018759	1.000000

Table 194: Pure Error Variance for TOC Removal Efficiency

For Replicate Set	
Mean	94.75
sum of residuals squared	0.75
degrees of freedom	3
pure error variance	0.25

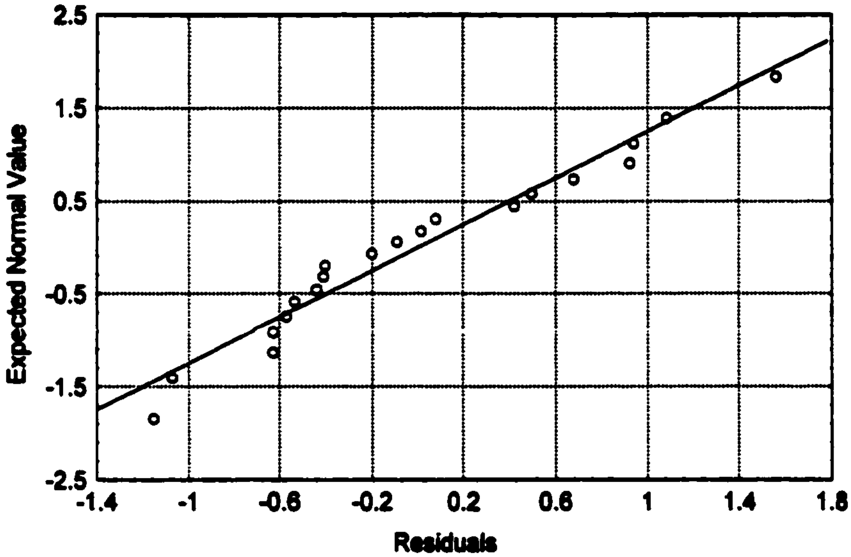

Figure 25: Expected Normal Value versus Residual for the TOC removal Efficiency Model

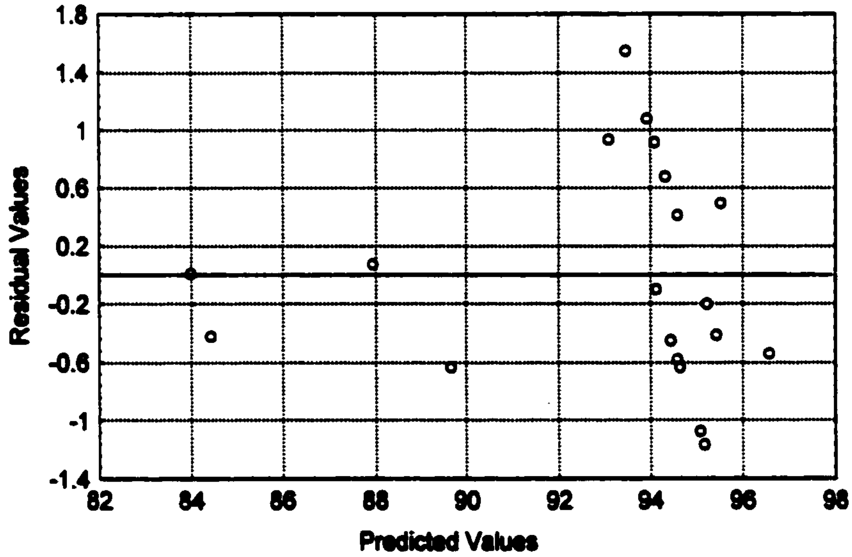

Figure 26: Residual versus Predicted Value for the TOC Removal Efficiency Model

NH_3 Removal Efficiency = $\beta_0 + \beta_1 x_1 + \beta_{34} x_3 x_4$

Table 195: Parameter Estimate for NH_4 Removal Efficiency

	β_0	β_1	β_{34}
Estimate	91.7582	5.484111	2.202937
Std.Err.	.3855	.588225	.501082
t(16)	238.0465	9.323157	4.396360
p-level	.0000	.000000	.000451

Variance Explained = 95.823% R=0.91899

Table 196: ANOVA Table for NH_3 removal Efficiency

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	$F_{.05,v1,v2}$
Regression	3	236.827	78.957	35.154	3.24
Residual	16	43.593	2.7246		
(Lack of Fit)	13	40.843	3.1418	3.426	8.72
(Pure Error)	3	2.75	0.917		
TOTAL	19	280.42			

Table 197: Correlation Matrix of Parameter Estimates for NH_3 Removal Efficiency

	β_0	β_1	β_{34}
β_0	1.000000	-.170207	-.148757
β_1	-.170207	1.000000	.476340
β_{34}	-.148757	.476340	1.000000

Table 198: Pure Error Variance for NH_3 Removal Efficiency

For Replicate Set	
Mean	93.25
sum of residuals squared	2.75
degrees of freedom	3
pure error variance	0.917

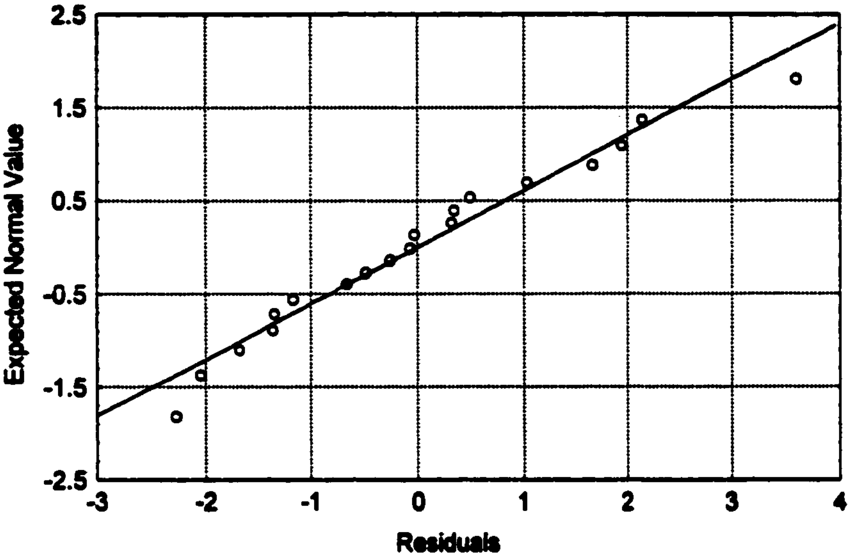

Figure 27: Expected Normal Value versus Residual, NH_3 Removal Efficiency Model

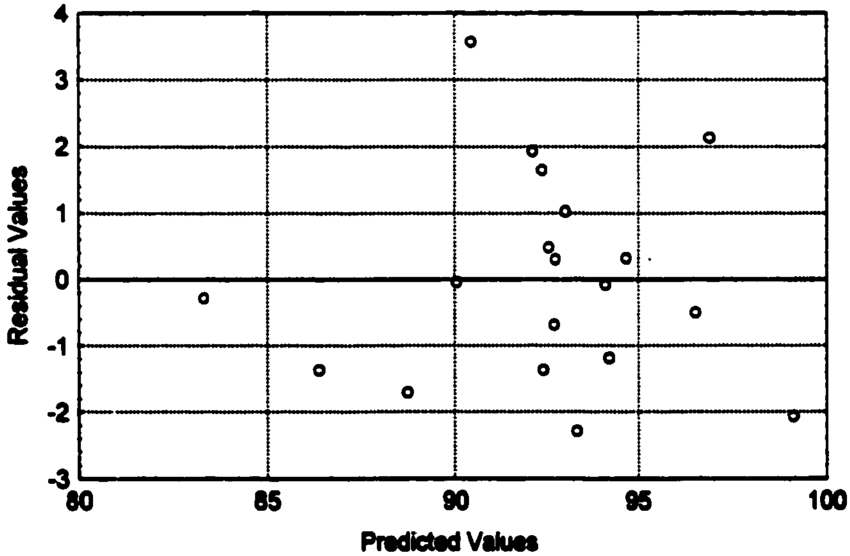

Figure 28: Residual versus Predicted Value, NH_3 Removal Efficiency Model

$$Cl^- \text{ Removal Efficiency} = \beta_0 + \beta_1 x_1 + \beta_3 x_3 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{34} x_3 x_4 + \beta_{33} x_3^2$$

Table 199: Parameter Estimates for Cl$^-$ removal Efficiency

	β_0	β_1	β_3	β_{13}	β_{23}	β_{34}	β_{33}
Estimate	86.2733	10.82996	-9.80404	6.013151	3.354166	1.656867	-3.61594
Std.Err.	.6072	.80047	1.11333	1.232011	.881597	.442965	1.31171
t(13)	142.0944	13.52942	-8.80602	4.880760	3.804650	3.740402	-2.75666
p-level	.0000	.00000	.00000	.000300	.002188	.002472	.01633
Variance Explained = 96.323%						R = 0.98144	

Table 200: ANOVA Table for Cl$^-$ removal Efficiency

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	$F_{.05,v1,v2}$
Regression	7	509.74	72.82	44.908	2.91
Residual	12	19.4586	1.62155		
(Lack of Fit)	9	18.4586	2.0510	6.1592	8.81
(Pure Error)	3	1.00	0.333		
TOTAL		529.2			

Table 201: Correlation Matrix of Parameter Estimates for Cl$^-$ Removal Efficiency

	β_0	β_1	β_3	β_{13}	β_{23}	β_{34}	β_{33}
β_0	1.000000	-.409985	.452037	-.446490	.186039	.073764	-.247741
β_1	-.409985	1.000000	-.794364	.784081	.150145	.121665	-.528704
β_3	.452037	-.794364	1.000000	-.711012	-.304701	-.111908	.675059
β_{13}	-.446490	.784081	-.711012	1.000000	.028234	-.299139	-.411126
β_{23}	.186039	.150145	-.304701	.028234	1.000000	.167094	-.617125
β_{34}	.073764	.121665	-.111908	-.299139	.167094	1.000000	-.188322
β_{33}	-.247741	-.528704	.675059	-.411126	-.617125	-.188322	1.000000

Table 202: Pure Error Variance for Cl$^-$ Removal Efficiency

For Replicate Set	
Mean	92.50
sum of residuals squared	1
degrees of freedom	3
pure error variance	0.333

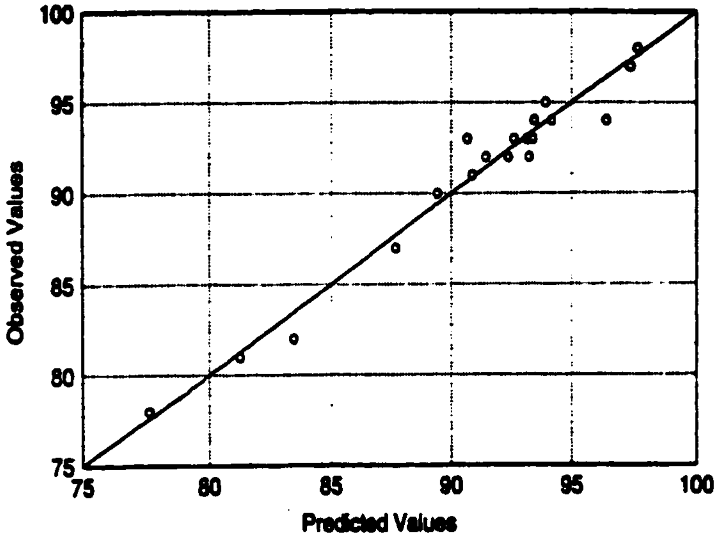

Figure 29: Expected Normal Value versus Residual, Cl⁻ Removal Efficiency Model

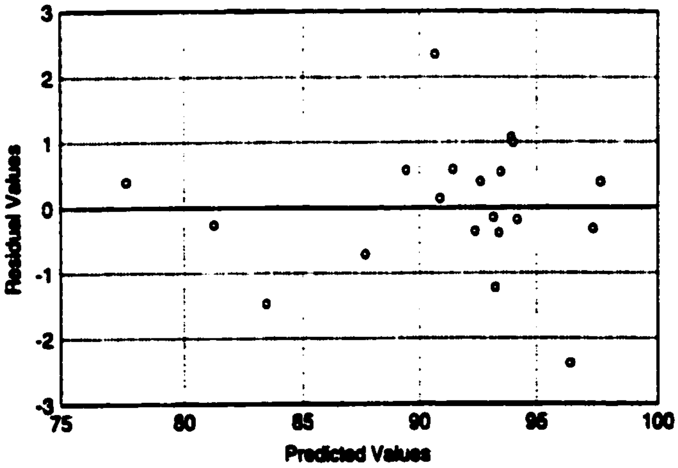

Figure 30: Residual versus Predicted Value, Cl⁻ Removal Efficiency Model

APPENDIX C: Analytical Methods

Chemical Oxygen Demand (COD)

Greenberg et al., 1992 (Method 5220C)

Reagents:

Digestion Solution, 0.0167 M $K_2Cr_2O_7$

1. To about 500 ml of water, add 4.913 g $K_2Cr_2O_7$ (previously dried at 130 °C for 2 hours), 167 ml concentrated H_2SO_4 and 33.3 g $HgSO_4$;
2. Dissolve, cool to room temperature, and dilute to 1 l.

Sulfuric acid Reagents

1. Add 11 g of Ag_2SO_4 per 4 l bottle of H_2SO_4;
2. Stir on a magnetic stirrer for 1 to 2 days to dissolve Ag_2SO_4.

Standard potassium hydrogen phthalate (KHP)

1. Lightly crush and then dry KHP to a constant weight at 120 °C;
2. Dissolve 425 mg in distilled water and dilute to 1 l. KHP. This solution has a theoretical COD of 1.176 mg O_2/mg and the solution 500 mg O_2/ml.

0.10 M Ferrous Ammonium Sulphate (FAS)

1. Dissolve 39.2 mg $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ in distilled water;
2. Add 20 ml of concentrated sulphuric acid and dilute to 1 l.

Procedure:

1. Wash tubes and caps with H_2SO_4 and add 10 ml of the sample, 6 ml of $K_2Cr_2O_7$ and 14 ml of H_2SO_4 reagent. A blank sample of water, and at least one dilution of standard (KHP), should be prepared with each run.
2. Mix, heat at 150 °C for 2 hours, and cool at room temperature.
3. Titrate sample with FAS and ferroin indicator.

Calculation:

$$M = \frac{V_p * 010}{A},$$

where: M is the concentration of FAS, mol/l,

V_p is the volume of 0.0167 M $K_2Cr_2O_7$, and

A is the volume of FAS required in titration for blank, ml.

$$COD = \frac{(A-B) * M * 8000}{V_s},$$

where: COD is the chemical oxygen demand, mg O_2/l,

B is the volume of FAS required for the sample, ml, and

V_s is the volume of the sample used, ml.

pH

The pH was measured using a Radiometer Copenhagen pH meter model 26, which was calibrated using CanLab standards for pH 4, 7 and 10.

Total Organic Carbon – Calibration Curves

Three Calibration Curves are used by the TOC – 5000 high temperature Shimadzu Total Organic Carbon Analyser.

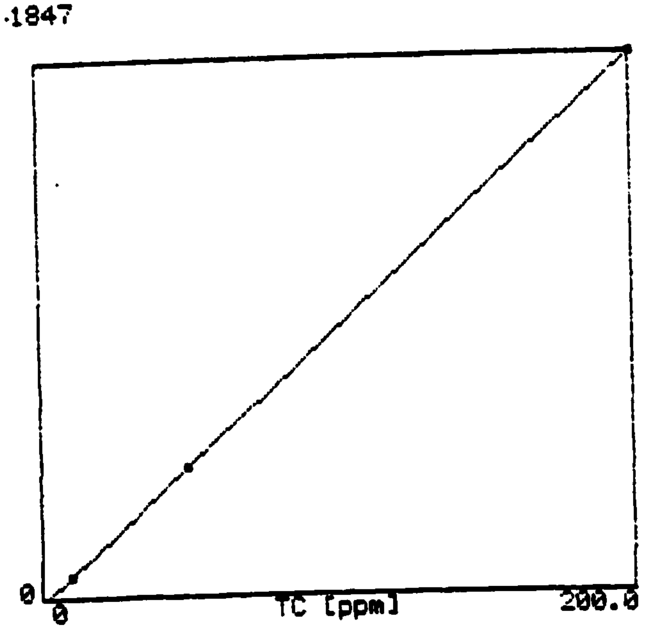

Figure 31: TOC Calibration Curve #4

Table 203: TOC Calibration Curve #4

Standard Concentration mg/l	Area	# injections	Standard Deviation
200.0	41847	4	740
50.0	10057	4	367
10.0	1692	4	44

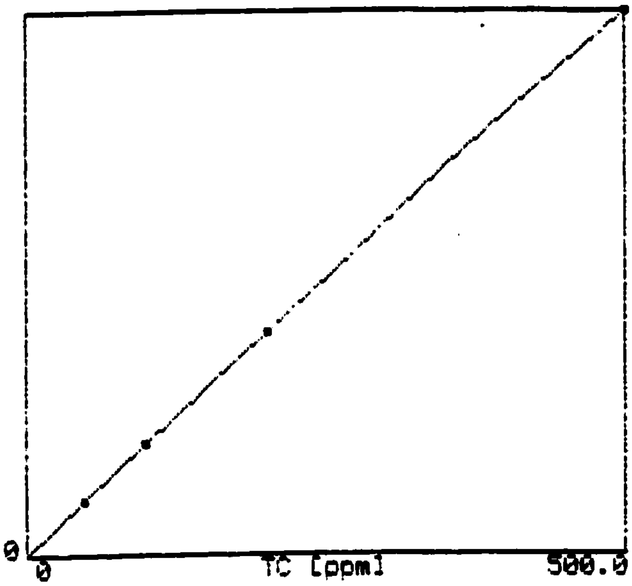

Figure 32: TOC Calibration Curve #5

Table 204: TOC Calibration Curve #5

Standard Concentration mg/l	Area	# injections	Standard Deviation
500.0	42406	4	491
200.0	17363	4	75
100.0	8620	4	131
50.0	4309	4	26

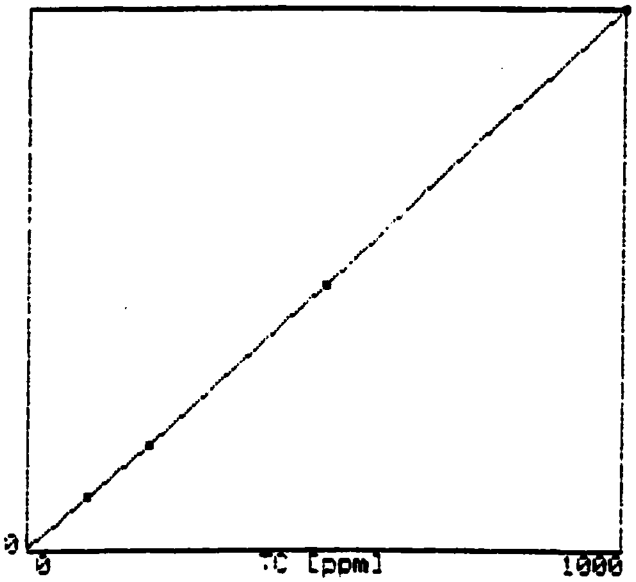

Figure 33: TOC Calibration Curve #6

Table 205: TOC Calibration Curve #6

Standard Concentration mg/l	Area	# injections	Standard Deviation
1000.0	44125	4	259
500.0	21716	4	383
200.0	8591	4	138
100.0	4415	4	24

APPENDIX D: Sample Calculations

Sample Calculations

Pure-Water Permeate Rate, Product Rate, Removal Efficiency

For Membrane Characterization – 100 psi (Tables 23 – 25) Cell #5.

Measured Values

Mass initial = 77.21 g
PWP sample time = 540 s
PR sample time = 1380 s
PWP mass final = 87.29 g
PR mass final = 91.73 g

Conductivity Measurements

PWP (composite sample) = 2.0
RO = 1.0
Product = 29.0
$\text{Feed}_1 = 936$
$\text{Feed}_2 = 947$

PWP operating temperature = 26C
PR operating temperature = 27C

Membrane Area = 14.5 cm^2 ($1.45x10^{-3}$ m^2)

Calculations

Temperature Correction Factors

$aPWP = 0.98$

$$a_{PWP} = \frac{10^{\left(\frac{1.3272(20-26)-0.001053(26-20)^2}{(26+105)}\right)}}{1.002} = 0.8904$$

$aPR = 0.96$

Permeate Rates

Pure-Water Permeate

Rate (g/hr) = CF * Mass (g) * 60 (s/min) * 60 (min/hr) / Sample Time (s)

Mass (g) = PWP Mass Final (g) – Initial Mass (g)
Mass (g) = 87.29 g – 77.21 g
Mass (g) = 10.08 g

Rate (g/hr) = 0.98 * 10.08 g * 60 s/min * 60 min/hr / 540 s
Rate (g/hr) = 65.7

Flux (l/m^2/hr) = Rate (g/hr) / ρ (g/l) / surface area (m^2)
Flux (l/m^2/hr) = 65.7 g/hr / 1000 g/l / 1.45x10^{-3} m^2
Flux (l/m^2/hr) = 45.3

Product Rate

Mass = Final Mass – Initial Mass
Mass = 91.73 g – 77.21 g
Mass = 14.52 g

Rate = 0.98 * 14.52 * 3600 / 1380
Rate = 36.2 g/hr

Flux = 36.2 g/hr / 1000 g/l / 1.45x10^{-3} m^2
Flux = 25.0 l/m^2/hr

Percent Separation

$$\%separation = \frac{(F_1 + F_2)/2 - RO - (PR - PWP)}{(F_1 + F_2)/2 - RO} * 100\%$$

$$\%separation = 97\%$$

$$\%separation = \frac{(936 + 947)/2 - 1.0 - (29 - 2.0)}{(936 + 947)/2 - 1.0} * 100\%$$