CERTIFICATION OF APPROVAL

Flux and Rejection of Salt Using Membrane

by

Nurul Aznin Bt Mamat

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
CHEMICAL ENGINEERING

Approved by,

____

(Mrs. Nor Yuliana Yuhana)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK.
November 2004

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified source or persons.

NURUL AZNIN MAMAT

ABSTRACT

The concept of separating liquid mixtures (salt solution) using membrane technology has gained tremendous applications in the industry. This is due to the number of advantages possessed by the membrane, such as ease of operations, low energy consumption, easy for expansion, small floor area, cost effectiveness and good weight and space efficiency.

The reverse osmosis membranes are specified in terms of their "percentage rejection of salts". The membranes that are supplied are classified as tubular type, which is widely used and have turbulent flow conditions. Liquid permeates through the membrane and feed emerges in a more concentrated form on exit from module.

The objectives of this research are to investigate the performance of membrane in order to determine the flux and rejection salt, also to determine the importance parameters such as concentration at different pressure, permeability of water and percentage of salt remove by using different type of chemicals. The experimental equipment consisted of four RO membranes with same material and in-line system sensor, which allows data acquisition system on a continuous base on pressure, flow rates and also weight of permeates. In the process, retentate is recycled to the feed tank and permeate is collected separately.

From the data obtained and graph plotted, it shows that flux and rejection increased as increasing the pressure but decreased with the concentration. More concentrated the solution will reduce the number of flux and rejection in the RO membrane. Different type of chemicals was used in order to compare the flux and rejection based on the molecular weight and ionic size. Higher in molecular weight and ionic size shows lower the flux and rejection.

Parameters are analysed so that optimum-operating conditions are suggested. In this approach, the activity of the membrane selected is noted and compared with the literature/theoretical results.

ACKNOWLEDGEMENT

The author would like to take this opportunity to thank all parties involved in making the Chemical Engineering Final Year Research Project (ECB 5034) a success. Greatest gratitude goes to Universiti Teknologi PETRONAS's Final Year Research Project Committee for giving her the opportunity to explore her intellectual capabilities by participating in the research project. The author would also like to give special acknowledgement to Mrs. Nor Yuliana Yuhana and Dr Hilmi Mukhtar, acting as the supervisors who offered valuable comments about the writing of this dissertation. In addition further acknowledgements to the supervisors for their tireless efforts, by providing guidance and assistance throughout this challenging experience. My deepest appreciates also go to Chemical Engineer of Solution Engineering Sdn. Bhd, Mr. Chong Gun Hean and his technician, Mr. Najad Ahmad for their support and patience in providing quality education.

Thanks and appreciations also go to lecturers and UTP staffs who have spend time to provide additional support and advice throughout the training. The author's gratitudes also go to Mr. Zaaba Mohammad, Mr. Mahathir Mohammad and other technicians for their time, support and expertise.

A message of thanks and appreciation to all people who assisted directly and indirectly to the completion of the project.

The author.

List of Figures **Page**

Appendix:

List of Tables

Page

Appendix:

List of Abbreviations

ρ_w - Water permeability of the membrane, $m^2/Pa.s$

Π - Osmotic pressure, Pa

R_m - Membrane resistance, Pa.s/m

vn_s - Total concentration of ions, $kmol/m^3$

R - Constant, 8.313 $kPa.m^3/kmol.K$

Z - Thickness of the membrane active layer

C_f - Concentration in the feed

C_p - Concentration in the permeate

D_i - Diffusivity in the membrane

J_s - Solute flux, mmol / $cm^2.s$

A - Pure water permeation, m /s. bar

C - Constant depending on membrane porosity

D_{wter} - Salt diffusivity in solution, cm^2 / s

J_w - Flux of pure water in the product, m3 / m2.s

M_w - Salt molecular weight, g/mol

N - Hydration number

N_A - Avogadro's number

P - Operating pressure, bar

Q_p - Product flow

R - Rejection coefficient

ΔP - Applied pressure difference

$\Delta \pi$ - Osmotic pressure difference

Q_s - Salt flow across membrane

Q_w - Water flow across membrane

CPF - Concentration Polarization Factor

TABLE OF CONTENT

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW/THEORY

CHAPTER 3: METHODOLOGY / PROJECT WORK

CHAPTER 4: RESULT AND DISCUSSION

APPENDIX

CHAPTER 1

INTRODUCTION

1.1 Membrane technology

Studies of membrane can be traced in the 18th century. Through the 19th and 20th centuries, membranes had no industrial or commercial uses, but rather used as laboratory tools to develop science theories. Since then, membrane have gained and important role in chemical technology. Nowadays they are used in a broad range of applications either in industrial or medical purposes. The main asset that is exploited is the ability of a membrane to allow and control the permeation rate of chemical species through the membrane. Membrane processes are designed to carry out physical and physiochemical separations. Although most membrane applications are water based, there also exist gas-liquid and gas-gas separation processes, although these are more recent developments and have not yet achieved widespread implementation. In terms of membrane sales, the most important application by far is hemodialysis, as carried for by this one application. The development of membrane-based bulk water and wastewater treatment processes, as defined in Table 1, is nonetheless significant, since they offer three clear advantages over convectional techniques:

1.1.1 Separation is achieved without requiring a phase change, and is therefore more energetically efficient than distillation.

1.1.2 Little or no accumulation takes place in the process which therefore operates continuously under steady-state condition without necessitating regeneration cycles, unlike adsorptive separation processes.

1.1.3 Little or no chemical addition is required, unlike convectional clarification which generally relies on the addition of chemical coagulants and flocculants.

Table 1: *Development of membrane-based bulk water and wastewater treatment processes*

PROCESS	USUAL OBJECTIVE
Reverse Osmosis (RO)	Removal of inorganic ions
Nanofiltration (NF)	(Selective) removal of multivalent ions and certain charged or polar molecules
Ultrafiltration (UF)	Removal of both large, dissolved solute molecules and suspended colloidal particles
Microfiltration (MF)	Removal of suspended solids, including microorganisms

1.2 Membrane and membrane process definition

There are a number of definitions of the word "membrane", which can vary considerably in comprehensiveness and clarity. It is a very widely used term, and can mean anything from a cell wall to damp proofing material. Three definitions, arbitrarily chosen from pertinent technical literature from last 20 years are provided below:

1.2.1 "An intervening phase separating two phases and/or acting as an active or passive barrier to the transport of matter between phase" – *the European Society of Membrane Science and Technology.*

1.2.2 "An interphase separating two homogenous phases and affecting the transport of different chemical components in a very specific way" – *Prof. Heine Strathmann, former Head of the Department of Membrane Technology, University of Twente.*

1.2.3 "A material through which one type of substance can pass more readily than others, thus presenting the basis of a separation process" – *Prof. George Solt, former Director of the School of Water Sciences, Cranfield.*

Solt's definition can be considered adequate: it is that property of the membrane which permits the separation of components in and / or from water that is of key interest. For many processes the membranes acts to reject the pollutants, which may be suspended or dissolved, and allow the "purified" water through it. In some cases, however, the membrane may act so as to extract pollutants from the wastewater. In these cases the membrane is employed to allow selective permeation of specific components dissolved in the water. In these processes it is the bulk water that passes through the membrane under an applied pressure, leaving the pollutants in concentrated form and the unpermeated side of the membrane. (*Simon Judd et. al, 2000*)

1.3 Application of Membrane for Salt Separation

The following are a few examples of application where the membranes have been used successfully (*Inge Bisconer, 1998*):

1.3.1 Seawater desalination. One of the major obstacles to efficiently desalting seawater is the tendency for RO membranes to become fouled with silt and organics. UF can remove these fouling constituents before the water reaches the RO membrane, reducing fouling and increasing efficiency.

1.3.2 Sugar industry. NF and UF membranes are routinely used to concentrate sugar and clarify sugar streams in the sugar industry. NF typically is used where traditional heat concentration processes are undesirable or inefficient. NF membranes consistently separate sugars of a specific molecular weight and remove 60 percent of the water, concentrating raw juice from 12 to 30 Brix, a scale that measures the weight of sugar in solution. UF membrane's sharp molecular weight cut-off capabilities are used to clarify sugar streams. Color, tannins and other undesirable organic components are preferentially rejected while sugar molecules are allowed to pass.

1.3.3 Dairy industry. Some of the most successful membrane applications are in the dairy industry where the production of whey, a protein by-product of cheese making, creates a pollution and disposal problem. Although whey consists of high-quality protein and lactose, the high ratio of lactose to protein and the low solids content make it unusable as is. In modern cheese-making facilities, UF, NF and RO are used to render liquid cheese whey into whey protein powder, concentrated lactose and reusable water. Typically, whey is first treated with UF to reject and concentrate the protein fraction, from which protein power is then produced. The UF permeate containing the lactose and salts is then nanofiltered to concentrate the lactose and pass most of the salts. Finally, the NF permeate (salty water) is then desalinized by RO for reuse in the dairy operation.

1.3.4 Textile industry. The textile industry uses valuable dyes, which are clearly visible if discharged into public waterways. In addition, these dyes have been shown to be trihalomethane (THM) precursors processing carcinogenic properties. Thus their disposal creates both an aesthetic and environmental wastewater problem. At the same time, the textile industry continually seeks to conserve water and would economically benefit from dye recovery. NF membranes address all these issues. First, textile dyes are rejected, recovered and reused. Second, waterway pollution is avoided. And third, reusable water is produced. The textile industry also uses synthetic sizing agents, which are expensive and non-biodegradable and pose significant waste treatment problems. Ultrafiltration membranes are used to recover and reuse these agents, avoiding expensive chemical and waste treatment costs. NF and UF membrane technologies continue to meet customer demands on a daily basis.

1.4 Properties of Membrane Structure and Material

Although membrane materials vary vastly according to chemical composition and process type, the principal objectives in membrane manufacturer are always the same. An ideal material will:

1.4.1 Have reasonable mechanical strength.

1.4.2 Maintain a high throughput

1.4.3 Be selective for the desired permeate constituent

These last two parameters are mutually counteractive, since a high degree of selectivity is normally only achievable using a membrane having small pores and thus an inherently high hydraulic resistance (or low permeability). The permeability also increases with increasing density of pores, and the overall membrane resistance is directly proportional to its thickness (in accordance with Darcy's law).

Finally, selectivity will be compromised by a broad pore size distribution. An optimum physical structure for any membrane materials is thus:

1.4.4 A thin layer of material
1.4.5 A narrow range of pore size
1.4.6 A high porosity

Membrane materials can be categorized as either dense or porous, and by the mechanism by which separation is actually achieved (Table 2). Separation by dense membranes relies to some extent on physicochemical interactions between the permeating components and the membrane material, and relate to separation processes having the highest selectivity. Porous membranes, on the other hand, achieve separation mechanically by size exclusion (i.e. sieving), where the rejected material may be either dissolved or suspended depending on its size relative to that of the pore. (*Simon Jude et. al, 2000*)

Table 2: Category of membrane material

Dense	**Porous**
Reverse Osmosis (RO) Separation achieved by virtue of differing solubility and diffusion rates of water (solvent) and solutes in water.	*Ultrafiltration (UF)* Separation by sieving through mesopores (2-50nm)
Nanofiltration (NF) Formerly called leaky reverse osmosis. Separation achieved through combination of charge rejection, solubility-diffusion and sieving through micropores (<2 nm).	*Microfiltration (MF)* Separation of suspended solids from water by sieving through macropores (>50 nm)

In this research, we are going to discuss and focus only on the membrane of Reverse Osmosis (RO). The reverse osmosis membrane is specified in terms of the "percentage rejection of salts". The actual pore size of RO membranes is of little practical consequence, since there are other mechanisms more dominant than simple sieving that determine membrane performance. The purification performance of this membrane can only be rated according to their actual demonstrated permselectivity, i.e. the extent of the rejection of key contaminants by the membrane, under some defined set of conditions.

RO membranes are designed to reject all species other than water, although they are unable to offer a significant barrier to dissolved gases and certain low-molecular-weight organic molecules. Membranes are always rated for flux and rejection. NaCI is always used as one measure of rejection, and for a very good RO membrane, it will be 99 percent or more. Test results are very much a function of how the test is run, and membrane suppliers are usually specific on the test conditions. Salt concentration will be specified as some average of feed and exit concentration, but both are bulk values. Salt concentration at the membrane governs performance.

RO is a high pressure, energy efficient technique for dewatering process streams, concentrating low molecular weight substances in solution, or purifying wastewater. It has the ability to concentrate all dissolved and suspended solids. RO is widely used in the desalination of seawater. In general, RO membrane is capable of separating substances as small as ions from feed streams. All the membrane types allow water to pass. For example, RO membranes typically reject most of the ionic and organic species from the feed stream, allowing only water to pass. RO membrane is rated by terms of percent salt rejection and flow. (*Robert H. Perry et. al, 1997*)

1.5 Problem statement

It is essential to expand application of membrane technology in this current day. But to make this happen, the membrane process must be economically feasible, can obtain a highly permeable and selective membranes are good in mechanical aspect and achieved thermal stability. Table 3 shows the parameters of membrane design. A remarkable progress has been made in the development of high-performance polymers for liquid separation and recently, more and more studies have been done to apply membrane in any area of industry. This research project is another significant effort to determine the characteristic, performance and special traits of membrane for development of membrane technology.

Table 3: Membrane design depends on quality of parameters

Parameter	**Impact**
Feedwater composition	Osmotic pressure, scaling, membrane stability, permeate quality
Feedwater temperature	Flux, membrane stability
Permeate flux	Transmembrane pressure, concentration polarization, fouling, pressure loss
Cross-flow velocity	Concentration polarization, fouling, pressure loss
Membrane material	Membrane stability, permeate quality, fouling

1.6 Objectives and Scope of Study

The objectives of this research are:

1.6.1 To investigate the performance of the membrane in order to determine the flux and rejection of salt.

1.6.2 To study the effect of flux and rejection on different concentrations, pressures and type of chemicals,

The scopes of the study are:

1.6.6 Using similar types of membrane (RO membrane) for each experiment.

1.6.7 Conducting several experiment to check the characterization membrane.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 Limitations in Membrane

In RO, osmotic pressure is a critically important design consideration. Osmotic pressure Π is always calculated for the bulk-feed stream. It varies along the membrane train as salt concentration rises. The osmotic pressure that really matters is the one at the membrane, higher by the amount polarization raises the concentration there. As a general rule for a new membrane application, the inlet concentration is limited to about 0.5 N, for which Π ≅ 2.5 MPa, giving a final concentrate Π of 5 MPa for 50 percent conversion. A few systems may be designed at much higher pressure. It is rated for 65 percent conversion on ocean water, and can concentrate sucrose to 60 percent using a special technique and membrane.

Membrane material used in this research is aromatic polyamide (aramid). Polyamides were an obvious group of polymers to make membranes out of. However the aliphatic polyamides failed to meet many of the environmental demands and failed to realize a major position. Polyamids are naturally more hydrophilic than the polysulphones. This membrane is a copolymer of 1-3 diaminobenzene with 1-3 and 1-4 benzenedicarboxylic acid chlorides that can be seen in figure below (Figure 1).

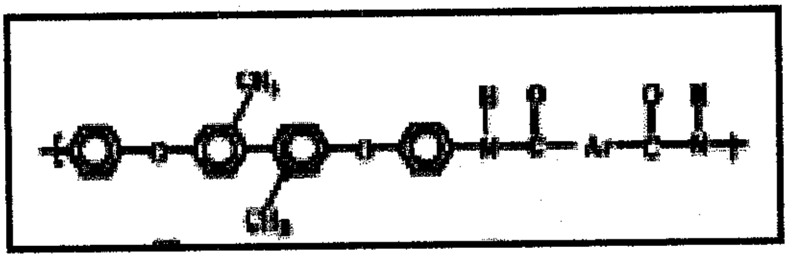


Figure 1: *Synthetic route aromatic polyamide*

They are usually made into fine hollow fibers, 93 μm outer diameter by 43 μm inner diameter. Some flat sheet is made for spirals as shown in Figure 2. (*Solteq manual, 2004*)

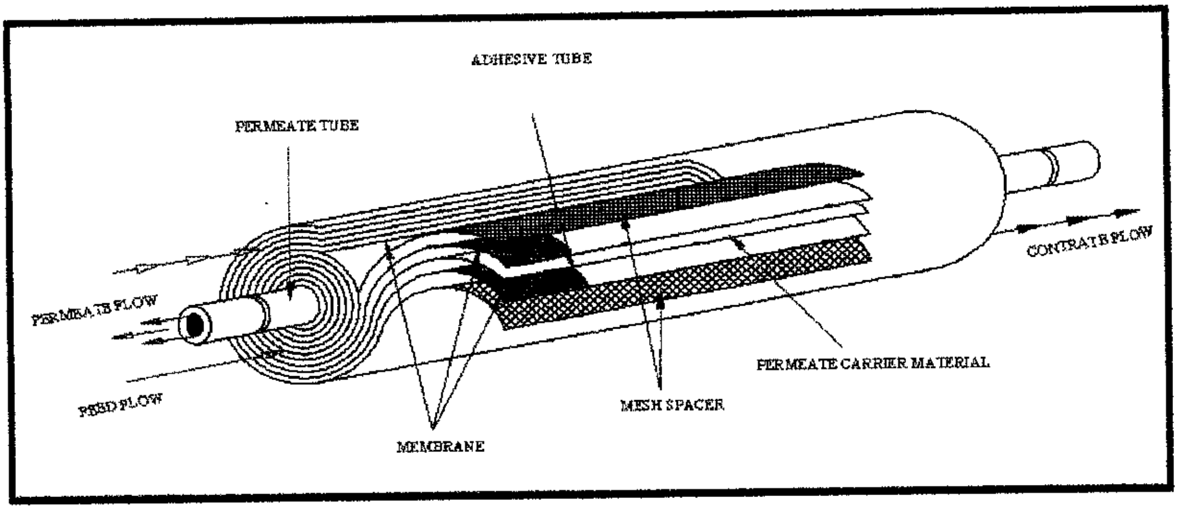


Figure 2: *Schematic of membrane element showing cut-away section of internals*

Aromatic polyamides have a much higher resistance and may be used in a wider pH range (4-11). These membranes are widely used for seawater desalination and to some extent to other process applications. The hollow fibers are capable of very high-pressure operation and have considerably greater hydrolytic resistance than cellulose acetate (CA). Their packing density in hollow-fiber form makes them very susceptible to colloidal fouling and they have essentially no resistance to chlorine. The major weakness of membranes made from polyamide is that they have limited oxidative resistance. Another weakness if that at extreme pHs the amide group can hydrolyze.

Concentration polarization is a function of both fluxes, which increases the mass rate of material stranded at the membrane and cross-flow velocity, which reduces polarization by enhancing feed-side mass transfer. Polarization is far less of a problem in reverse osmosis and nanofiltration than it is in ultrafiltration or microfiltration, but it cannot be ignored. If cross-flow velocity is insufficient, rejected species concentrate near the membrane to an unacceptable level. The resulting increase in osmotic pressure and the precipitation of sparingly soluble species (scaling) are concerns. Scale inhibitors are normally added to water when they are appropriate and, for these feeds, careful consideration of cross-flow velocity is required. Hollow-fiber modules operate at low flux and at low cross-flow velocity so diffusion is better able to reduce polarization; spirals have much better redispersion rates, but can be overdriven if operated at fluxes above the design values.

For most membrane application, particularly for RO, pretreatment of the feed is essential. If pretreatment is inadequate, success will be transient. For most applications, pretreatment is location specific. Well water is easier to treat than surface water and that is particularly true for sea wells. If heavy metals are present in the feed even in small amount, they may catalyze membrane degradation. If surface sources are treated, chlorination followed by through dechlorination is required for high-performance membranes. It is normal to adjust pH and add antiscalants to prevent deposition of carbonates and sulfates on the membrane. The same treatment is appropriate for other colloidal materials. Ultrafiltration or microfiltration is excellent pretreatments, but in general they are uneconomic. (*P.T. Cardew et. al, 1998*)

2.2 Basic Principles of Operation

RO is pressure-driven processes where the solvent is forced through the membrane by pressure, and the undesired co products frequently pass through the membrane by diffusion. The major processes are rate processes, and the relative rates of solvent and solute passage determine the quality of the product. The general consensus is that the solution-diffusion mechanism describes the fundamental mechanism of RO membranes, but a minority disagrees. Fortunately, the equations presented below describe the observed phenomena and predict experimental outcomes regardless of mechanism. For RO, Eq. (1) becomes:

$$J = \frac{\rho_w}{z}(P_f - P_p) - (\Pi_f - \Pi_p) = \frac{\rho_w}{z}(\Delta P - \Delta\Pi) \qquad (1)$$

Where ρ_w is the water permeability of the membrane, $m^2/Pa.s$ and the subscripts *f* and *p* refer to feed and permeate. Π is the osmotic pressure, Pa. Since the thickness of the active layer *z* is almost never known. Eq. (1) is usually modified to the form

$$J = (\frac{1}{R_m + R_n .....})(\Delta P - \Delta\Pi) \qquad (2)$$

Where R_m is the membrane resistance, Pa.s/m. other resistance terms (R_n.....) may be added, such as terms for fouling or compaction. Normally, the important terms are the inherent membrane resistance, the driving force *P*, and the osmotic pressure in the feed, Π. For a high rejection RO membrane, the back-pressure and pressure terms for the permeate are insignificant. For most work, the van't Hoff approximation for osmotic pressure gives an adequate estimate:

$$\Pi = vn_s RT \tag{3}$$

Where vn_s is the total concentration of ions, kmol/m^3 and R= 8.313 kPa.m^3/kmol.K. This equation should not be used for any unusually high concentration operation, or where accuracy is important.

Salt flux across a membrane is due to effects coupled to water transport, usually negligible, and diffusion across the membrane. Fick's law may be written:

$$N_i = D_i \frac{(C_f - C_p)}{z} = D_i \frac{\Delta C}{z} \tag{4}$$

Where z is the thickness of the membrane active layer, and C_f and C_p are concentrations in the feed and the permeate, respectively. D_i is the diffusivity in the membrane. Equation (4) describes the basic diffusion equation for solute passage. It is independent of pressure, so as $\Delta P - \Delta\Pi \rightarrow 0$, rejection → 0. This important factor is due to the kinetic nature of the separation. Salt passage is dependent on $P - \Pi$. Therefore, when the membrane is operating near the osmotic pressure of the feed, the salt passage is not diluted by much permeate water. The flux equation assumes constant temperature. As T rises, Π rises slowly, but around 25°C the viscosity of water drops enough to produce about a 3 percent rise in flux per °C. (*Robert H. Perry et. al, 1997*)

2.3 Theoretical Background

Membrane separation technology has evolved from a small-scale laboratory technique to a large-scale industrial process during the pass 30 years. Numerous theoretical models for nanofiltration and reverse osmosis have been proposed along with the identification of new factors controlling flux or mass transfer through membranes. The basic operating patterns are best outlined in terms of the hydrodynamic resistance resulting from the buildup of deposited materials on the membrane surface. The flux, J will be given by:

$$J = \frac{1}{A_m}\frac{dV}{dt} = \frac{\Delta \mathrm{P}}{v(R_m + R_c)} = \frac{\Delta \mathrm{P}}{v[R_m + (\alpha V C_b / A_m)]} \qquad (5)$$

For most biological materials, α is a variable depending on the applied pressure and time (the compressible deposit), so that the expression requires a numerical solution.

A useful method for the effects of cross-flow removal of depositing materials is to write:

$$J = \frac{\Delta \mathrm{P}}{v(R_m + R_d - R_r)} \qquad (6)$$

Removal of solute by cross-flow is sometimes assumed constant, and equal to the convective particle transport at steady state ($J_{ss}C_b$), which can be obtained experimentally or from an appropriate model. In many situations however, steady state of filtration is seldom achieved. In such cases, it is possible to describe the time dependence of filtration by introducing an efficiency factor, β, representing the fraction of filtered material remaining deposit rather than being swept along by the bulk flow. This gives:

$$R_c = \frac{\beta \alpha V C_b}{A_m}, Where\, 0 < \beta < 1 \qquad (7)$$

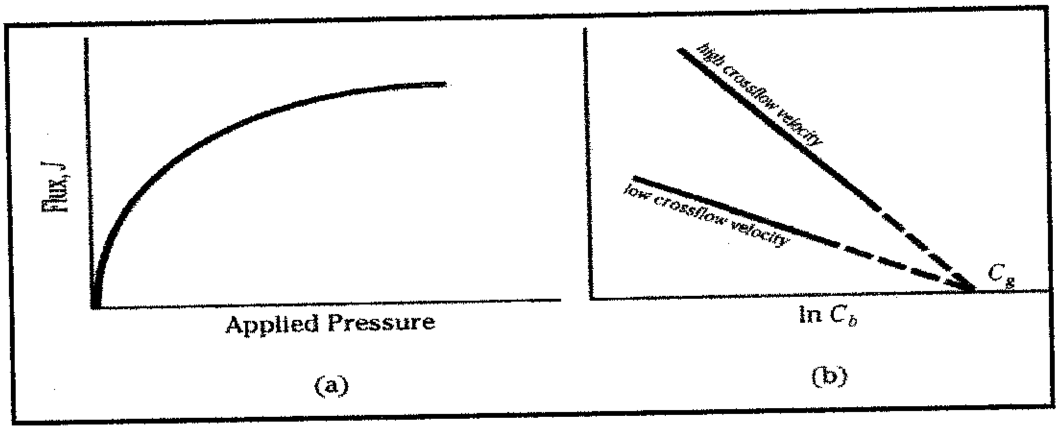


Figure 3: *Typical dependence of membrane flux. (a) Applied pressure difference, (b) Solute concentration,*

Solution containing macromolecular gel-forming solute will form a gel on the surface of the membrane. The gel formation will contribute to formation of dynamic membranes. The mechanism is as follows:

Due to convective flux through the membrane a concentration of the solution at the surface C_w increases and eventually reaches a gel formation concentration C_g (Figure 3b).

The flux, J through the membrane depends on a concentration according to the relationship:

$$J = k.In\frac{C_w}{C_b} \qquad (8)$$

Combining equations (1) and (4),

$$In\frac{C_w}{C_b} = \frac{\Delta P}{v(R_m + R_p)k} \qquad (9)$$

As long as concentration C_w is less than C_g, C_w will increase with pressure, but the moment C_w, equals Cg, an increase of the layer resistance R_p, and the flux will no longer vary with pressure (3a). Assuming no fouling effect, the membrane resistance R_m can be calculated from the flux equation below:

$$J = \frac{\Delta P}{v.R_m} \qquad (10)$$

The slope obtained from the plot of flux, J versus ΔP is equal to $\frac{1}{v.R_m}$.

The retention of any solute can be expressed by the rejection coefficient, R

$$R = \frac{\ln(C_f / C_0)}{\ln(V_0 / V_f)} \qquad (11)$$

Where, C_f is final macrosolute concentration in the retentate

C_0 is initial macrosolute concentration

V_0 is initial volume

V_f is final retentate volume

This expression assumes complete mixing of retentate seldom accomplished due to concentration polarization. For material entirely rejected, the rejection coefficient is 1 (100% rejection), for freely permeable material it is zero. (*Solteq manual, 2004*)

In reverse osmosis and nanofiltration, the membrane selectivity is usually quoted as a rejection (or retention), and is defined in terms of the fraction of the solute in the feed that appears in the permeate:

$$R = \left(1 - \frac{C_p}{C_f}\right) \text{x } 100\% \qquad (12)$$

where C_p is the concentration of the permeate and C_f is the concentration of the feed rejections are usually quoted on a percentage basis. In benchmarking for RO, sodium chloride is the most commonly used solution. For solution mixtures the various solutes/ ions have different rejections. Most ions have positive rejections, but in a number of cases, certain species (usually those involved with weak acids) can chow a strong negative rejection. In practice, the rejecting properties of a membrane can be characterized through any relevant measure of the composition. Common measures are:

2.4.1 Conductivity

2.4.2 Refractive index

The most widely used measure in RO is conductivity, while refractive index is widely used in food applications.

Rejection is a function of molecular size and shape. Nominal cut-off levels, defined with model solute, are convenient indicators. Fractional rejection by membranes with low MW cut-off spans a narrower range of molecular size than by more open membranes. For maximum retention of a solute, select a membrane with nominal cut-off well below the MW of the species. Many biological macromolecules tend to aggregate so that effective size may be much larger that the "native" molecule, causing increased rejection. Degree of hydration, counter ions and steric effects can cause molecules with similar molecular weights to exhibit very different retention behavior. The predicted behavior of rejection and flux is shown in Figure 5. (*P. T. Cardew et. al, 1998*)

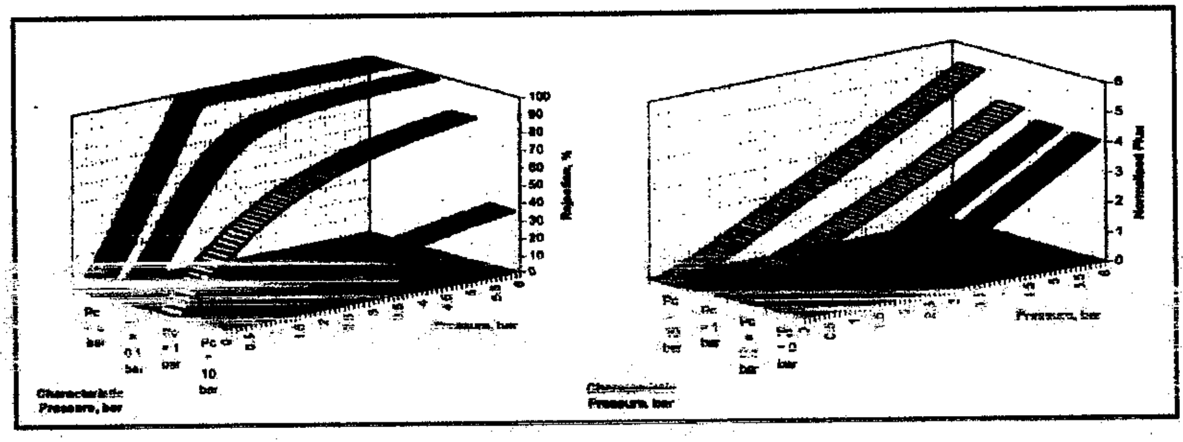


Figure 4: *Plots of rejection and flux versus pressure for membranes with various characteristics pressures.*

2.4 Literature review / Theory for other research that had been done

2.4.1 The rejection of specific organic compounds by reverse osmosis membranes by C. Frederik Schutte, Department of Chemical Engineering, University of Pretoria, South Africa, February 2003.

The performance characteristics of two commercially available reverse osmosis (RO) membranes, one cellulose acetate and the other composite polyamide, were investigated with respect to the rejection of different organic compounds to investigate correlation with certain solute physical-chemical parameters. It is shown that solute flux in the membrane is a function of effective molecular size of the solute.

Tables 4 and 5 summarize alcohol and phenol rejection data respectively, while Figure 5 graphically shows rejection of linear alcohols by the two membranes as a function of molecular mass. From this figure there is a pattern for the rejection of the linear homologues by the composite membrane. On the other hand rejection of the linear homologues by the cellulose acetate membrane is much lower and does not follow the same pattern of high rejection of 25-30% are obtained for methanol and 1-propanol, while rejection of 1-hexanol, for example, is much lower at about 10%.

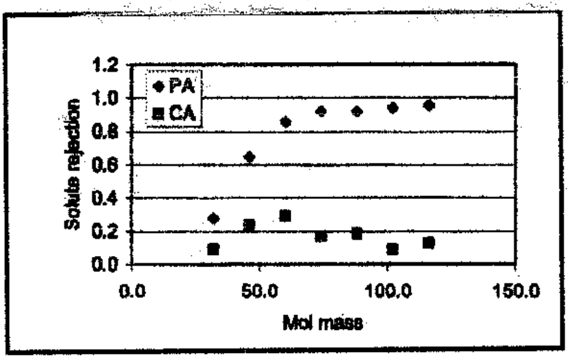


Figure 5: *Rejection of linear alcohol vs molecular mass by composite polyamide and cellulose acetate membranes.*

Table 4: Alcohol rejection data dilute feed solutions 5.0 mmol/l, 25°C.

Solute	Composite PA membrane rejection			Mol. mass	CA membrane rejection		
	1405 kPa	2810 kPa	5620 kPa		1405 kPa	2810 kPa	5620 kPa
Methanol (1)	0.22	0.28	0.36	32.0	NA	0.094	
Ethanol (2)	0.55	0.65	0.75	46.1	0.24	0.182	0.27
						0.24	
1-propanol (3)	0.82	0.86	0.88	60.1	NA	0.293	NA
2-propanol (4)	0.93	0.95	0.976	60.1	NA	0.480	NA
1-butanol (5)	0.89	0.92	0.93	74.1	0.17	0.218	0.23
						0.17	
2-butanol (6)	0.962	0.970	0.982	74.1	NA	0.497	NA
2-methyl-1-propanol (7)	0.970	0.975	0.984	74.1	NA	0.497	NA
2-methyl-2-propanol (8)	0.983	0.990	0.994	74.1	0.80	0.868	0.84
						0.80	
1-pentanol (9)	0.90	0.92	0.944	88.2	NA	0.185	NA
1-hexanol (10)	0.93	0.94	0.955	102.2	0.11	0.155	0.07
						0.09	
1-heptanol (11)	0.93	0.955	0.967	116.2	NA	0.131	NA

NA = Not available.

Table 5: Reverse osmosis data for phenols. Dilute feed solutions 2.0 mmol/l, 25°C.

Solute	PA rej. at 1405 kPa	PA rej. at 2810 kPa	PA rej. at 5620 kPa	Mol. mass	CA rej. at 1405 kPa	CA rej. at 2810 kPa	CA rej. at 5620 kPa
Phenol (1)	0.87	0.92	0.94	94.1	0.02	0	-0.04
4-methyl phenol (2)	0.91	0.94	0.967	108.1	NA	NA	NA
4-ethyl phenol (3)	0.93	0.96	0.970	122.2	NA	NA	NA
2,6-dimethyl phenol (4)	0.975	0.978	0.991	122.2	0.44	0.31	0.20
4-n-propyl phenol (5)	0.967	0.976	0.980	136.2	0.20	0.11	0.05
4-isopropyl phenol (6)	0.978	0.984	0.988	136.2	0.38	0.35	0.23
Benzene (7)	0.80	0.86	0.88	78.1	NA	NA	NA
Toluene (8)	0.84	0.90	0.94	92.2	NA	NA	NA

NA = Not available.

The general trend of rejection of linear alcohols by the composite PA membrane indicates that a simple correlation exists with molecular mass. However, rejection of the branched isomers does not fall into this pattern. It should be noted that rejection of branched isomers is higher than for linear isomers of equal molecular mass. For the rejection of alcohols by the composite PA membrane, molecular mass of the particular alcohol gives a good indication of the degree of rejection that may be attained taking into account that rejection of branched isomers will be higher than rejection of the linear equivalent. Rejection of the different phenols by the PA composite membrane (Table 5) follows the same general trend as for the alcohols with higher rejections as the molecular mass and molecular size of the solute increase. Rejection by the cellulose acetate membrane is in general very much lower than rejection by the composite membrane and even negative rejections of phenol are recorded.

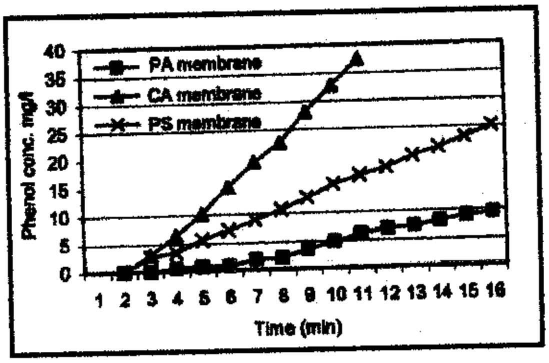


Figure 6: *Phenol permeation vs time.*

Figure 6 shows the rate of phenol permeation through the three membranes. The very low permeation rate through the composite PA membrane compared to the CA membrane is in line with phenol reverse osmosis data for these two membranes.

Table 6 shows that when solute rejection is considered, membrane rejection R gives a good reflection drops from 0.95 to 0.90 the number of moles rejected drops proportionally, i.e. from 9.5 to 9.0 in this example.

Table 6: Rejection compared to permeation

Rejection	Feed conc., C_f mmol/l	Permeate conc, C_p mmol/l	mmol/l rejected	mmol/l permeated
0.50	10	5.0	5.0	5.0
0.80	10	2.0	8.0	2.0
0.90	10	1.0	9.0	1.0
0.95	10	0.5	9.5	0.5
0.990	10	0.10	9.90	0.10
0.995	10	0.05	9.95	0.05

When rejection drops from 0.95 to 0.90 (i.e. a 5% drop), there is a 100% increase in the number of moles permeating the membrane from 0.5 to 1.0 mol. Similarly when rejection drops form 0.995 to 0.95 (i.e. about 5%), there is a tenfold increase in the number of moles permeating the membrane. Although these differences are only relative, they are important when considering the actual passage of molecules through a membrane and in attempting to relate changes in permeation to molecular characteristics. This is true especially when small differences in the high rejection range > 0.90 are important. In such cases solute flux J_s offers a better means of comparison.

2.4.2 Observations on solvent flux and solute rejections across solvent resistant nanofiltration membranes by Emma Gibbins, Marco D'Antonio, Dinesh Nair, Lloyd S. White, Luisa M. Freitas dos Santas, Ivo F.J. Vankelecom, Andrew G. Livingston, Department of Chemical Engineering, Imperial College, United Kingdom, March 2002.

Solvent flux decline and membrane separation properties are investigated (including their dependence on pressure), using methanol with quaternary alkyl ammonium bromide salts with molecular weights (MW) in the range 322 to 547 Daltons as solutes. The membranes are characterised in terms of an equivalent uniform pore size using three simple pore flow models: Ferry model, Steric Hindrance Pore (SHP) model and Verniory model.

Figure 7 shows the effect of pressure on initial and final (steady) solvent flux. Both fluxes increase linearly with pressure, consistent with both the pore flow and solution diffusion models. Figure 8 shows the percentage solvent flux decline (from initial to steady) as a function of pressure. MPF50 responds quickly to pressure, reaching steady state almost immediately; the percentage flux decline is almost independent of pressure. The flux decline in STARMEM 122 reaches a steady value of 70% as pressure increases, taking longer to equilibriate to its final compaction level at higher pressures.

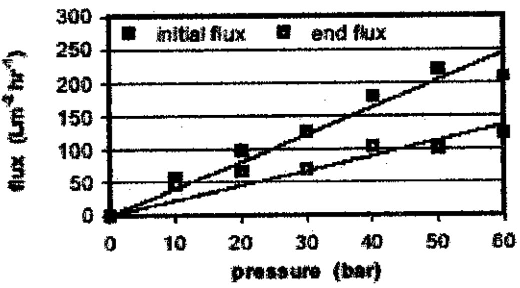


Figure 7: *Influence of pressure on initial and end fluxes for pure methanol and STARMEM 122.*

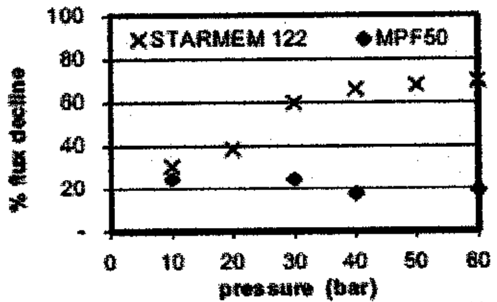


Figure 8: *Influence of pressure on % flux decline for pure methanol, STARMEM 122 and MPF50.*

It was demonstrated that as the amount of methanol permeated across the membrane prior to quat filtration was increased, the rejection improved. The effect of pressure on the rejection of the membrane was studied for a range of quats. A clear positive dependence was observed for all membranes. Figure 9 shows the pressure trend for STARMEM 122 and Figure 10 shows the trends for all membranes at 30 bar.

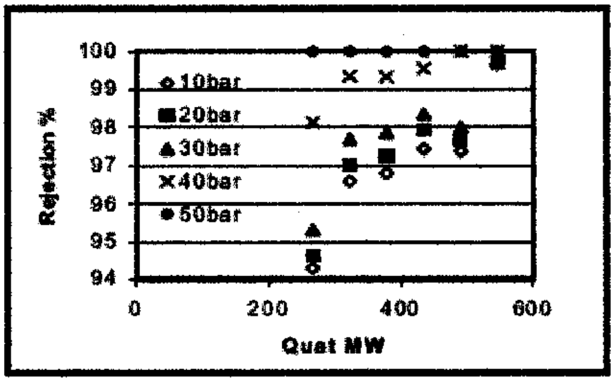


Figure 9: *Influence of MW and applied pressure on rejection of a MW spread of quats in methanol for STARMEM 122.*

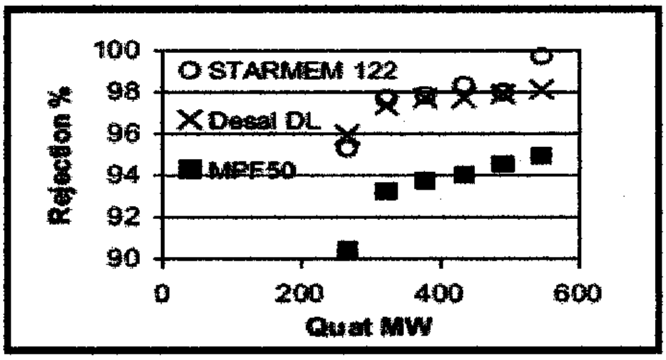


Figure 10: *Rejection data at 30 bar for all membranes studied.*

The predicted pore size varies with applied pressure and solute size, though these variations are small enough that they may be neglected. Thus, the membrane pore size can be quoted on the basis of an average over all pressures and solutes.

2.4.3 The specific behaviour of NF membranes in the separation of high ionic strength electrolyte solutions by A. Schonauer and W. M. Samhaber, Institute of Process Engineering, Johannes Kepler University Linz, Austria.

The measurements were carried out with single-salt solutions containing $MgCl_2$, NaCl and Na_2SO_4 by using commercially available polymeric nanofiltration membrane. In Figure 11 the rejection is plotted against the salt concentration in the feed of the solution.

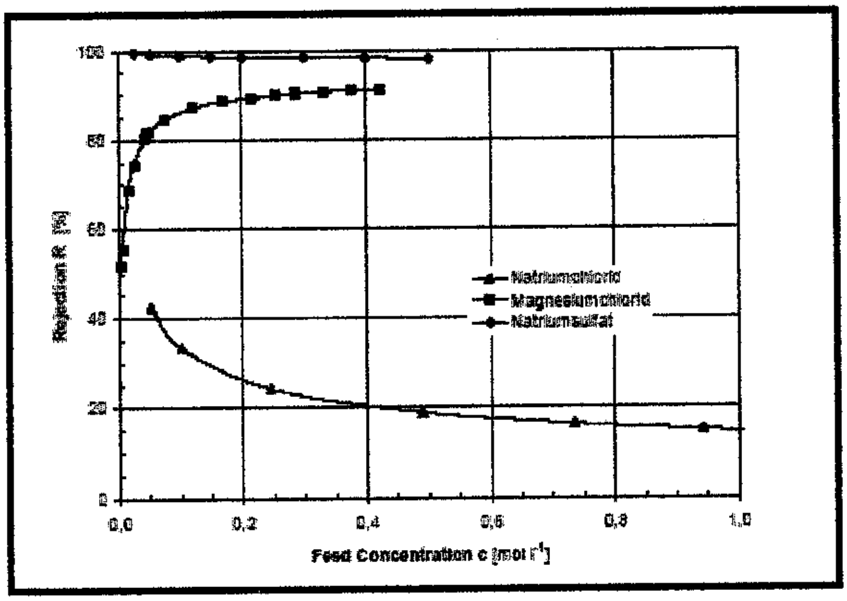


Figure 11: *Rejection R of different salts as a function of the feed concentration c for a DK membrane*

The diluted solutions the membrane shows the following salt rejection sequence: R ($MgCl_2$) < R (NaCl) << R (Na_2SO_4). In this case, the rejection sequence is explained by two ways. From *Peeters* (1998) differences in diffusion coefficients between the different salts is responsible for the sequence. As shown in Table 7 the diffusion coefficient decreases going from NaCl, $MgCl_2$ to Na_2SO_4. The salt with the lowest diffusion coefficient shows the highest rejection, whereas that with the highest diffusion coefficient shows the lowest rejection. From *Xu* (1999) explained it with the "sieve effect". The sieve effect depends essentially on the steric hindrance parameter of the solute on the interface. For a given solute, the sterice hindrance parameter of a solute depends on the chemical nature of the solvent and the material of the membrane surface. The value of the Stokes can be used as an approximation.

Table 7: Comparison of Rejection with Diffusion coefficients and their Stokes radius of different electrolytes in water

Elektrolyte	**Rejection *R* [-]** $c_0 = 0{,}4$ [mol l^{-1}], $J_v = 27{,}3$ [kg m^{-2} h^{-1}]	**Diffusion coefficient** D [10^{-9} m^2 s^{-1}]	**Stokes radius** r_S [10^{-10} m]
NaCl	0,20	1,612	1,52
$MgCl_2$	0,90	1,254	1,96
Na_2SO_4	0,98	1,230	1,99

Figure 11 also shows the dependency of the rejection on feed concentration. The NaCl and the Na_2SO_4 rejection slightly decrease with increasing salt concentration for the DK membrane. For $MgCl_2$ the rejection increases with with increasing salt concentration. This is might be affected by the steric hindrance behaviours of the hydrated magnesium ion. In conclusion, for the membrane high retention were found for Na_2SO_4 and for $MgCl_2$ in concentrated solutions.

2.4.4 Effects of surface force interactions on an NF/UF membrane by Steven J. Harrold, Dvaid J. Paulson, Greg S. Ross and Brian J. Rudie, April 1992.

In this work, it was observed the separation characteristics of a novel, anionically charged membrane with UF and NF capabilities. The objective of this study was to demonstrate surface force interactions between the solutes and the membrane resin.

Separation data for B-type membranes with large nonionic organics are shown in Figure 12. The PEG and polysaccharide solutes are typical of those used to characterize the size exclusion properties of UF membranes. The data suggest that the B-type membrane is best described as a "tight" ultrafilter with an MWCO ranging from about 2k000 daltons for polysaccharides to around 5,000 daltons for PEG's. The MWCO result for PEG's is higher than that for polysaccharides because PEG's are adsorbed by the B-type membrane while polysaccharides are repelled by the membrane.

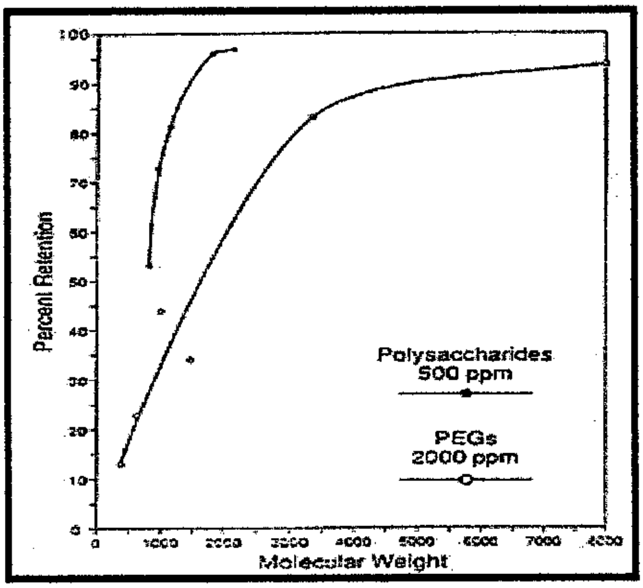


Figure 12: *B-type membrane retention of nonionic organics.*

Figure 13 demonstrates that B-type membranes can function as an NF membrane in the context of salt separations despite high MWCO ratings for uncharged organics.

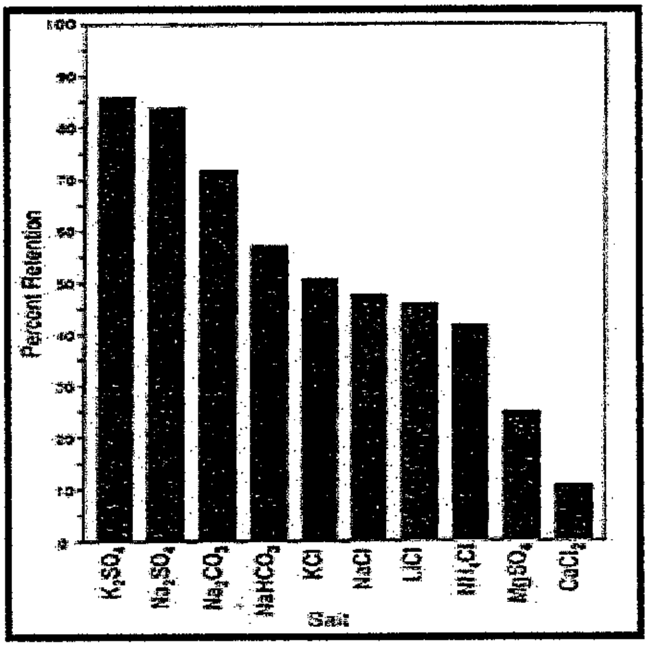


Figure 13: *B-type membrane salt retention test conditions. [0.32 m/s crossflow velocity; 250 psig (17 bar), 2000 ppm salt concentration].*

Charge repulsion between salt anions and the membrane surface complement separation due to physical sieving. Sulfate has twice the charge of chloride and is also much larger. Charge repulsion occurs further from the membrane surface and hence sulfate is more easily excluded from membrane pores. Another feature is the effect of calcium and magnesium on salt separation. Figure 14 show that higher salt concentrations also decrease salt separation. Increased salt passage reduces the difference in salt concentrations across the membrane, consequently reducing osmotic pressure and increasing the available effective pressure. The effective pressure driving permeate flux is the result of osmotic pressure subtracted from applied pressure as measured by a gauge. Higher effective pressure results in higher permeate water flux.

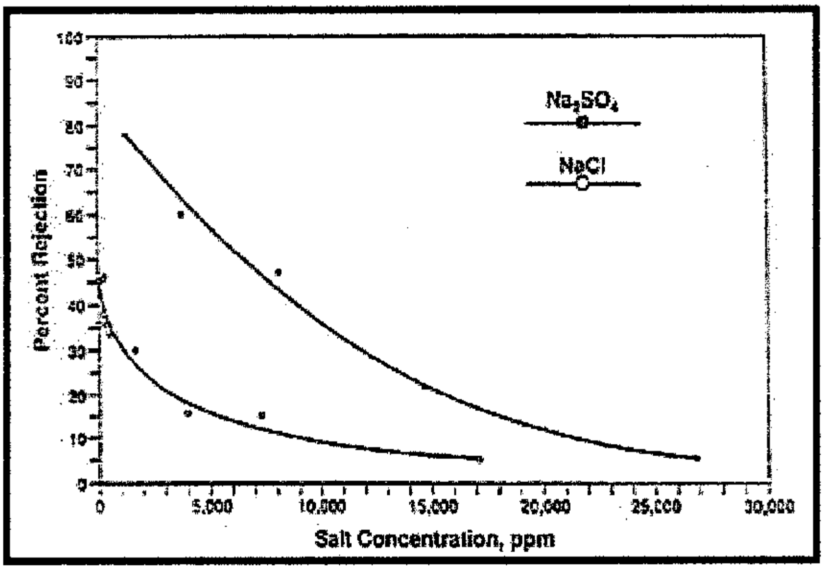


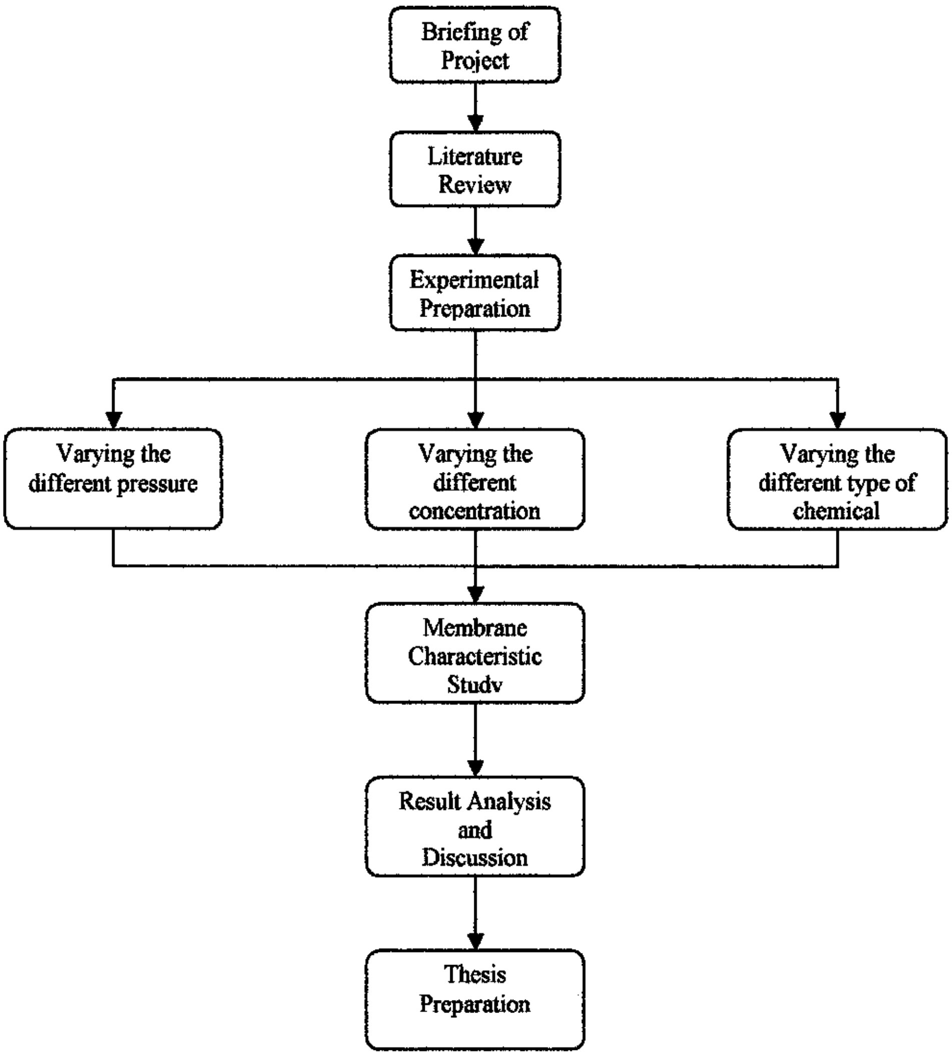
Figure 14: *Effect of salt concentration on retention.*

From this study, it shows that separation of the divalent species was higher. This suggests that the membrane discriminates between monovalent and divalent salts on the basis of both ionic size and charge repulsion.

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 Project Flow Diagram



3.2 Procedure Identification

From this experiment, it can study those objectives and analysis the data obtain on two different types of membranes. The basic approach is to set up the critical conditions for the feed composition and the pressures of both permeate and the retentate stream. The performances of the separation are analyzed by carrying the following condition:

3.2.1 Varying the feed concentration
3.2.2 Varying the pressure
3.2.3 Varying the chemical

This experiment requires different chemicals which are Sodium Chloride (NaCl) and Calcium Chloride ($CaCl_2$). The detail procedures are as below:

3.2.4 Salt solution (NaCl and $CaCl_2$,) were prepared by adding respective amount of chemical into 20 liter of de-ionized water to obtain the concentration needed (i.e 0.2M, 0.5M and 1.0M).
3.2.5 The tank was filled up with the solution or salt water prepared in step above. The feed shall always be maintained at room temperature (25 °C).
3.2.6 The working pressure was set at 5 to 20 bar. The flowrate could be controlled at 10 LPM by adjusting regulator PR1 and valve V8.
3.2.7 The plunger pump was started in order to run the equipment and let it stabilized. Set membrane inlet pressure to the appropriate value by adjusting the retentate control valve.
3.2.8 The system was allowed to run for 5 to 10 minutes. Start collecting sample from permeate sampling port. The weight and conductivity reading of permeates were recorded.
3.2.9 Permeate and reject were continuously recycled to the feed tank.
3.2.10 The plunger pump was stopped and valves were closed.
3.2.11 Membrane was placed in solutions of different concentrations and the changes in concentration of the solution were monitored until equilibrium was reached.
3.2.12 The membrane was washed in deionised water until virtually all chemicals were leached out before run next experiment.
3.2.11 The graphs were plotted from the data obtained in order to find the objectives.

3.3 Tools and Equipment

For description of membranes, there are four membranes which are RO, NF, UF and MF membranes that were supplied in the equipment but for this study, it is focused only on RO membrane due to time constraint. The equipment that will be used is SOLTEQ Membrane Test Unit (Model: TR08) from Solution Engineering Sdn. Bhd. It is specially designed to allow students and researchers to carry out the membrane processes that are widely used in biotechnology and process industries. This equipment is supplied with data acquisition system (DAS). Simply constructed in 316 stainless steel, the module has termination points allowing easy connection by flexible or welded couplings to existing equipment. The open channel, highly turbulent flow design allows a wide variety of process fluid to be concentrated. It also allows simple clean-in-place techniques to be entirely effective. The membrane is:

3.3.1 Membrane 1 : AFC 99 (Reverse Osmosis)
Material : Polyamide Film
Maximum Pressure : 64 bar
Retention Character : 99% NaCl
Length : 1.2 m
Diameter : 12.5 mm

* *(Please refer to Figure 1.1 and 1.2 in Appendix 1 for membrane selectivity).*

There two types of pumps are provided with the equipment which Centrifugal and Triple Plunger pump. The Centrifugal pump is used to circulate the liquid from the plate heat exchanger to the water tank while Triple Plunger pump is used to pump the liquid from the feed tank into the membrane. Pressure regulator also installed to regulate the operating pressure of the feed stream. The Membrane Test Unit is supplied with a feed tank and a product tank, both having maximum capacity of 20 liters. The feed and product tanks are made of stainless steel for corrosion and chemical resistance. The retentate line is equipped with a unit of shell and tube heat exchanger. The process diagram is illustrated in Figure 15.

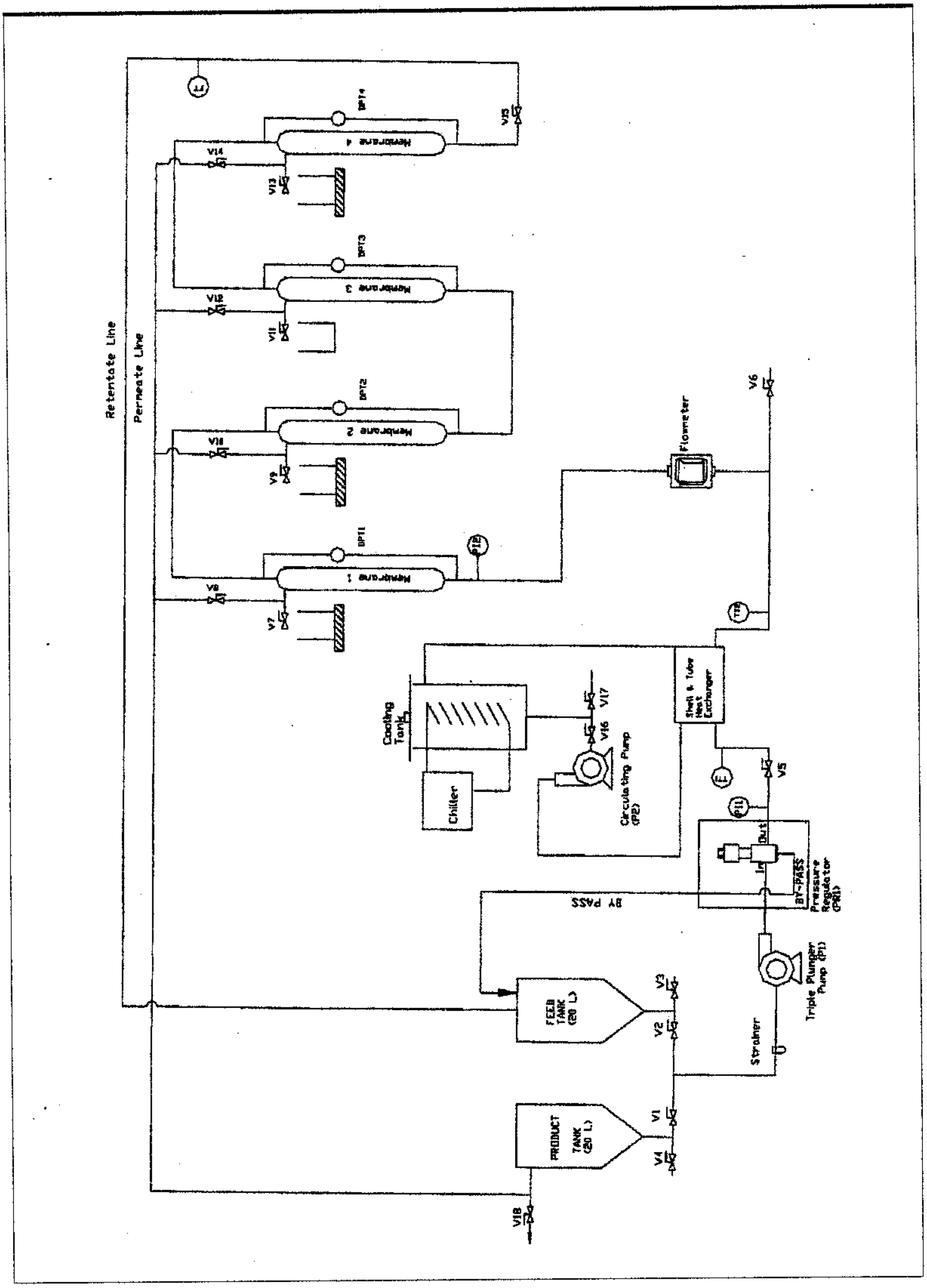


Figure 15: *Schematic Diagram for Membrane Test Unit (Model: TR 08)*

3.4 Experimental Chemicals and Apparatus

3.4.1 Chemical

The following chemical is used in the experiments.

3.4.1.1 NaCl

Name : Sodium Chloride
Appearance : Pellets
Supplier : Mallinckrodt Laboratory Chemicals.
Purpose : Aqueous solution for surface charges.

3.4.1.2 $CaCl_2$

Name : Calcium Chloride
Appearance : Pellets
Supplier : Mallinckrodt Laboratory Chemicals.
Purpose : Aqueous solution for surface charges.

3.4.2 Apparatus

The following apparatus are used in the laboratory.

3.4.2.1 Beaker (250, 500, 1000 and 2000 mL)
3.4.2.2 Spatula
3.4.2.3 Digital Balance
3.4.2.4 Conductivity meter
3.4.2.5 Glass rod

3.4.3 Procedure to clean apparatus

All apparatus used in the experiment are cleaned and dried. Following procedures outlined here to reduce contamination.

3.4.3.1 Remaining residue / solution is rinsed off using tap water.

3.4.3.2 Glassware is rinsed with de-ionized water at least twice.

3.4.3.3 Always rinse the conductivity meters before and after each use with deionised water. The buildup of salts will interfere with proper operation, and the carryover of salts from one solution to another can skew the readings.

3.4.3.4 Do not touch or otherwise abrade the electrode surfaces, except with a soft, nonabrasive cloth.

3.4.4 Personal Protection Equipment

For health and safety purposes, the following equipment were worn while conducting the experiments on sample preparation:

3.4.4.1 Lab coat

3.4.4.2 Rubber glove

3.4.4.3 Covered shoes

3.5 Safety Precautions

Safety precautionary steps are observed throughout the experiments to ensure health and safety of the author and others are not endangered.

3.5.1 Sample preparation

Basic laboratory outfit (lab coat and rubber glove) is worn throughout experiments.

CHAPTER 4

RESULT AND DISCUSSION

The equipment of Membrane Test Unit was run in order to determine and calculate the permeate composition. The parameters such as feed composition (concentration) and feed pressure are varied at constant flowrate. In order to determine the flux and rejection of salt, firstly, we need to investigate the performance of the membrane. The membrane used in this research is RO membrane. Charged RO membrane is used for the separation of many aqueous solutions.

RO is positively membrane and membrane type used in this research is polyamide (aramid). Polyamides are naturally more hydrophilic because it allows water to permeate. Besides that, this membrane can interact well with water because of the hydrogen bonding. Polyamide is water sensitive due to hydrogen bonding character of the amide group. Inside the polyamide membrane, there is not only consist hydrogen bonding. Between the molecules polyamide itself, there are Van der Waal and dipole-dipole bonding but it is more strong to hydrogen bonding when interact with water. Polyamide has very strong tensile strength compared other polymer because it consist all these bonding.

The performances of the separation are analyzed by carrying the following condition:

4.1 Effect on feed concentration
4.2 Effect on pressure
4.3 Effect on different type of chemical

Below are observation, result and the discussion of the experiment. Method and procedure of the experiment already explained in Chapter 3.

4.1 Effect on feed concentration

The objectives of this part are to study the effect at different concentration and also to observe the conductivity changes in the feed and product tank. Concentration control is probably the most complex and difficult target to achieve, yet of the aim of a process is to produce a product of a consistent quality. For the study, the feed concentrations used are 0.2, 0.5 and 1.0 M at two different aqueous solutions which are Sodium Chloride (NaCl) and Calcium Chloride ($CaCl_2$). The concentration is determined by using conductivity meter in order to obtain the conductivity value. Before continued for the experiment, firstly, the conductivity reading has been taken at different concentration. From the conductivity value, the concentration of permeate water can be obtained.

There are differences between conductivity because of the different of ions. Conductivity of solutions depends on the concentration and charges of ions in solution. Ions with higher charges tend to have higher conductivity because they not only carry more charge but they respond more strongly to an electric field. An ion of calcium (Ca^{2+}) has higher conductivities than sodium (Na^{+}). Ion calcium with a charge of +2 will carry two times as much current as a +1 sodium ion. The conductivity will increase proportional to an increase in amount of ions present in solution. The relation between conductivity and concentration can be seen in following figure:

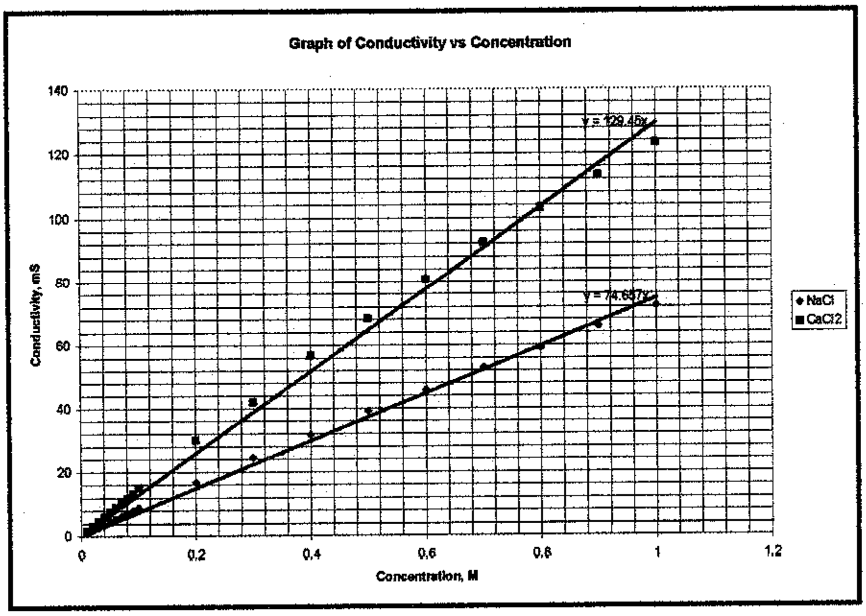


Figure 16: *Relation between conductivity and concentration of salt solution*

In RO, the membrane selectivity is usually quoted as a rejection, and is defined in terms of the fraction of the solute in the feed that appears in the permeate:

$$R = \left(1 - \frac{Cp}{Cf}\right) x100\% \tag{13}$$

where C_p is the concentration of the permeate and C_f is the concentration of the salt feed rejections. The membrane rejection is defined as the difference between the feed concentrations and permeates concentration (*Karrie D. Houston*). The principle of situation is shown in figure below (Figure 17):

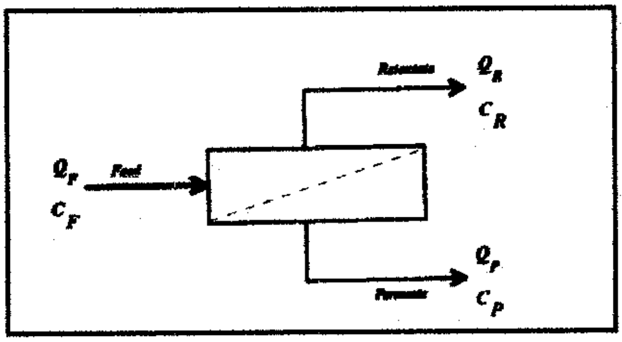


Figure 17: *Schematic outline of membrane separation process*

The flux, J is given by following formula:

$$J = \frac{1}{A_m} \frac{dV}{dt} \tag{14}$$

where A_m is membrane area and dV/dt is gradient from graph of volume against time plotted.

In the process, retentate is recycled to the feed tank and permeate is collected separately. As the time and pressure increases, the volume of permeate collected increases. The permeate produced at any instant of time is called the instantaneous permeate. Since the permeate is removed continuously from the feed, the volume of the feed decreases, the feed becomes more concentrated with time but it is only slightly change. The change of feed volume and concentration can be neglected. The feed in this type of process can also be referred to as the concentrate. In this study, it was assumed that the mixture in feed tank was well mixed. Thus the concentration of the feed to the membrane equals the concentration in the feed tank. (*P. T. Cardew et. al, 1998*)

From the observation, as can be seen in Figure 19 and 20, the different concentration in the feed affects the rejection and the flux characteristics. Figure 18 shows that higher salt concentration will reduce the rejection from 99.26% to 72.25% and Figure 19 shows flux (in the presence of NaCl) through the membrane drop from 14.7 to 0.09 L/m^2.h at maximum pressure as the concentration in the feed is increased from 0.2 to 1.0 M. The flux and rejection values were calculated by using equation (13) and (14) respectively.

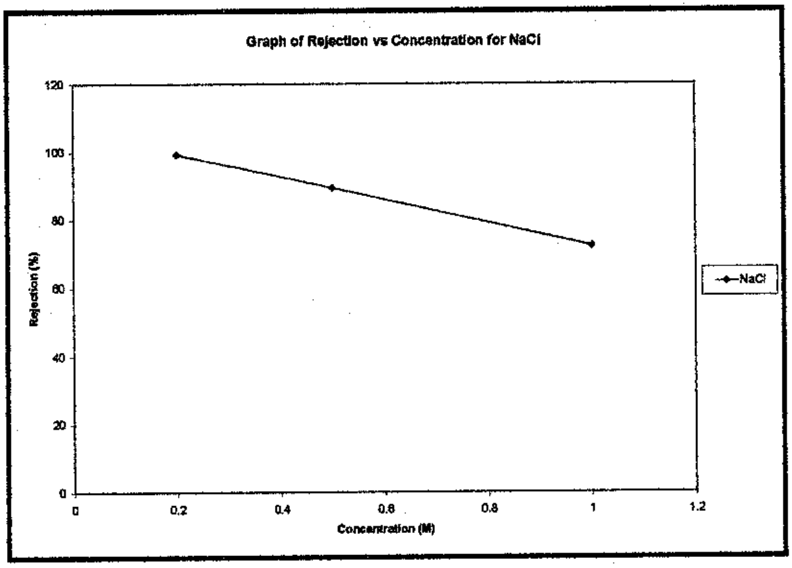


Figure 18: *Effect of rejection on different of concentration for Sodium Chloride*

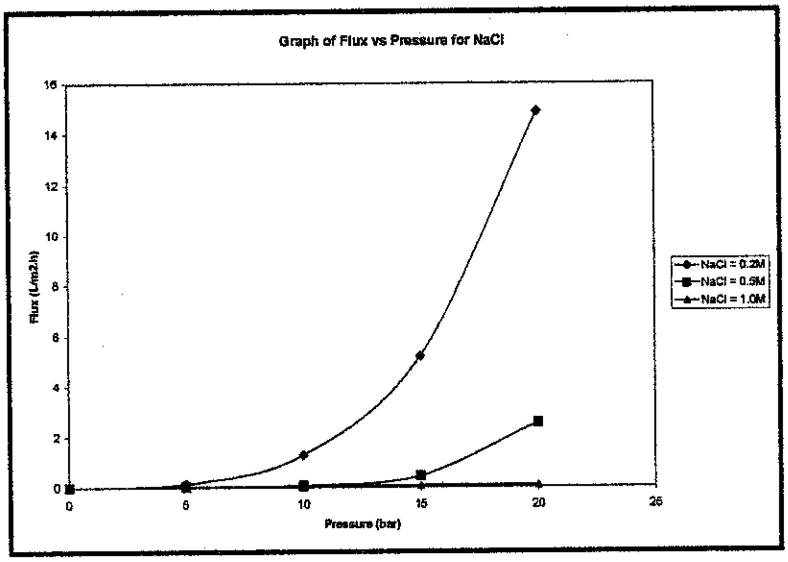


Figure 19: *Effect of flux on different pressures for Sodium Chloride*

While in presence of $CaCl_2$, the rejection also shows the same condition as NaCl. The rejection tends to decrease as the concentration increased even though at different salt solution. The Figure 20 below presents the rejection of $CaCl_2$ at different concentration.

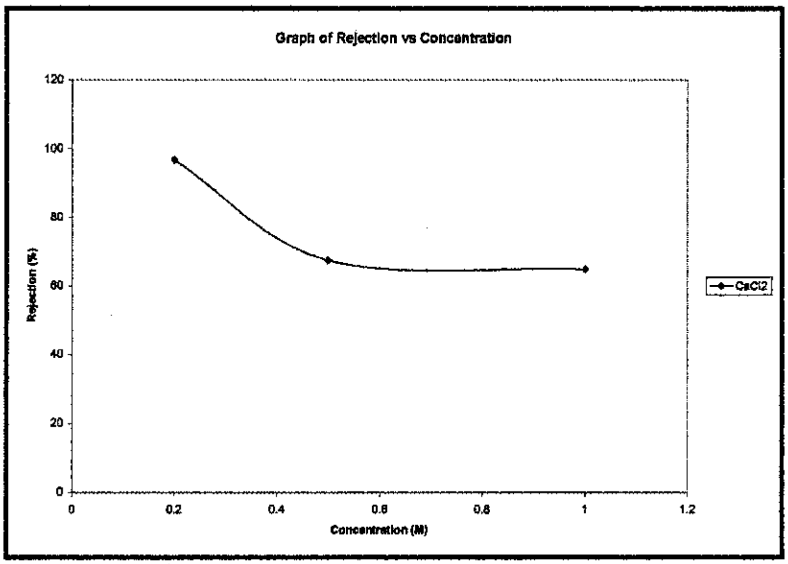


Figure 20: *Effect of rejection on different of concentration for Calcium Chloride*

The rejection is reduced from 96.83 % to 64.83% as the concentration is increased while flux also decreased from 4.16 to 0.28 L/m^2.h (refer Figure 21) as increase the concentration at maximum pressure.

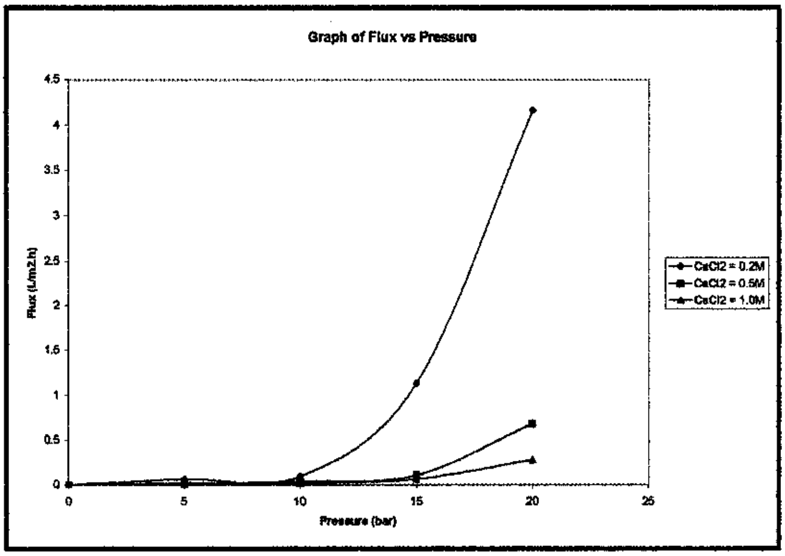


Figure 21: *Effect of flux on different pressure for Calcium Chloride*

From the both graphs above, it shows the dependency of the flux and rejection on feed concentration. The reducing in the rejection can be due to the ion being too large to pass through the membrane.

Although a positively charged RO membrane could have high rejections of salt at low concentration due to charge repulsion. At high concentration of salts, the charge effects would be masked and it would be expected that the rejection of the salt decreases significantly. This result is expected since as the salt concentration is increased, the partial rejection of the salt ions, decreases. The results obtained in this research are complied with *A. Schonauer et. al*, and *Steven J. Harrold et. al, 1992.*

For a membrane under steady state condition, when the solution flows through the system parallel to the membrane surface at a given rate, both the solute and the solvent are forced to pass through the membrane owing to the action of the pressure difference. The solvent can pass through the membrane completely but most of the solute accumulates at the surface due to the rejection caused by the membrane. Thus a concentration gradient is built between the membrane surface and bulk solution, which makes the solute diffuse back towards the bulk solution. The higher the solute concentration at the membrane surface the lower will be solute permeation rate of the solvent. This unfavorable phenomenon is called concentration polarization.

In other meaning, as water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt concentration in the bulk solution. This increase of salt concentration is called concentration polarization. The effect of concentration polarization is to reduce actual product water flow rate and salt rejection versus theoretical estimates.

The concentration polarization factor (CPF) can be defined as a ratio of salt concentration at the membrane surface (C_s) to bulk concentration (C_b).

$$\text{CPF} = \frac{C_s}{C_b} \tag{15}$$

An increase in permeate flux will increase the delivery rate of ions to the membrane surface and increase Cs. An increase of feed flow reduces the thickness of the high concentration layer near the membrane surface.

4.2 Effect on pressure

The mechanism of pressure effect is high-pressure pump pumps salt solution into a module separated by a semi permeable membrane into two volumes, which are permeate and retentate. The membrane lets water flow through it but blocks the transport of salts, so the water in the volume beyond the membrane, called permeate, and the salt is left behind in the volume in front of the membrane. The concentrated salt water in this volume leaves the membrane via a pressure control valve. Figure 22 and 23 show the effect of pressure on solvent flux. The pressure is varied from minimum (5 bar) to maximum (20 bar) and both fluxes for different graph increase linearly with pressure. The graph of flux is shown below for NaCl solution. By increasing the pressure, the value of flux increased, while as the concentration increased the flux slightly increased.

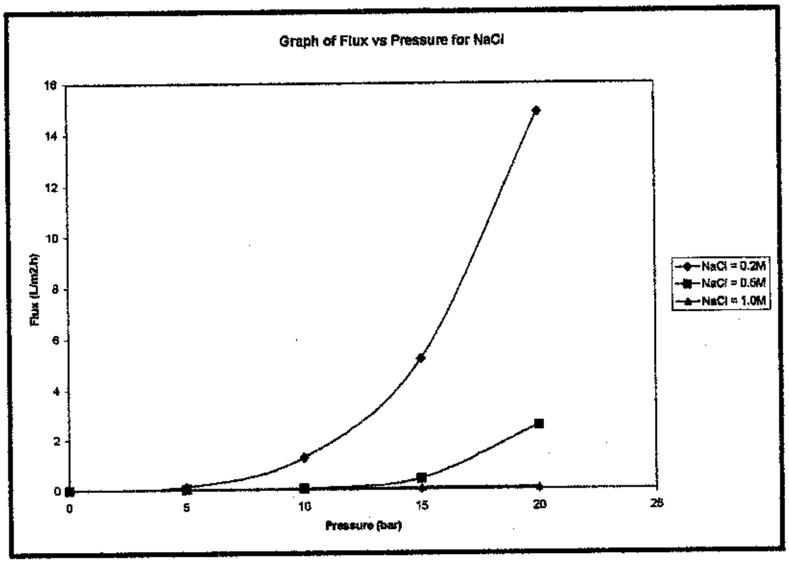


Figure 22: *Effect of flux on different pressures for Sodium Chloride*

For $CaCl_2$, the trend of the graph is same as trend of the graph for NaCl. Figure 23 shows the graph of flux for $CaCl_2$ solution.

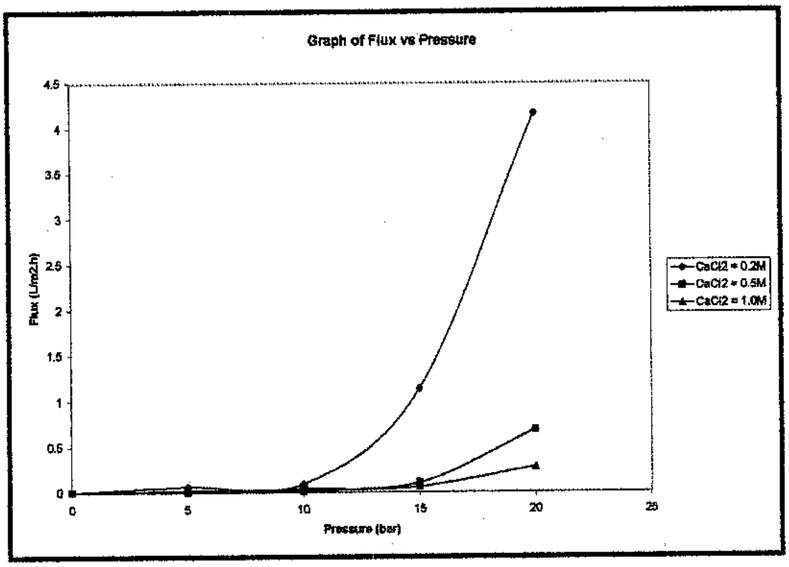


Figure 23: *Effect of flux on different pressure for Calcium Chloride*

Both graphs for NaCl and $CaCl_2$ show similarly behaviour. As we can seen from both graph above, the increasing the pressure will increase the value of flux. But as the concentration increase, the value of flux will become smaller. It also shows the different flux at different salt solution (NaCl and $CaCl_2$). The value of flux for NaCl is greater than the value of flux for $CaCl_2$. This is because of the different chemicals that gave the different flux. The detailed explanation will be discussed in the part of effect on chemicals.

The effective pressure driving permeate flux is the result of osmotic pressure subtracted from applied pressure as measured by a gauge. Higher effective pressure results in higher permeate water flux. Using the standard equation for water flux in a pressure driven membrane is defined as:

$$J_w = A(\Delta P - \Delta \pi) \tag{15}$$

where A is the water permeability coefficient, ΔP is the applied pressure difference, and Δπ is the osmotic pressure difference. As can be seen, the flux will be expected to increase linearly with applied pressure. The solvent flux of the permeate depends on the pressure applied across the membrane, minus the difference in the osmotic pressure of the solutions of the feed and permeate side of the membrane. (*Emma Gibbins et. al, 2002*)

Since the flux is dependent on pressure, an increase in pressure will increase solvent flux at constant solute flux. Consequently the percentage of the rejection will increase as increase in pressure. It can be prove by Figure 24 that shows the relation between rejection and pressure for salt solution. For both salt solutions, it shows the same trend of rejection.

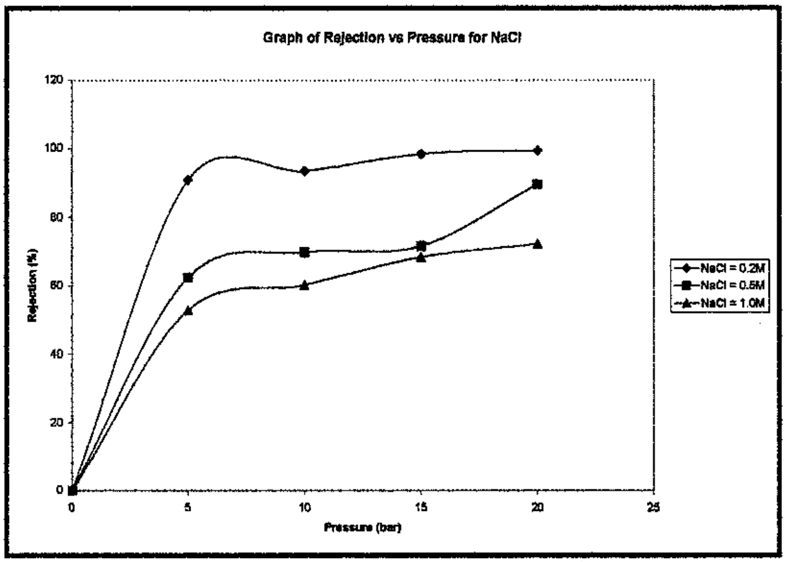


Figure 24: *Relation between rejection and pressure for Sodium Chloride*

If the feed becomes so concentrated, the flux drops, due to a large increase in the osmotic pressure of the feed. The osmotic pressure of solution increases with the increasing concentration and temperature directly. The results also consistent with the result of *P.T. Cardew et. al, 1998* and *Emma Gibbin et. al, 2002.*

The flux also is determined for pure water. The experiment done by using deionised water. The volume of the permeate increases with the time and pressure increased. The flux is increased as increasing the volume. From equation (15), for deionised water, $\pi_f = 0$, so $J_w = A\Delta P$, thus there is no rejection occur.

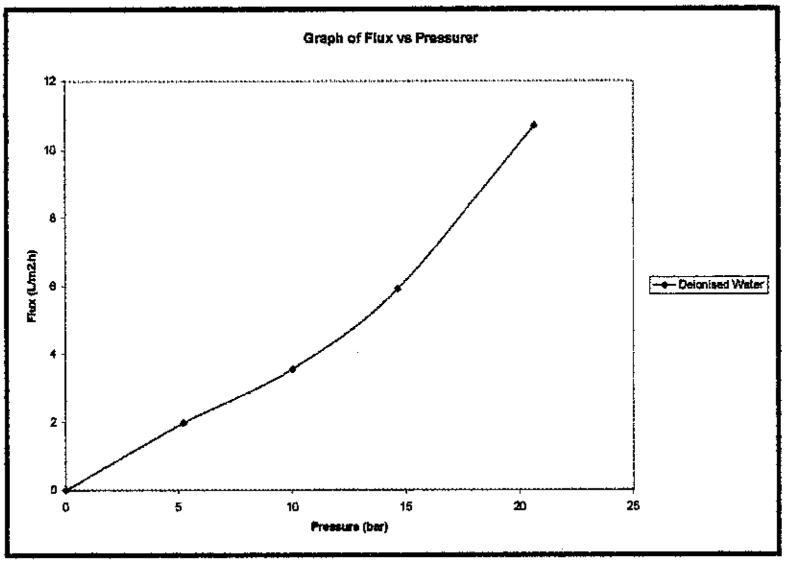


Figure 25: *Effect of flux for pure water on different pressure*

From Figure 25, the purpose to find the flux by using the deionised water is to compare the different of flux between NaCl and $CaCl_2$ solution. It can be seen that the flux of deionised water or pure water is much greater than both salt solution. This is because, inside the pure water, there is consisted no solute that will decrease the flux value and no rejection is occurred.

4.3 Effect on different type of chemicals

The behavior of RO membrane in the separation of high ionic strength electrolyte solutions composed of different charged ions was studied. In this part of result and discussion, experiments with single salt solutions will be described which were carried out with a commercially available RO membrane. Also in this study different solution systems will be used to compare the rejection behaviour of RO membrane monovalent and divalent cations of sodium sulphate and calcium chloride, respectively. The separation mechanism of RO membrane was investigated with different ionic systems and with higher ionic strength solutions.

In Figure 26, the rejection is plotted against the salt concentration in the feed of the solution.

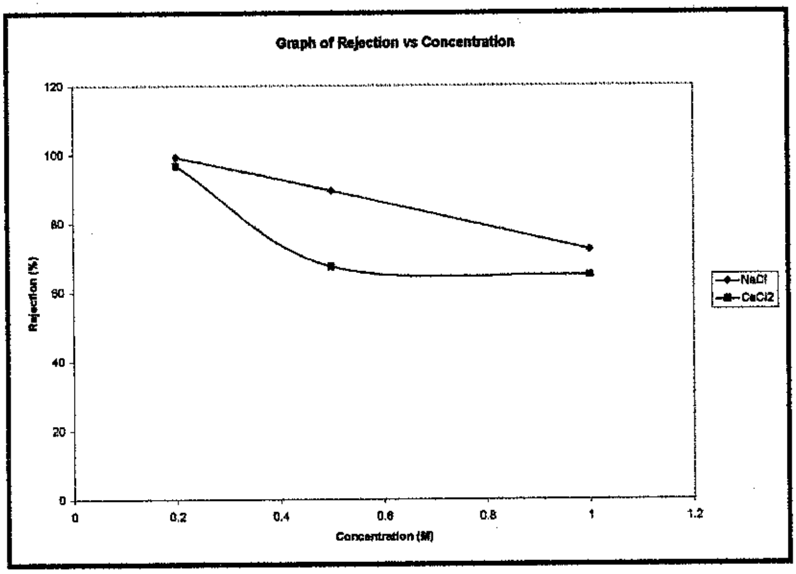


Figure 26: *Relationship between rejection and concentration on different chemicals*

In infinitely diluted solutions the membrane shows the following salt rejection (R) sequence:

$$R\ (CaCl_2) < R\ (NaCl)$$

The different of these two ions due to the surface charge on the membrane. The mechanism of this condition is shown in Figure 27 below. RO membrane is positively charge. Aqueous solution electrolyte contains negative and positive ions in it. The surface charge of the polymer membrane would repel the same charge particles of the electrolyte and leave the remaining charges inside the solution.

The rejection of $CaCl_2$ is reduced not because of the divalent ions of Ca^{2+} in the calcium chloride aqueous but because of the molecular weight and ionic radii of calcium itself.

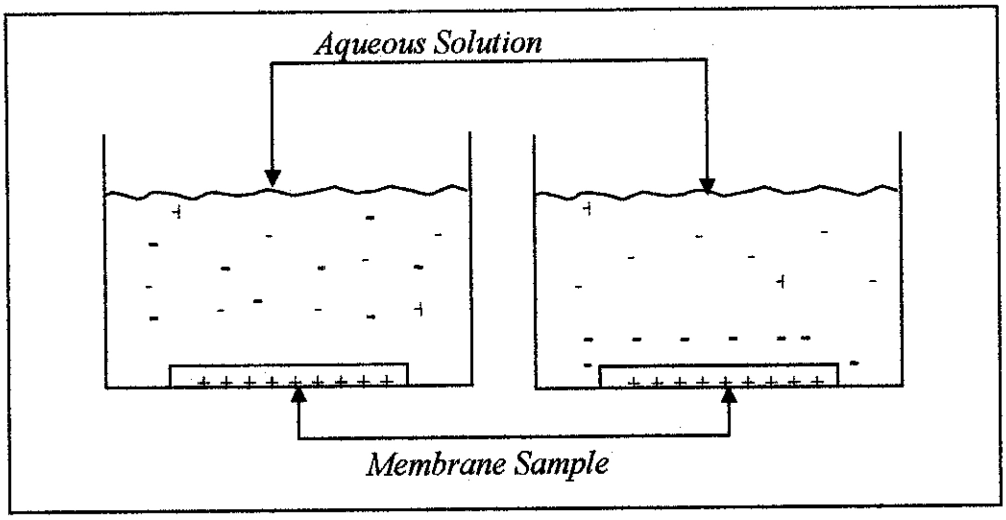


Figure 27: *Effect of Surface Charges to Aqueous Solution*

For $CaCl_2$, the rejection increases with increasing salt concentration but decreases with the divalent ions of Ca^{2+}. Charge repulsion between salt cations and the membrane surface complement separation due to physical sieving. In this case, for example, the membrane's ability to discriminate between NaCl and $CaCl_2$. Calcium has twice the charge of sodium and also much larger. Charge repulsion occurs further from the membrane surface and hence calcium is easily excluded from membrane pores. But for this case, it is different. The larger molecular weight will decrease the rejection even though the ion has +2 charges. Molecular weight for Na^+ is 23 is much lower than Ca^{2+} which 40.1. Thus, the sodium is easy to separate from NaCl solution compared to calcium from $CaCl_2$ solution.

The rejection of $CaCl_2$ also decreases because of the ionic radii. Higher in ionic radii is decreased the rejection. The same situation is happened to calcium. An ionic radius for calcium is bigger than sodium. The calcium is hardly to separate from membrane pores. Because of this factor, the rejection declined as the concentration decreased. The relationship between rejection and concentration is inversely proportional. The rejection of $CaCl_2$ is lower than the rejection of NaCl. The comparison between calcium and sodium is shown in Table 9 and 10 below. Thus, the result for this study is complied with theory done by *Steven J. Harrold et. al, 1992.*

Table 8: Atomic or molecular weights

Element or compound	*Chemical symbol*	*Atomic or molecular weight*	*Ion Radii*	*Valence*
Calcium ion	Ca^{+2}	40.1	0.99 Å	+2
Sodium ion	Na^{+}	23.0	0.95 Å	+1

Table 9: Rejection of different solutes by RO membrane

Solute	**Molecular Weight (g/mol)**	**Rejection (%)**
Sodium Chloride	58	>99
Calcium Chloride	111	99

RO membrane did separate monovalent and divalent salts; separation of the divalent ion was higher. This suggests that the membrane discriminates between monovalent and divalent salts on the basis of ionic size, molecular weight and charge repulsion.

4.4 Experimental error

In this research, the experiments faced some difficulties due to the equipment problem. The leakage occurred on this equipment. This leakage will affect the volume of permeate. Thus, it will affect the value of the flux obtained. Discussion of the errors is included to aid future students or researchers avoid similar problems.

4.5 Initiative taken to improve results

The project has deviated several times from the original schedule and plans to test at least three sets of chemicals by varying the concentration and pressure at different membranes which are RO and NF membrane, would give higher level of confidence. Currently, only two chemicals have been tested on RO membrane due to time constraint.

4.5.1 A "pre-trial" run was completed to ensure the usefulness of each membrane. After the equipment was washed with deionised water, the experimental set up was assembled and the tank was filled with ultra pure water (deionised water). The flux was measured at five minute intervals. At the end of an hour, the flux readings were compared. If the flux measurements were consistent, the membrane was considered undamaged and therefore suitable for testing.

4.5.2 Some of the membranes contained residual chemicals that gave falsely high readings initial test. All the membranes were therefore washed in deionised water until all chemicals were leached out before next experiment. The purpose is to remove the unreacted chemicals and the most important is inside the membrane in order to get the accurate data.

4.5.3 The volume of permeate through the membrane was measured until it became steady.

4.5.4 The conductivity meter was rinsed before and after each use with deionised water. The buildup of salts will interfere with proper operation, and the carryover of salts from one solution to another can skew the readings.

4.5.5 The average reading is taken from each four membrane of RO. It will give a better reading in order to improve the result.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The purpose of this study was to show the performance and characteristic of charged RO membrane in aqueous solution and relate these properties to measurable parameters such as pressure, concentration and type of chemicals. It has been shown that a flux and rejection increased with pressure but decreased with concentration. More concentrated the solution will reduce the rejection in the positively charged RO membrane. As well as the rejection characteristics of aqueous solution, the flux of RO membrane in the presence both solvent sand salts were established. With highly hydrophilic RO membrane, the flux decreased through the membrane due to the increasing of concentration.

In RO membrane, the rejection and flux of NaCl is greater than $CaCl_2$ in concentrated solutions. The ionic radius and molecular weight of Na^+ is smaller compared to Ca^{2+}. Thus, NaCl gave higher flux and rejection compared to $CaCl_2$.

It can be shown that the flux and rejection is the function of pressure and concentrations.

- Flux and rejection decreased as the salt concentration is increased.
- Flux and rejection increased with increasing the pressure across the membrane.
- Higher in molecular weight and ionic size, reduced the flux and rejection.

From several experiments that have been performed, objectives of this research have been achieved. Therefore, additional study and research have to be conducted in order to enhance the performance of the membrane. The problem of leakage in the equipment during the experiment should be overcome in order to give higher accuracy in the result obtained.

REFERENCES

A. Schonauer and W. M. Samhaber, *The Specific Behaviour of NF Membranes in The Separation of High Ionic Strength Electrolyte Solutions*, Institute of Process Engineering, Johannes Kepler University Linz, Austria.
(Source: www.biophysj.org/cgi/content/full/80/1/195)

C. Frederik Schutte, *The rejection of specific organic compounds by reverse osmosis membranes*, Department of Chemical Engineering, University of Pretoria, South Africa, February 2003.
(Source: www.elsevier.com/locate/desal)

David Harrison, *FORCES BETWEEN MOLECULES*, School of Education and Humanities, North East Wales Institute of Higher Education, North Wales.
(Source: www. newi.ac.uk./buckleyc/fbmolecules.htm)

Emma Gibbins, *Observations on solvent flux and solute rejection across solvent resistant nanofiltration membranes*, Department of Chemical Engineering, Imperial College, United Kingdom, March 2002.
(Source: www.elsevier.com/locate/desal)

Karrie D. Houstan, *Increasing Ion Rejection in Nanofiltration Membranes*, Howard University.

Lefi Danile Kodisang, *Separation of CO_2 from CH_4 Using Membrane Technology*, Chemical Engineering Universiti Teknologi Petronas, November 2001.

P.T. Cardew and M.S.Le, RS.C, *MEMBRANE PROCESSES: A Technology Guide*, 1998, page 1-10 to 2.1.

Robert H. Perry, Don W. Green, Mc Graw Hill, *PERRY'S CHEMICAL ENGINEERS' HANDBOOK*, 1997, page 22-48 to 22-51.

Simon Judd and Bruce Jefferson, ELSEVIER, *Membranes for Industrial Wastewater Recovery and Re-use*, 2000, page 14 to 46.

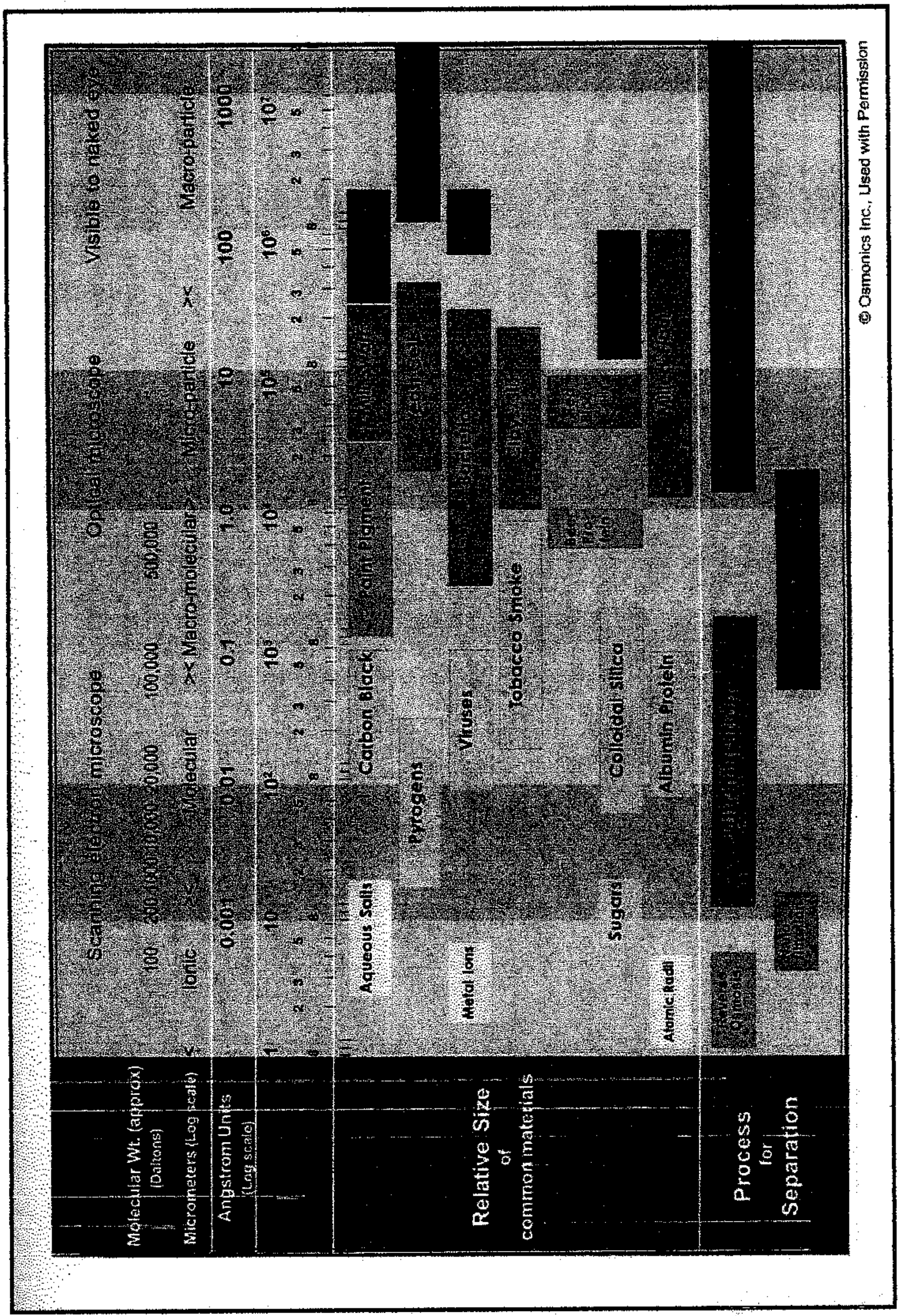
SOLTEQ, *Membrane Test Unit (Model: TR 08)*, Solution Engineering Sdn. Bhd., Technology Park Malaysia, 2004.

S.P.P Nunes and K.-V Peinemann, WILEY-VCH, *MEMBRANE TECHNOLOGY in the Chemical Industry*, 2001

Steven J. Harrold, David J. Paulson, Greg S. Ross and Brian J. Rudie, *Effects of Surface Force Interactions on an NF/UF Membrane*. April 1992.
(Source: www.environmental-center.com/articles/article382/article382.htm)

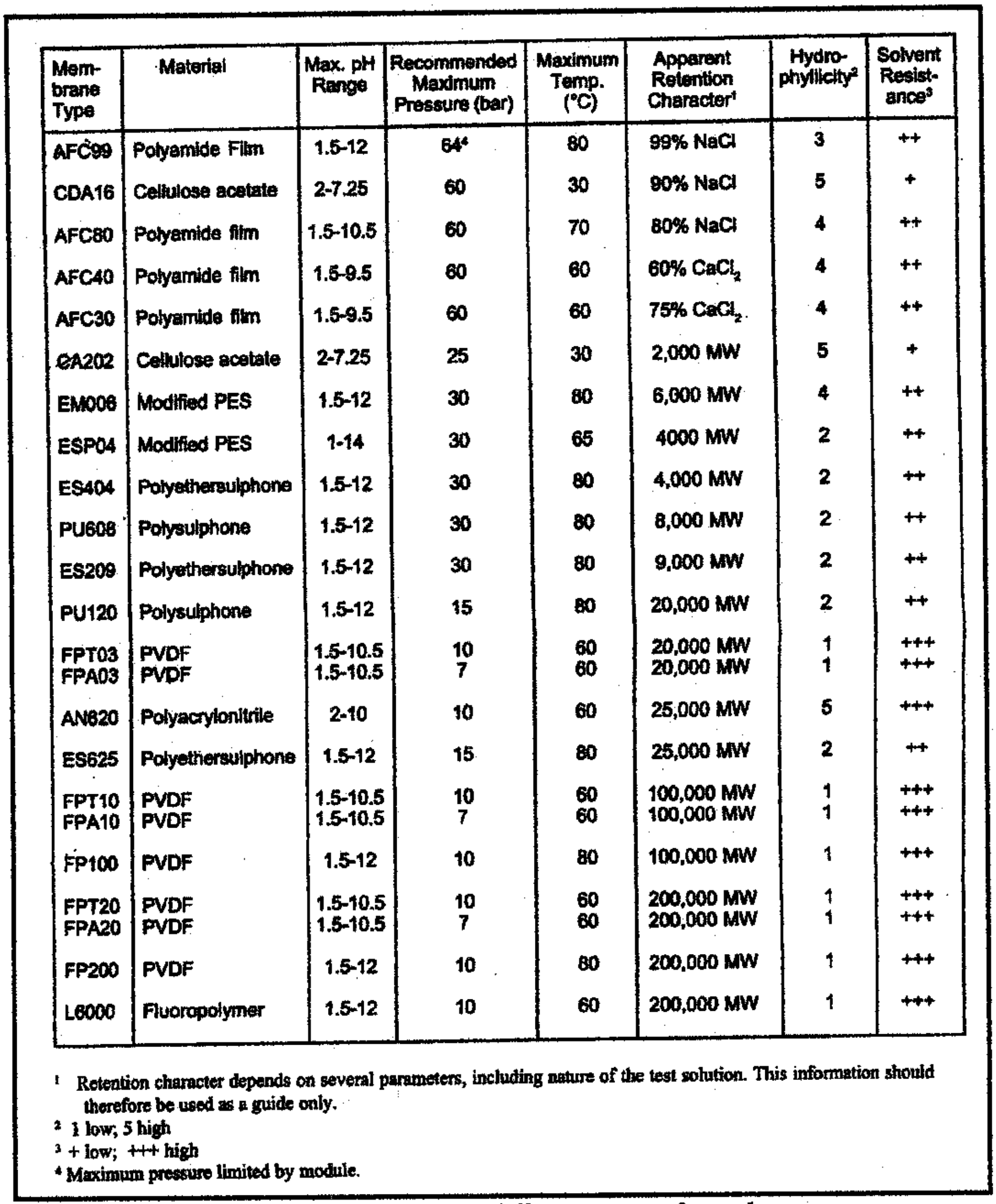
APPENDIX

APPENDIX 1: SPECIFICATION AND PARAMETERS FOR MEMBRANES



© Osmonics Inc., Used with Permission

Figure 1.1: *Filtration Spectrum*



Membrane Type	Material	Max. pH Range	Recommended Maximum Pressure (bar)	Maximum Temp. (°C)	Apparent Retention Character[1]	Hydrophylicity[2]	Solvent Resistance[3]
AFC99	Polyamide Film	1.5-12	64[4]	80	99% NaCl	3	++
CDA16	Cellulose acetate	2-7.25	60	30	90% NaCl	5	+
AFC80	Polyamide film	1.5-10.5	60	70	80% NaCl	4	++
AFC40	Polyamide film	1.5-9.5	60	60	60% $CaCl_2$	4	++
AFC30	Polyamide film	1.5-9.5	60	60	75% $CaCl_2$	4	++
CA202	Cellulose acetate	2-7.25	25	30	2,000 MW	5	+
EM006	Modified PES	1.5-12	30	80	6,000 MW	4	++
ESP04	Modified PES	1-14	30	65	4000 MW	2	++
ES404	Polyethersulphone	1.5-12	30	80	4,000 MW	2	++
PU608	Polysulphone	1.5-12	30	80	8,000 MW	2	++
ES209	Polyethersulphone	1.5-12	30	80	9,000 MW	2	++
PU120	Polysulphone	1.5-12	15	80	20,000 MW	2	++
FPT03	PVDF	1.5-10.5	10	60	20,000 MW	1	+++
FPA03	PVDF	1.5-10.5	7	60	20,000 MW	1	+++
AN620	Polyacrylonitrile	2-10	10	60	25,000 MW	5	+++
ES625	Polyethersulphone	1.5-12	15	80	25,000 MW	2	++
FPT10	PVDF	1.5-10.5	10	60	100,000 MW	1	+++
FPA10	PVDF	1.5-10.5	7	60	100,000 MW	1	+++
FP100	PVDF	1.5-12	10	80	100,000 MW	1	+++
FPT20	PVDF	1.5-10.5	10	60	200,000 MW	1	+++
FPA20	PVDF	1.5-10.5	7	60	200,000 MW	1	+++
FP200	PVDF	1.5-12	10	80	200,000 MW	1	+++
L6000	Fluoropolymer	1.5-12	10	60	200,000 MW	1	+++

[1] Retention character depends on several parameters, including nature of the test solution. This information should therefore be used as a guide only.

[2] 1 low; 5 high

[3] + low; +++ high

[4] Maximum pressure limited by module.

Figure 1.2: *Data for different type of membranes*

APPENDIX 2: OVERVIEW OF MEMBRANE TEST UNIT (MODEL: TR08)

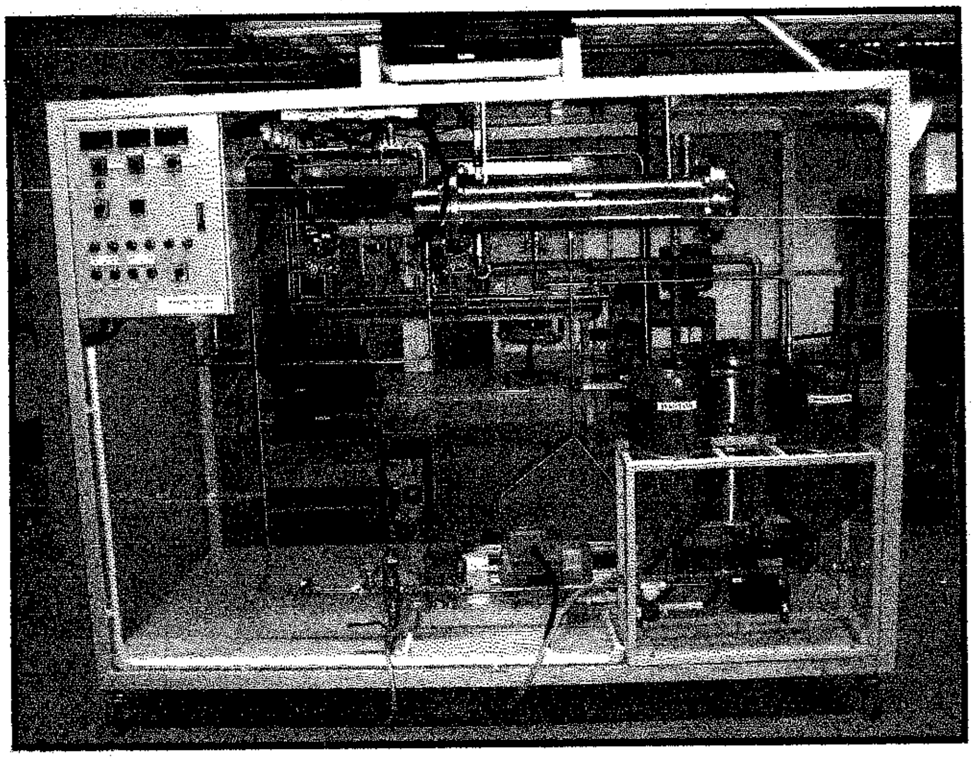


Figure 2.1: *Front view for equipment of Membrane Test Unit*

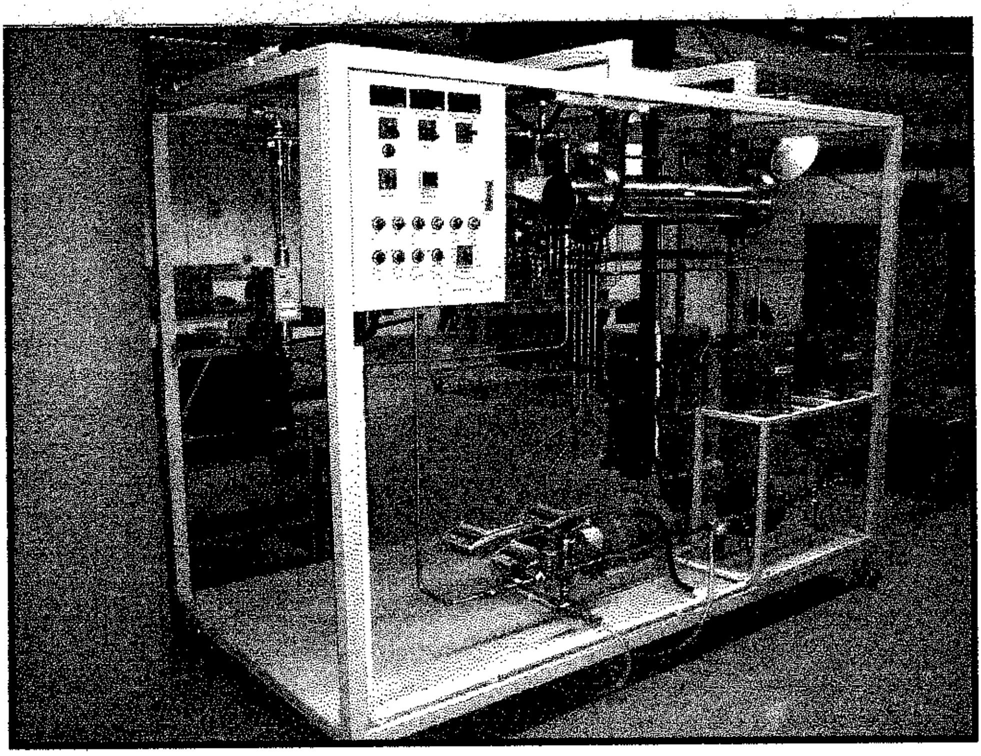


Figure 2.2: *Side view of Membrane Test Unit*

APPENDIX 3: DATA OF SODIUM CHLORIDE FOR CONCENTRATION = 0.2M

Table 1.1: Water permeate for 5 bar

P = 5 bar							
		Amount of water for each membrane					
Reading	**Time (min)**	**M1**	**M2**	**M3**	**M4**	**Average (g)**	**Average (mL)**
1	0	0	0	0	0	0	0
2	20	3.7	5.4	13.3	14.8	9.30	9.32756
3	40	4.0	5.9	13.5	15.9	9.83	9.85913
4	60	3.8	6.0	14.2	16.6	10.15	10.18008
5	80	3.9	6.0	15.3	17.0	10.55	10.58127
6	100	4.1	6.1	16.2	17.2	10.90	10.93230
7	120	4.4	6.1	17.2	17.5	11.30	11.33349
8	140	4.4	6.2	17.4	17.6	11.40	11.43379

Table 1.2: Water permeate for 10 bar

P = 10 bar							
		Amount of water for each membrane					
Reading	**Time (min)**	**M1**	**M2**	**M3**	**M4**	**Average (g)**	**Average (mL)**
1	0	0	0	0	0	0	0
2	20	43.5	41.7	37.1	25.3	36.90	37.00936
3	40	63.6	63.5	59.9	44.9	57.98	58.15184
4	60	76.6	77.0	74.5	57.6	71.43	71.64171
5	80	89.2	89.1	87.4	69.2	83.73	83.97816
6	100	103.3	104.1	116.6	83.2	101.80	102.10171
7	120	118.1	120.0	119.7	97.7	113.88	114.21751
8	140	132.6	134.2	135.3	110.8	128.23	128.61004

Table 1.3: Water permeate for 15 bar

P = 15 bar							
		Amount of water for each membrane					
Reading	**Time (min)**	**M1**	**M2**	**M3**	**M4**	**Average (g)**	**Average (mL)**
1	0	0	0	0	0	0	0
2	10	51.9	54.0	53.4	51.9	52.80	52.95649
3	20	81.5	85.2	86.0	81.2	83.48	83.72740
4	30	124.8	128.4	132.3	123.4	127.23	127.60708
5	40	157.3	162.2	168.0	156.1	160.90	161.37687
6	50	199.5	205.6	214.2	198.1	204.35	204.95564
7	60	237.6	245.2	255.8	235.9	243.63	244.35206
8	70	272.0	281.5	293.5	270.6	279.40	280.22807

Table 1.4: Water permeate for 20 bar

P = 20 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	5	95.6	98.1	101.7	94.7	97.53	97.81404
3	10	146.3	150.8	157.0	145.4	149.88	150.31919
4	15	177.7	183.8	210.2	177.1	187.20	187.75482
5	20	232.1	240.7	250.9	231.7	238.85	239.55789
6	25	273.3	283.2	295.7	272.5	281.18	282.00833
7	30	327.6	338.0	353.2	324.9	335.93	336.92060
8	35	388.3	401.8	419.6	385.3	398.75	399.93180

Table 1.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, C_p (mS)				Average (mS)	Conductivity feed, C_f (mS)
0	0				0	0
5	1.5				1.5	16.3
10	1.30	0.97	1.40	0.93	1.15	17.3
15	0.40	0.23	0.40	0.24	0.32	19.2
20	0.16	0.10	0.24	0.10	0.15	20.3

Table 1.6: Flux and rejection for different pressure

Pressure	Flux (L/m^2h)	Rejection%
0	0	0
5	0.1389	90.8
10	1.2767	93.35
15	5.1987	98.33
20	14.8647	99.26

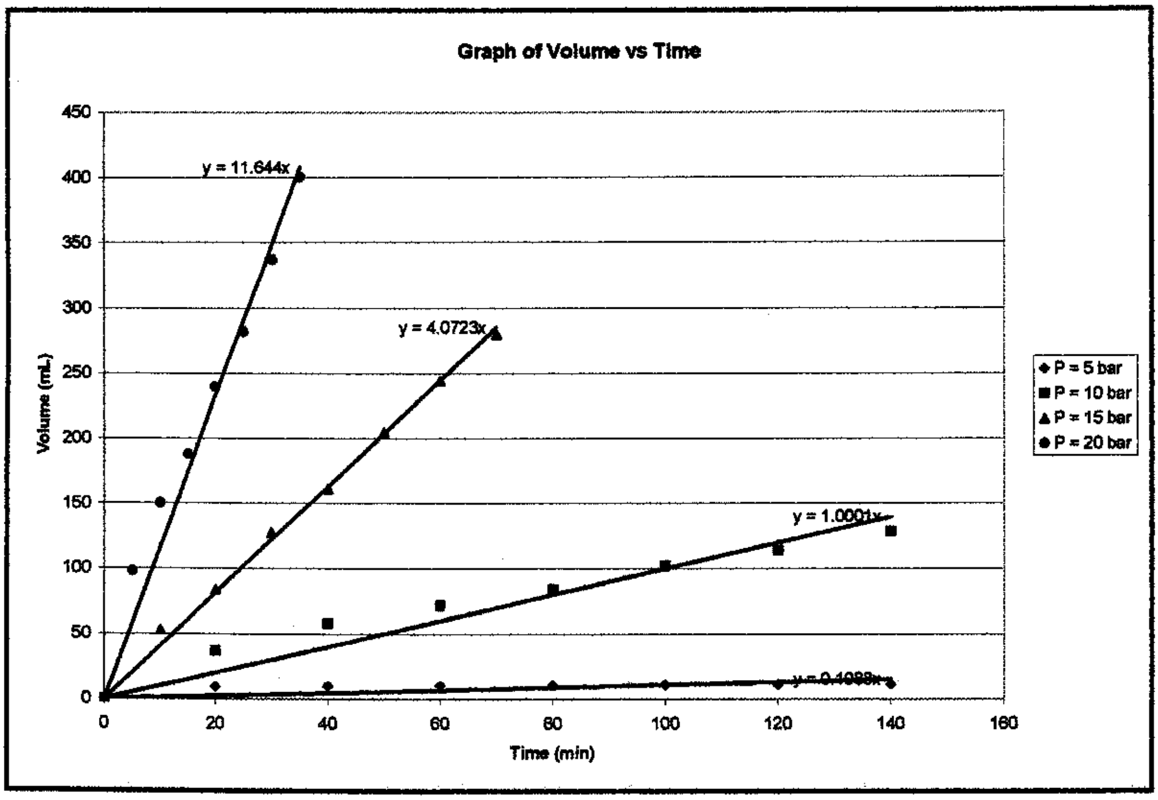


Figure 3.1: *Graph of volume against time for different pressure*

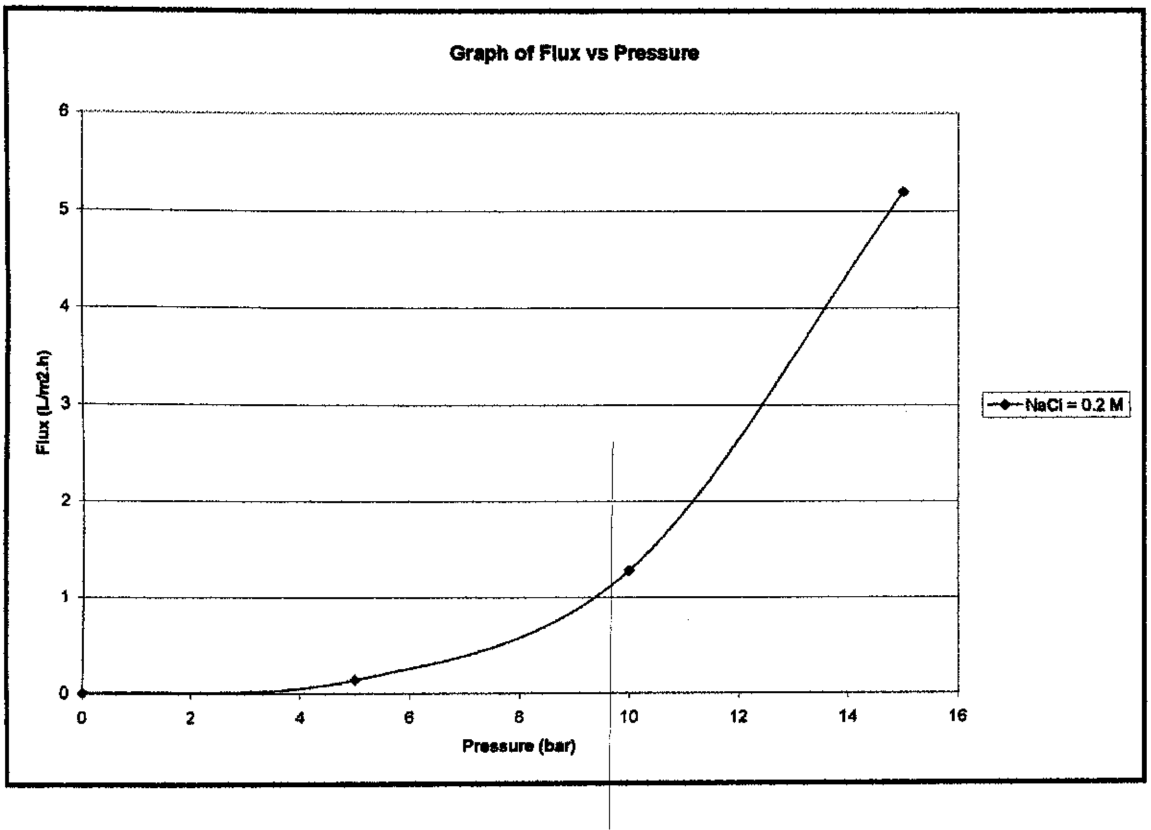


Figure 3.2: *Graph of flux against pressure*

APPENDIX 4: DATA OF SODIUM CHLORIDE FOR CONCENTRATION = 0.5M

Table 2.1: Water permeate for 5 bar

P = 5 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	1.3	1.0	1.4	3.0	1.68	1.68498
3	40	1.5	1.0	1.6	3.8	1.98	1.98587
4	60	1.7	1.1	2.0	4.4	2.30	2.30682
5	80	1.6	1.1	2.8	4.8	2.56	2.56759
6	100	1.8	1.2	4.0	4.9	2.98	2.98883
7	120	1.8	1.2	4.1	5.1	3.05	3.05904
8	140	1.9	1.2	4.5	5.2	3.20	3.20948

Table 2.2: Water permeate for 10 bar

P = 10 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.3	0.5	7.0	0.4	2.05	2.05608
3	40	0.7	0.9	9.7	0.3	2.90	2.90859
4	60	2.9	0.9	10.5	0.3	3.65	3.66082
5	80	3.5	1.0	11.5	0.3	4.08	4.09209
6	100	4.2	1.1	12.7	0.3	4.58	4.59357
7	120	4.6	1.1	13.9	0.3	4.98	4.99476
8	140	5.1	1.2	15.2	0.2	5.43	5.44609

Table 2.3: Water permeate for 15 bar

P = 15 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	10	6.6	13.8	13.2	0.2	8.45	8.47504
3	20	8.2	17.2	16.4	1.4	10.80	10.83201
4	30	10.2	19.5	20.1	3.4	13.30	13.33942
5	40	13.1	20.5	23.0	5.7	15.58	15.62618
6	50	17.2	21.8	25.3	7.9	18.05	18.10350
7	60	18.8	25.1	27.6	9.9	20.35	20.41031
8	70	20.3	26.0	29.8	12.3	22.10	22.16550

Table 2.4: Water permeate for 20 bar

P = 20 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	10	19.2	18.6	20.2	20.1	19.53	19.58788
3	20	27.8	27.5	29.7	28.4	28.35	28.43402
4	30	36.9	36.1	39.3	36.8	37.28	37.39049
5	40	43.7	43.0	46.6	43.5	44.10	44.23070
6	50	49.5	48.3	53.1	48.7	49.90	50.04789
7	60	56.4	55.4	60.7	54.8	56.83	56.99843
8	70	61.8	61.2	66.8	60.3	62.53	62.71532

Table 2.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, Cp (mS)				Average (mS)	Conductivity feed, Cf (mS)
0	0				0	0
5	12.2				12.20	32.5
10	10.30				10.30	34.2
15	11.40	14.20	8.40	7.00	10.25	36.1
20	3.40	3.60	5.40	3.60	4.00	36.7

Table 2.6: Flux and rejection for different pressure

Pressure	Flux (L/m^2h)	Rejection%
0	0	0
5	0.0359	62.46
10	0.0576	69.88
15	0.4566	71.61
20	2.5473	89.47

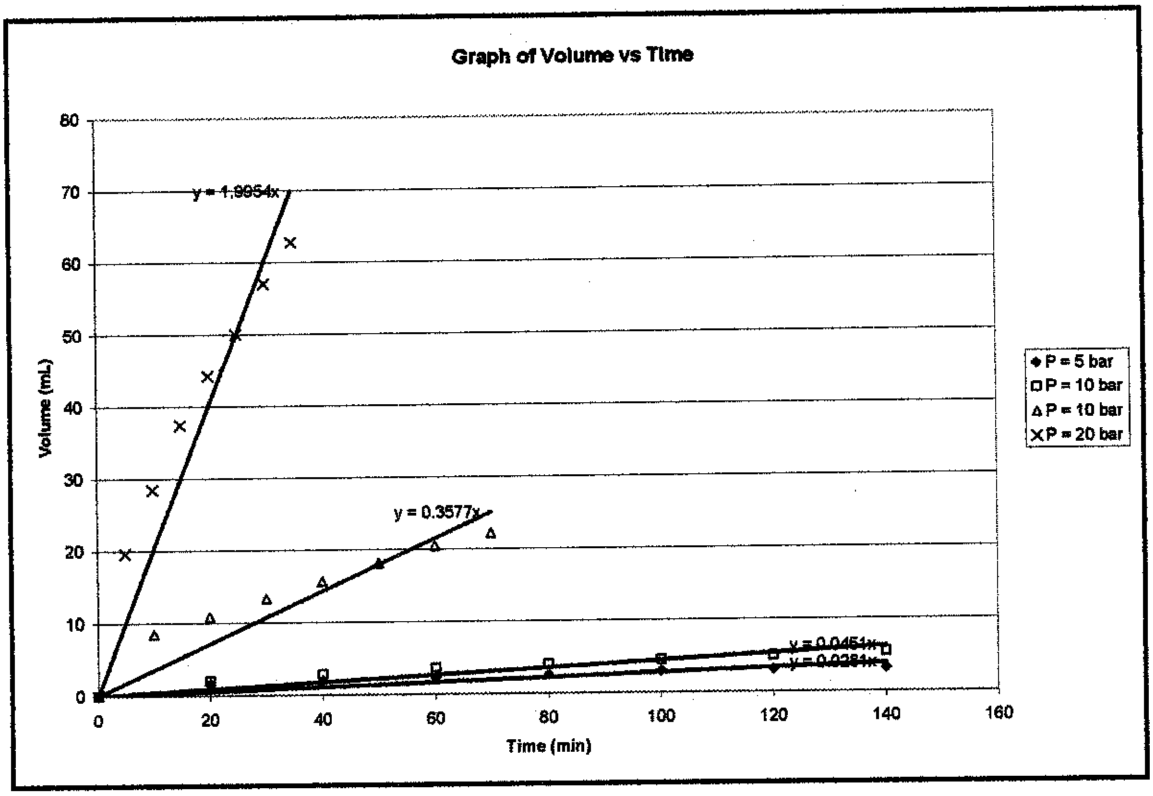


Figure 4.1: *Graph of volume against time for different pressure*

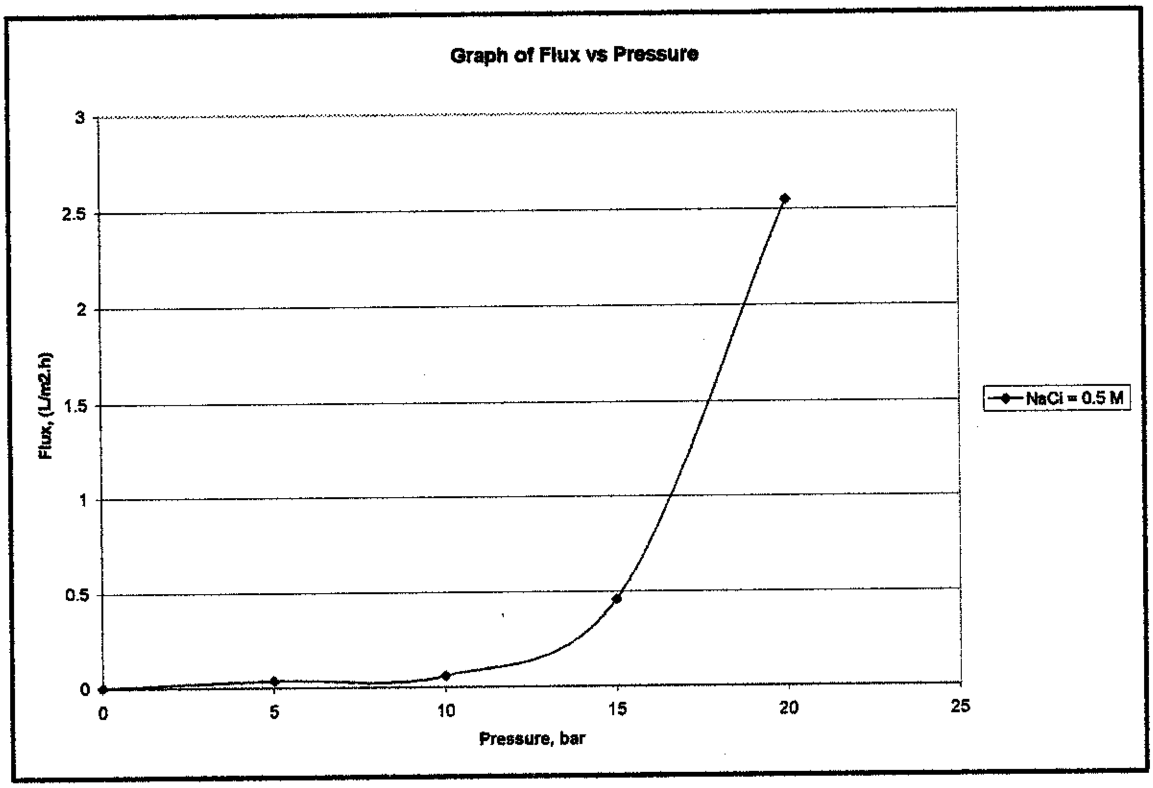


Figure 4.2: *Graph of flux against pressure*

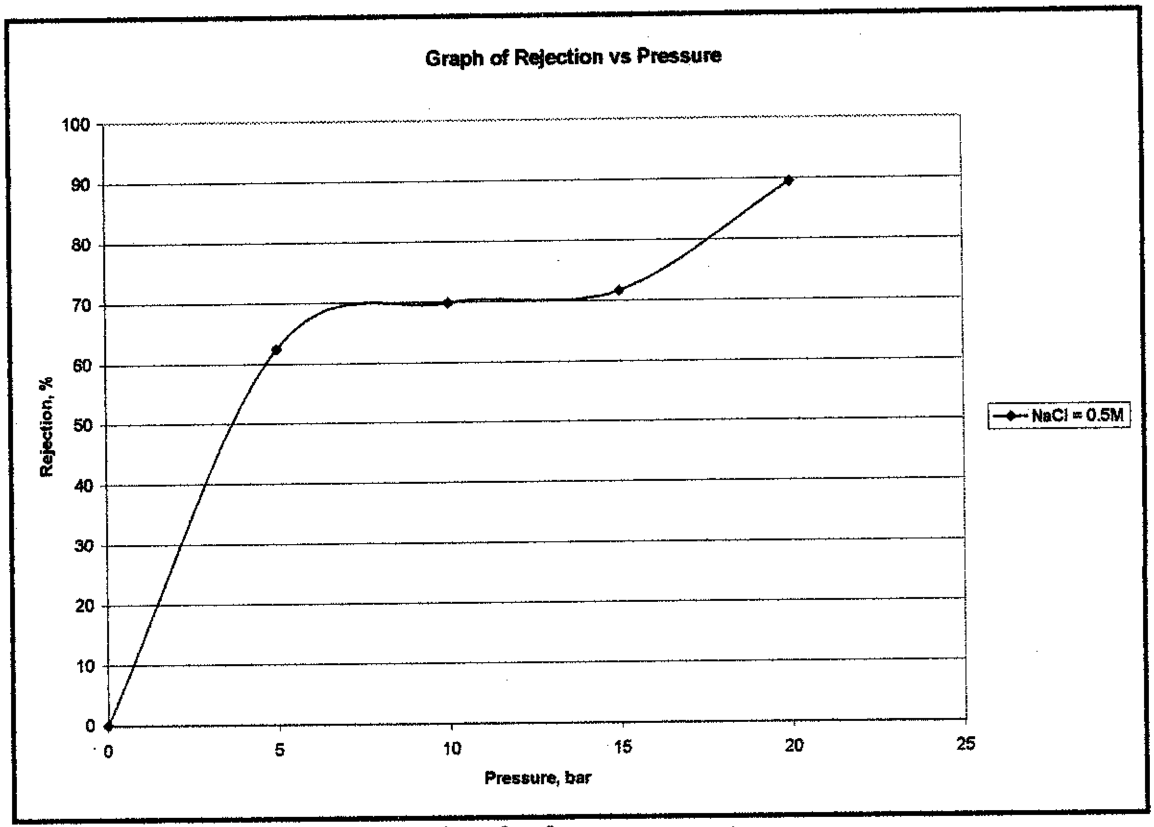


Figure 4.3: *Graph of rejection against pressure*

APPENDIX 5: DATA OF SODIUM CHLORIDE FOR CONCENTRATION = 1.0M

Table 3.1: Water permeate for 5 bar

P = 5 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.3	0.8	1.2	2.9	1.30	1.30385
3	40	0.3	1.0	1.2	3.4	1.48	1.48439
4	60	0.4	1.1	1.4	3.7	1.65	1.65489
5	80	0.5	1.2	1.5	3.9	1.78	1.78528
6	100	0.5	1.3	1.8	4.0	1.90	1.90563
7	120	0.5	1.3	2.7	4.1	2.15	2.15637
8	140	0.6	1.4	3.7	4.3	2.50	2.50741

Table 3.2: Water permeate for 10 bar

P = 10 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	1.7	0.3	4.6	0.2	1.70	1.70504
3	40	2.2	0.6	6.1	0.3	2.30	2.30682
4	60	2.7	0.7	7.1	0.3	2.70	2.70800
5	80	3.2	0.8	7.9	0.4	3.08	3.08913
6	100	3.7	1.0	8.7	0.3	3.43	3.44017
7	120	4.1	1.1	9.6	0.5	3.83	3.84135
8	140	4.7	1.5	10.9	0.4	4.38	4.39298

Table 3.3: Water permeate for 15 bar

P = 15 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	1.5	2.5	2.5	0.1	1.65	1.65489
3	40	2.4	3.1	4.1	0.3	2.43	2.43720
4	60	3.0	3.7	5.9	0.3	3.23	3.23957
5	80	4.7	4.5	8.4	0.3	4.48	4.49328
6	100	5.7	4.8	10.2	0.2	5.23	5.24550
7	120	6.6	5.4	11.9	0.3	6.05	6.06793
8	140	7.1	5.7	13.1	0.4	6.58	6.59950

Table 3.4: Water permeate for 20 bar

P = 20 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	3.1	2.2	5.3	0.0	2.65	2.65785
3	40	4.2	2.3	6.5	0.1	3.28	3.28972
4	60	4.9	2.8	7.4	0.1	3.80	3.81126
5	80	6.7	3.5	10.3	0.9	5.35	5.36586
6	100	7.9	5.3	12.3	1.9	6.85	6.87030
7	120	8.7	6.6	13.6	2.8	7.93	7.95350
8	140	9.7	8.0	14.9	4.1	9.18	9.20721

Table 3.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, Cp (mS)	Average (mS)	Conductivity feed, Cf (mS)
0	0	0	0
5	28.0	28.0	59.4
10	25.1	25.1	63.2
15	21.0	21.0	66.5
20	18.9	18.9	68.1

Table 3.6: Flux and rejection for different pressure

Pressure	Flux (L/m^2h)	Rejection%
0	0	0
5	0.02566	52.86
10	0.04379	60.28
15	0.06520	68.42
20	0.08604	72.25

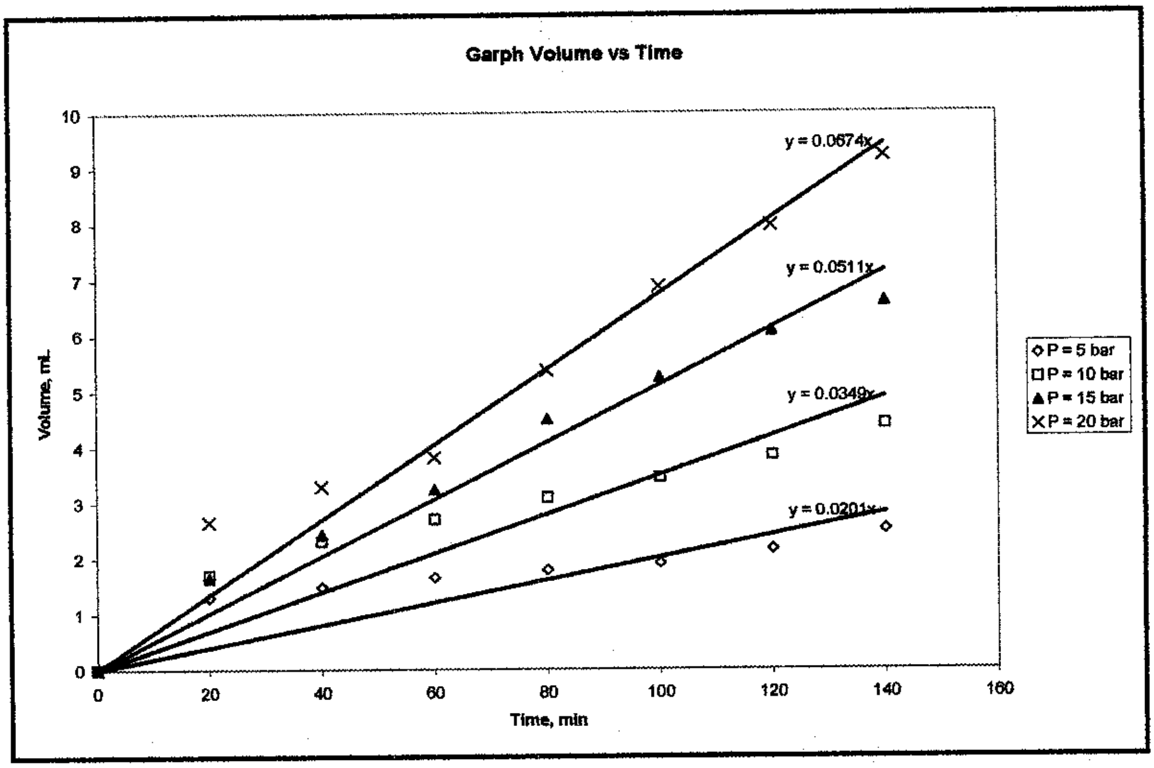


Figure 5.1: *Graph of volume against time for different pressure*

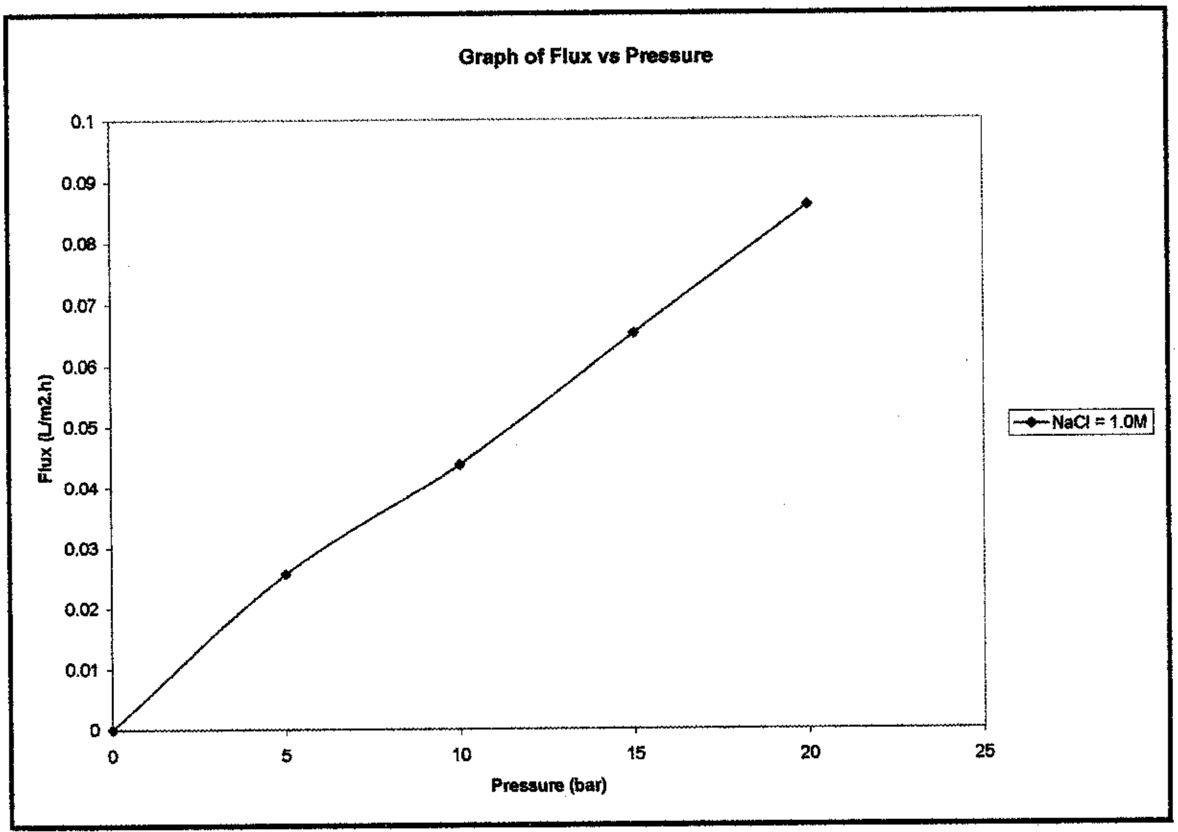


Figure 5.2: *Graph of flux against pressure*

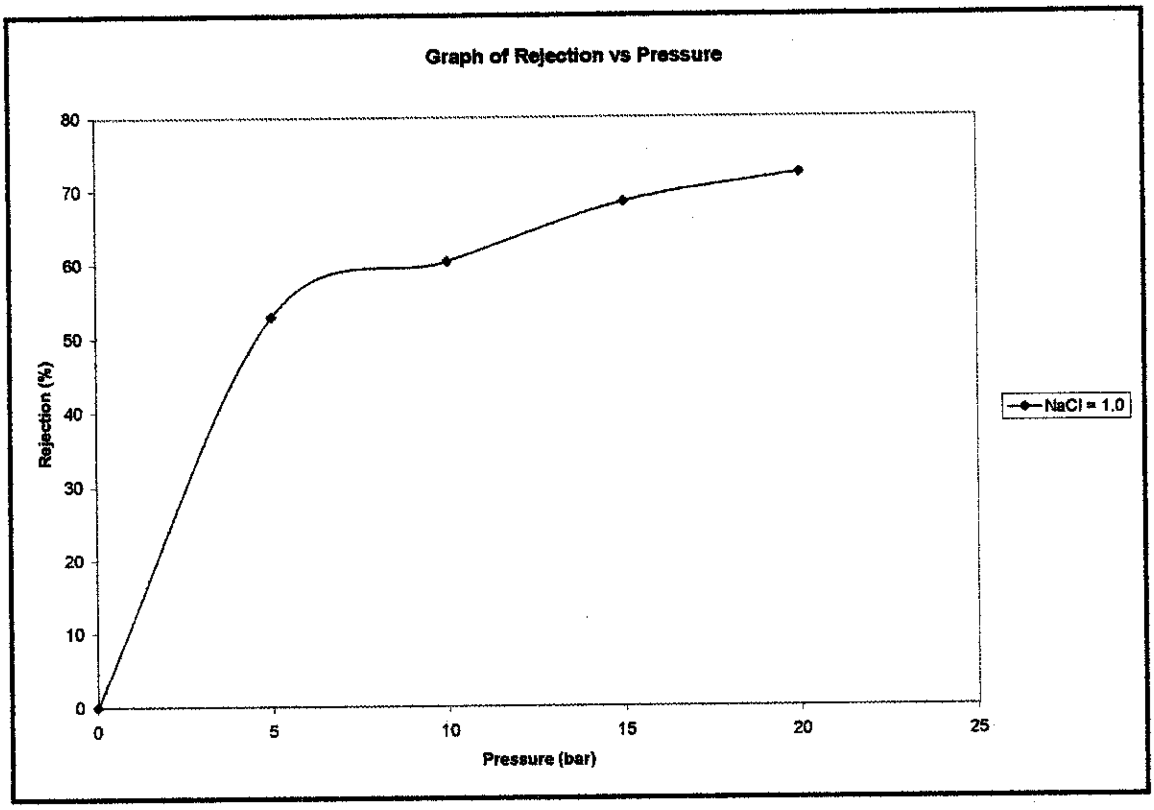


Figure 5.3: *Graph of rejection against pressure*

APPENDIX 6: DATA OF CALCIUM CHLORIDE FOR CONCENTRATION = 0.2M

Table 4.1: Water permeate for 5 bar

P = 5 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	1.5	2.4	2.5	7.1	3.38	3.39002
3	40	1.7	2.6	2.9	7.9	3.78	3.79120
4	60	2.0	2.7	3.3	8.3	4.08	4.09209
5	80	2.3	2.9	4.2	8.9	4.58	4.59357
6	100	2.6	3.0	5.0	9.3	4.98	4.99476
7	120	2.9	3.0	5.9	9.4	5.30	5.31571
8	140	3.2	3.1	6.7	9.5	5.63	5.64669

Table 4.2: Water permeate for 10 bar

P = 10 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	4.4	4.1	7.1	0.9	4.13	4.14224
3	40	5.6	4.1	8.8	1.2	4.93	4.94461
4	60	5.8	5.7	9.6	1.2	5.58	5.59654
5	80	6.6	6.5	11.1	1.3	6.38	6.39891
6	100	7.5	7.5	12.8	1.6	7.35	7.37178
7	120	8.9	8.3	14.1	2.0	8.33	8.35469
8	140	9.8	9.1	15.2	3.2	9.33	9.35264

Table 4.3: Water permeate for 15 bar

P = 15 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	10	15.1	14.2	16.3	5.6	12.80	12.83794
3	20	22.0	21.7	24.1	12.0	19.95	20.00913
4	30	30.1	29.8	32.6	20.6	28.23	28.31367
5	40	38.2	38.2	41.5	32.9	37.70	37.81173
6	50	46.8	46.8	51.0	41.1	46.43	46.56761
7	60	53.9	53.7	58.4	47.5	53.38	53.53821
8	70	58.6	53.4	61.2	53.2	56.60	56.76775

Table 4.4: Water permeate for 20 bar

P = 20 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	10	28.1	26.8	28.1	25.6	27.15	27.23047
3	20	42.1	42.0	55.6	39.3	44.75	44.88263
4	30	56.2	56.3	69.6	52.3	58.60	58.77368
5	40	68.0	68.6	83.0	63.3	70.73	70.93963
6	50	79.8	80.7	94.7	74.8	82.50	82.74451
7	60	89.4	90.8	105.7	84.0	92.48	92.75409
8	70	100.7	103.1	119.3	96.3	104.85	105.16075

Table 4.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, Cp (mS)				Average (mS)	Conductivity feed, Cf (mS)
0	0				0	0
5	28.8				28.8	9.6
10	30.3				30.3	8.5
15	3.70	3.90	3.80	5.70	32.2	4.4
20	0.90	0.90	1.50	0.80	32.5	1.03

Table 4.6: Flux and rejection for different pressure

Pressure	Flux (L/m^2h)	Rejection%
0	0	0
5	0.0629	66.67
10	0.0952	71.95
15	1.1312	86.34
20	4.1644	96.83

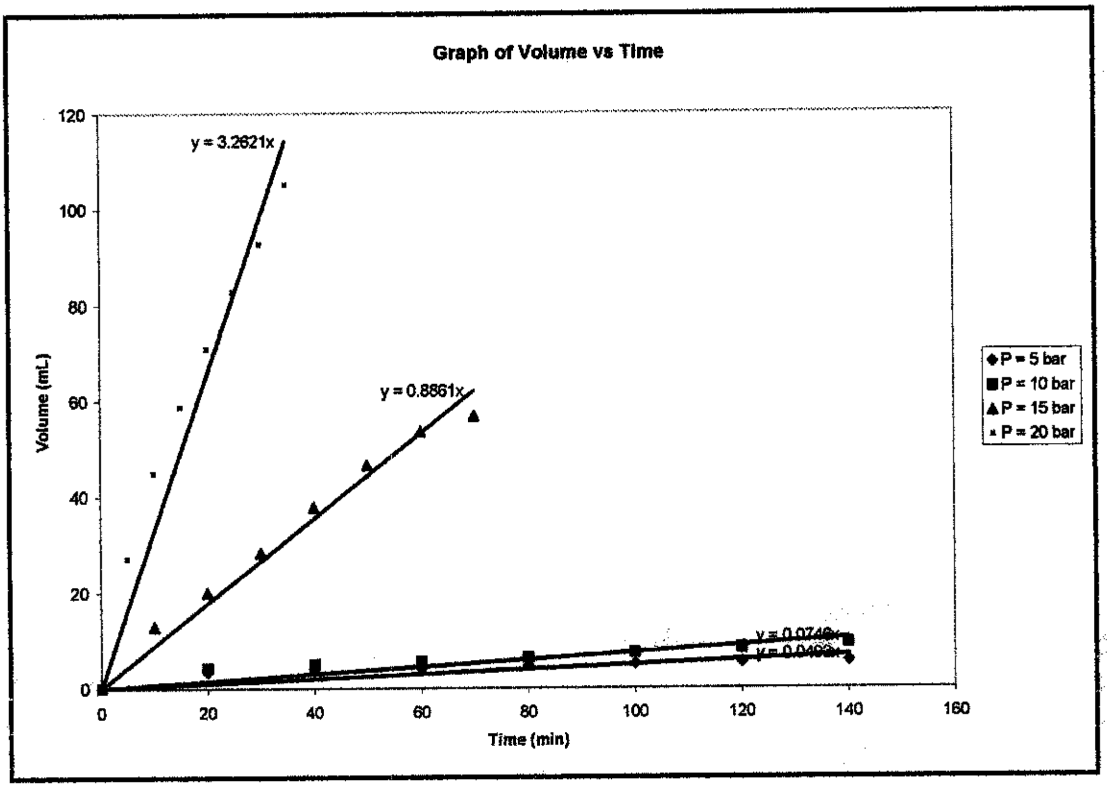


Figure 6.1: *Graph of volume against time for different pressure*

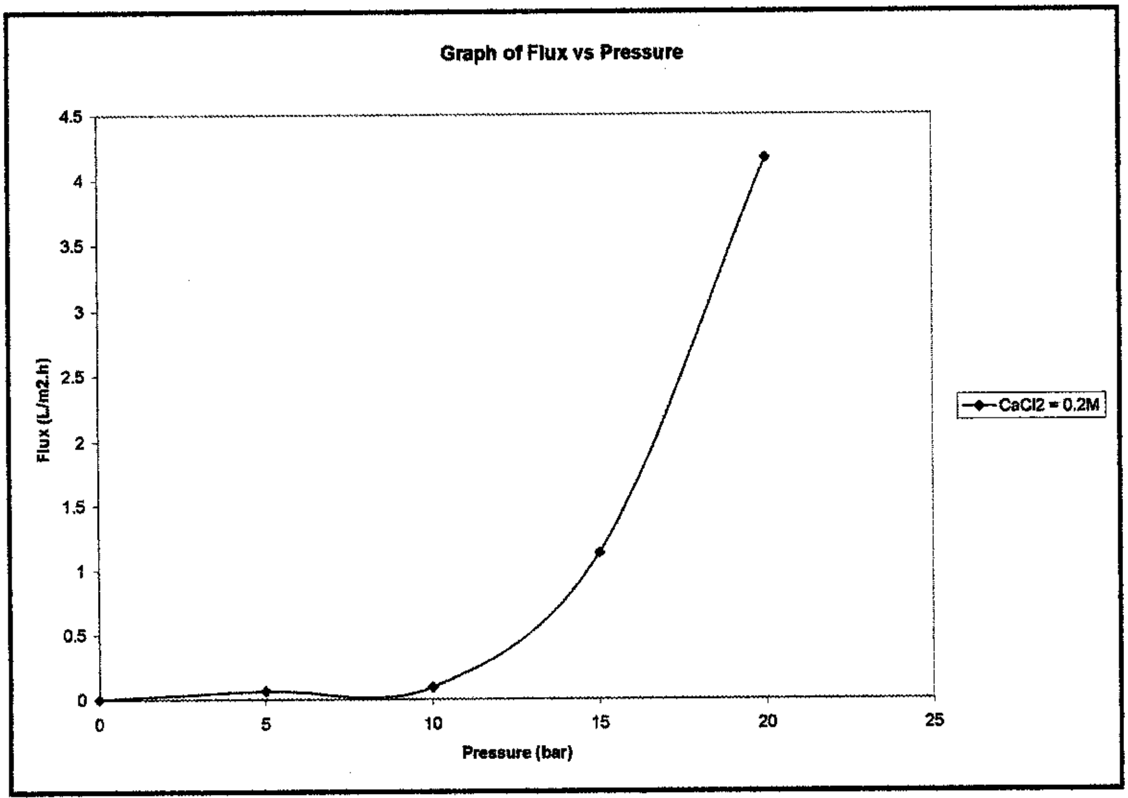


Figure 6.2: *Graph of flux against pressure*

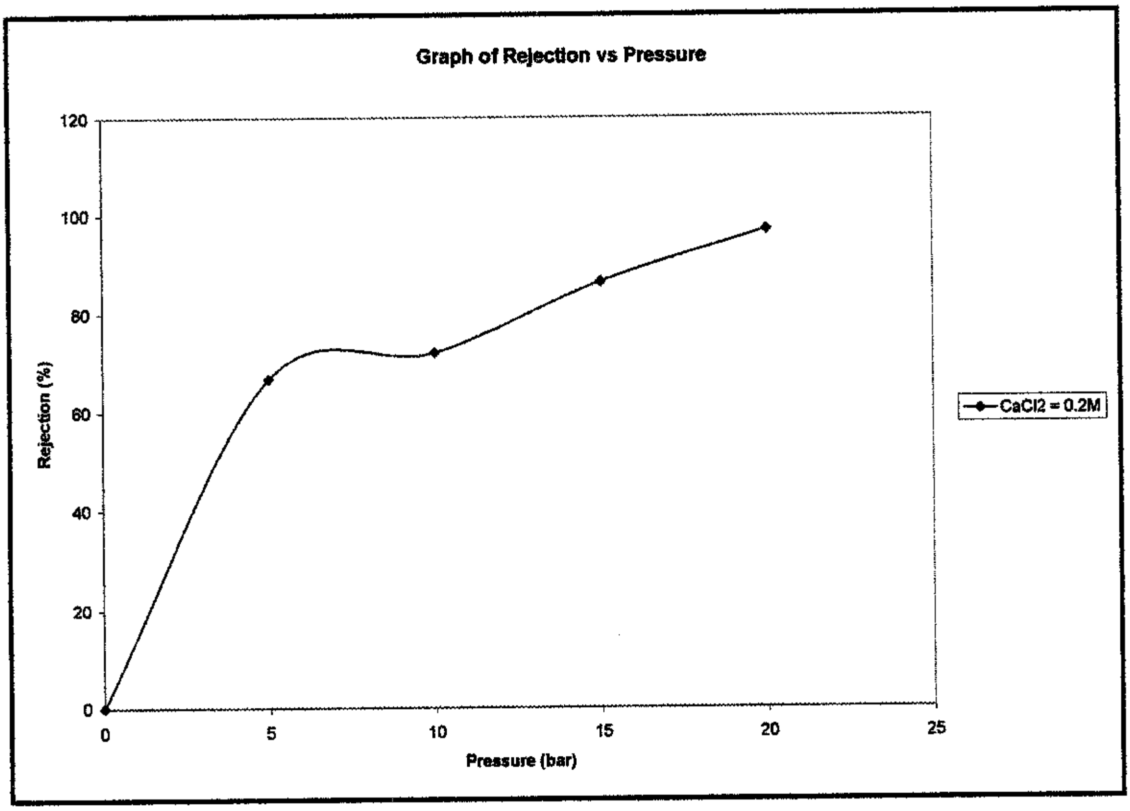


Figure 6.3: *Graph of rejection against pressure*

APPENDIX 7: DATA OF CALCIUM CHLORIDE FOR CONCENTRATION = 0.5M

Table 5.1: Water permeate for 5 bar

P = 5 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.1	0.5	0.4	0.5	0.38	0.38113
3	40	0.1	0.7	0.6	0.7	0.52	0.52154
4	60	0.1	1.1	1.0	0.9	0.79	0.79234
5	80	0.2	1.3	1.2	1.1	0.96	0.96285
6	100	0.2	2.0	1.8	1.7	1.44	1.44427
7	120	0.3	2.5	2.4	2.1	1.85	1.85548
8	140	0.3	3.0	2.9	2.6	2.21	2.21655

Table 5.2: Water permeate for 10 bar

P = 10 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.1	0.4	0.4	0.9	0.45	0.45133
3	40	0.4	0.5	2.5	1.0	1.10	1.10326
4	60	0.5	0.6	3.7	1.0	1.45	1.45430
5	80	0.9	0.9	5.8	1.0	2.15	2.15637
6	100	2.5	1.0	7.3	1.0	2.95	2.95874
7	120	3.1	1.1	8.0	1.0	3.30	3.30978
8	140	3.7	1.2	9.4	1.0	3.83	3.84135

Table 5.3: Water permeate for 15 bar

P = 15 bar							
Reading	Time (min)	Amount of water for each membrane					
		M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	2.2	0.5	4.5	0.0	1.80	1.80533
3	40	3.0	0.6	6.2	0.0	2.45	2.45726
4	60	3.8	0.7	7.4	0.4	3.08	3.08913
5	80	4.4	0.9	8.5	0.5	3.56	3.57055
6	100	4.9	1.1	9.8	0.6	4.10	4.11215
7	120	5.6	1.6	11.1	0.7	4.83	4.84431
8	140	6.3	1.9	12.1	0.8	5.24	5.25553

Table 5.4: Water permeate for 20 bar

P = 20 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	4.2	1.3	6.3	0.0	2.95	2.95874
3	40	7.4	4.7	10.4	0.2	5.68	5.69683
4	60	9.8	8.9	13.2	0.0	7.98	8.00365
5	80	12.5	12.0	17.0	0.2	10.38	10.41076
6	100	15.3	15.6	21.3	2.0	13.55	13.59016
7	120	17.6	17.7	24.4	4.5	16.05	16.09757
8	140	20.9	19.4	27.4	6.5	18.55	18.60498

Table 5.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, Cp (mS)	Average (mS)	Conductivity feed, Cf (mS)
0	0	0	0
5	20.40	20.40	49.30
10	19.60	19.60	51.90
15	19.20	19.20	54.10
20	18.80	18.80	57.80

Table 5.6: Flux and rejection for different pressure

Pressure	Flux (L/m^{2}h)	Rejection%
0	0	0
5	0.0189	58.62
10	0.0355	62.23
15	0.1063	64.51
20	0.6830	67.47

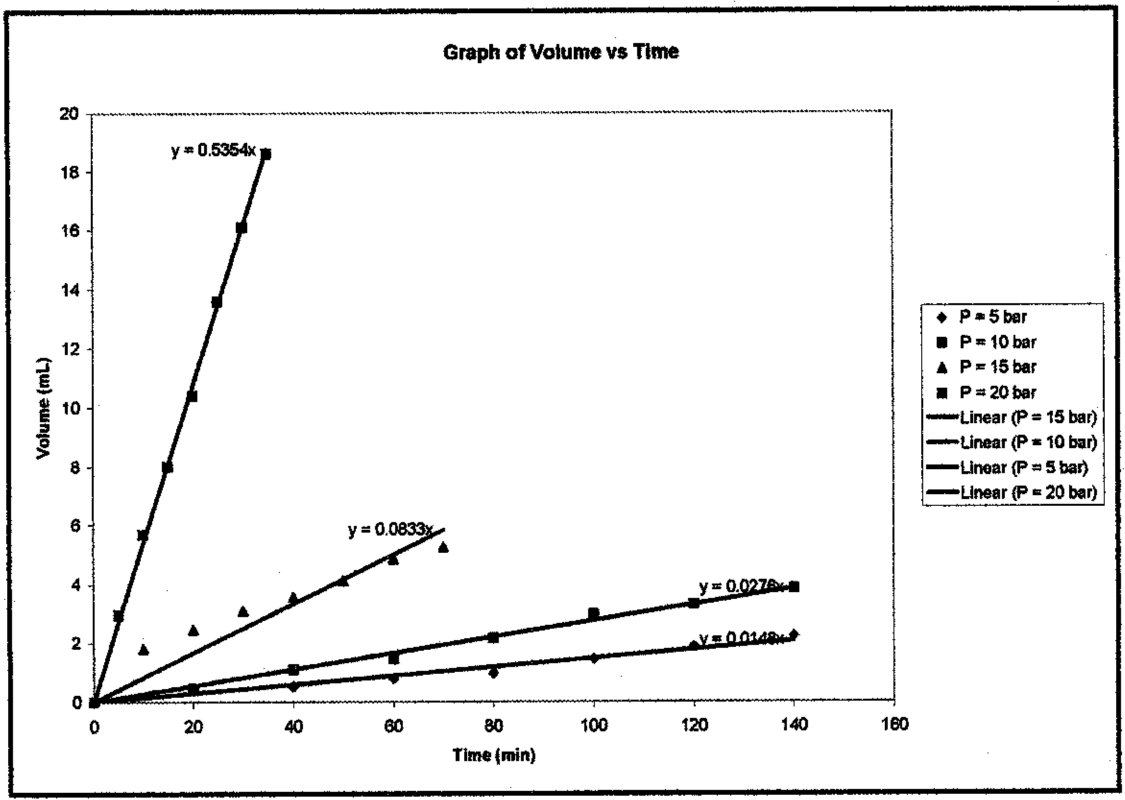


Figure 7.1: *Graph of volume against time for different pressure*

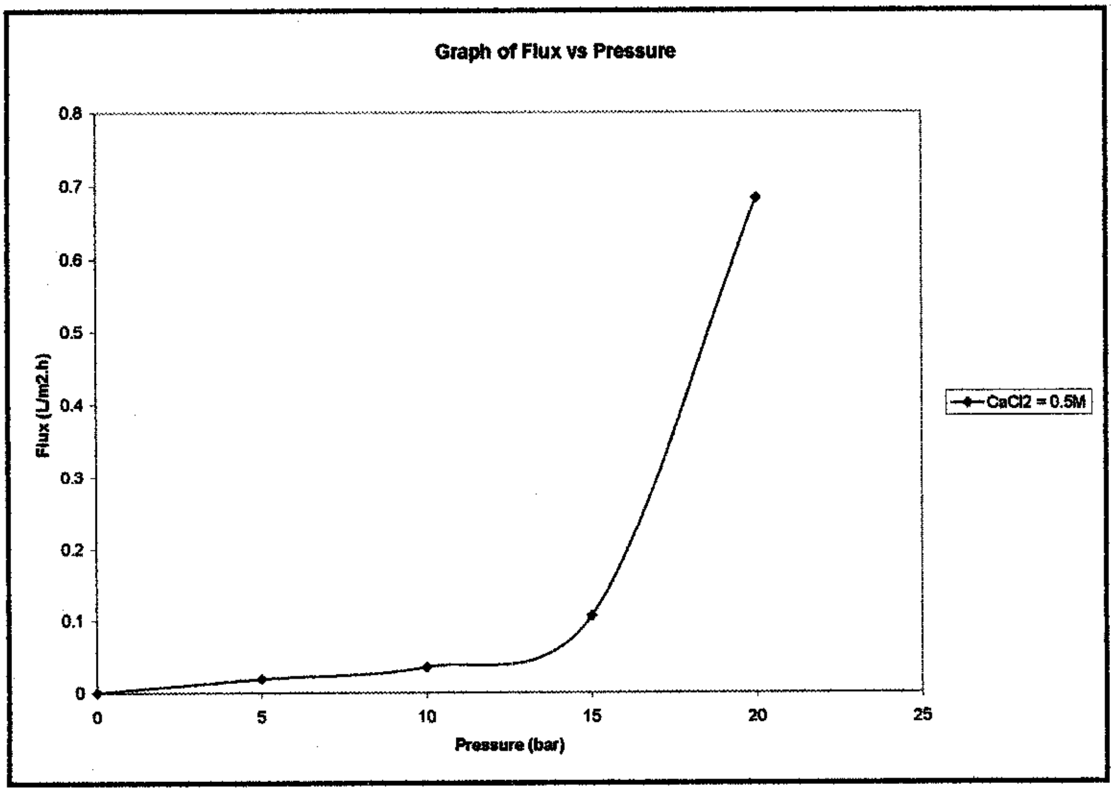


Figure 7.2: *Graph of flux against pressure*

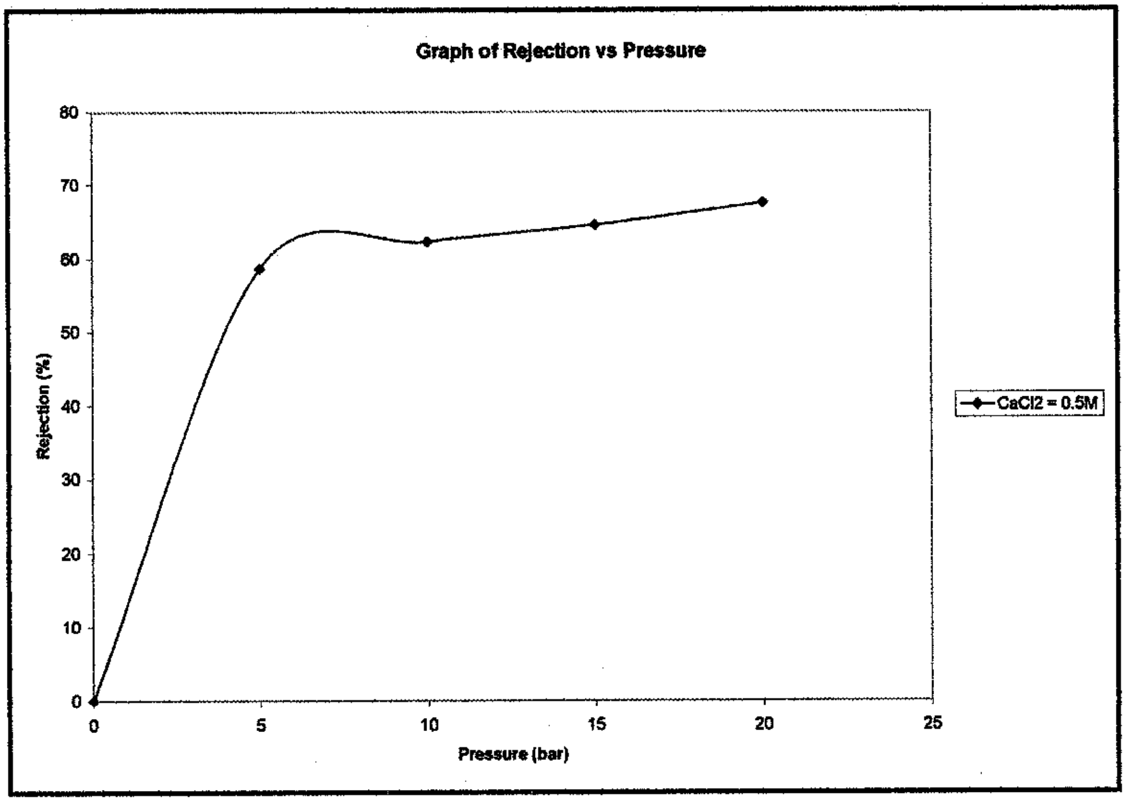


Figure 7.3: *Graph of rejection against pressure*

APPENDIX 8: DATA OF CALCIUM CHLORIDE FOR CONCENTRATION = 1.0M

Table 6.1: Water permeate for 5 bar

P = 5 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.1	0.3	0.2	0.0	0.15	0.15044
3	40	0.1	0.6	0.4	0.1	0.29	0.29086
4	60	0.1	0.7	0.5	0.1	0.35	0.35104
5	80	0.2	1.5	1.1	0.2	0.76	0.76225
6	100	0.2	2.5	1.5	0.3	1.12	1.12332
7	120	0.3	2.9	1.7	0.3	1.30	1.30385
8	140	0.3	3.4	1.9	0.4	1.49	1.49442

Table 6.2: Water permeate for 10 bar

P = 10 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.2	0.0	0.1	0.1	0.10	0.10030
3	40	0.2	0.5	0.7	0.4	0.45	0.45133
4	60	0.3	1.0	0.9	0.7	0.73	0.73216
5	80	0.4	2.0	1.4	1.0	1.20	1.20356
6	100	0.5	2.5	1.7	1.2	1.47	1.47436
7	120	0.5	3.3	1.9	1.5	1.81	1.81536
8	140	0.6	3.9	2.2	1.8	2.12	2.12628

Table 6.3: Water permeate for 15 bar

P = 15 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.2	0.3	0.1	1.4	0.50	0.50148
3	40	0.3	0.7	0.2	2.7	0.98	0.98290
4	60	0.4	1.2	0.5	4.0	1.52	1.52450
5	80	0.6	1.9	0.9	4.8	2.04	2.04605
6	100	0.7	2.6	1.3	5.3	2.48	2.48735
7	120	1.0	3.2	1.5	5.9	2.89	2.89857
8	140	1.3	3.7	1.9	6.7	3.40	3.41008

Table 6.4: Water permeate for 20 bar

P = 20 bar							
		Amount of water for each membrane					
Reading	Time (min)	M1	M2	M3	M4	Average (g)	Average (mL)
1	0	0	0	0	0	0	0
2	20	0.5	4.2	0.7	0.9	1.58	1.58468
3	40	0.9	4.6	1.2	1.5	2.06	2.06611
4	60	1.5	6.0	1.6	2.1	2.81	2.81833
5	80	1.8	6.5	1.9	2.8	3.26	3.26966
6	100	2.3	14.5	2.5	3.8	5.78	5.79713
7	120	2.7	17.3	3.4	4.6	6.99	7.01072
8	140	3.2	19.3	4.0	5.1	7.89	7.91338

Table 6.5: Data for conductivity of feed and permeate

Pressure	Conductivity permeate, Cp (mS)	Average (mS)	Conductivity feed, Cf (mS)
0	0	0	0
5	49.50	49.50	97.30
10	44.30	44.30	98.20
15	40.50	40.50	106.40
20	39.50	39.50	112.30

Table 6.6: Flux and rejection for different pressure

Pressure	Flux (L/m^2h)	Rejection%
0	0	0
5	0.0131	49.13
10	0.0188	54.89
15	0.0628	61.93
20	0.2803	64.83

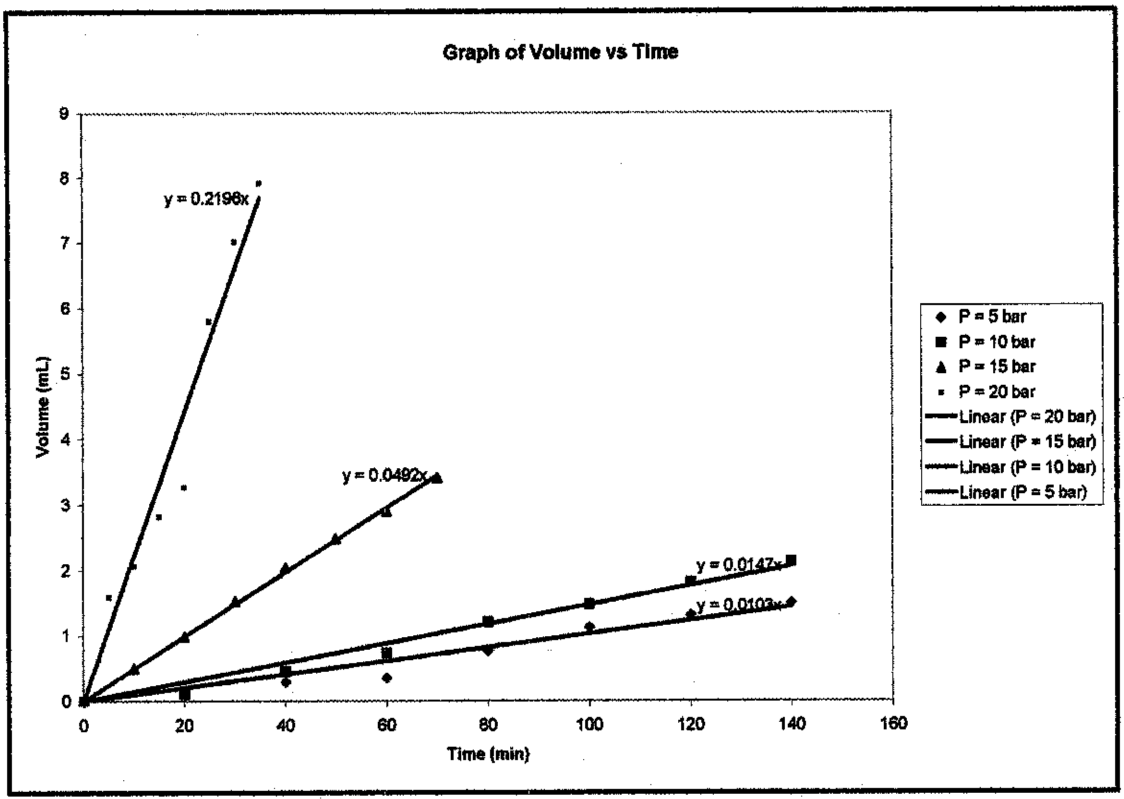


Figure 8.1: *Graph of volume against time for different pressure*

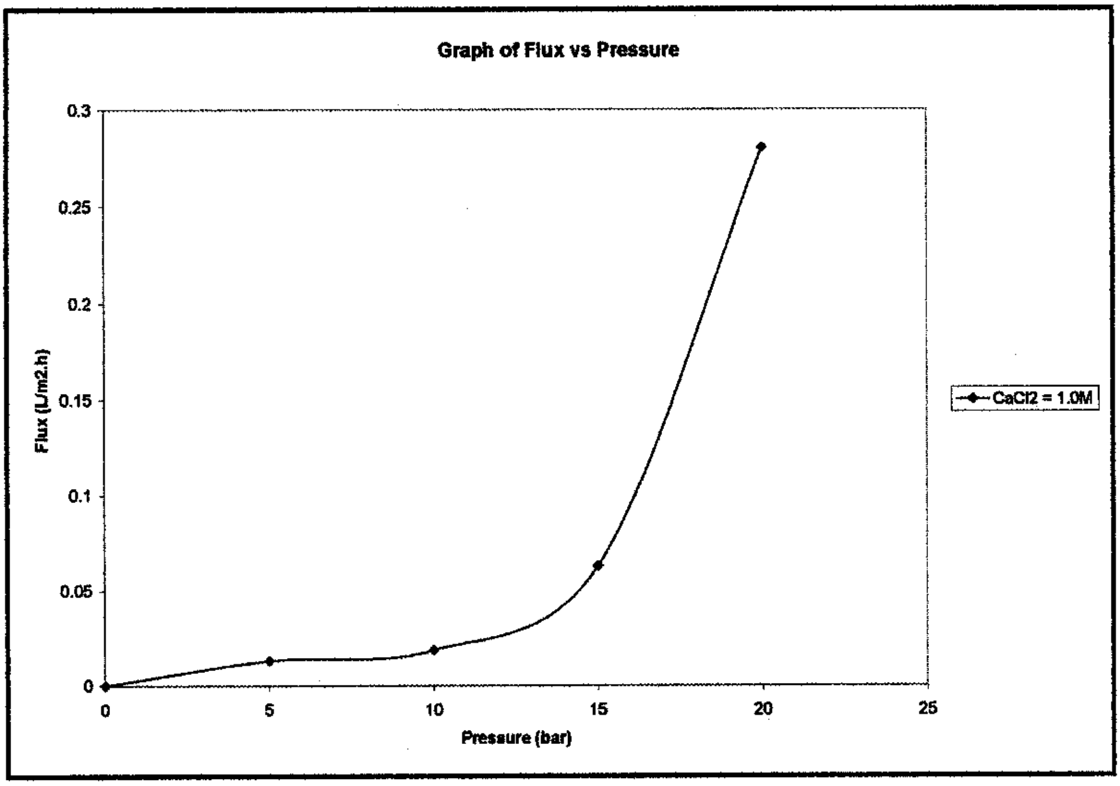


Figure 8.2: *Graph of flux against pressure*

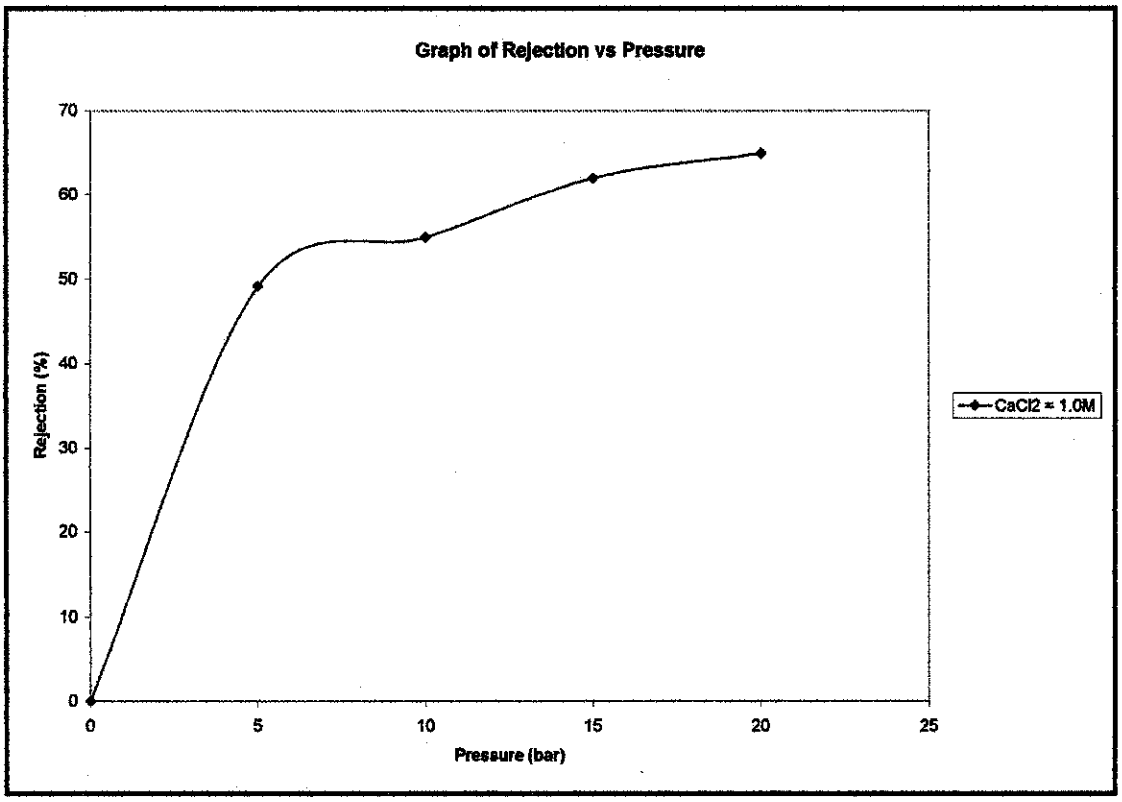


Figure 8.3: *Graph of rejection against pressure*