DEVELOPMENT OF AN ADVANCED TRANSVERSE FLOW NANOFILTRATION MEMBRANE PROCESS FOR HIGH PERFORMANCE DESALINATION

by

ZENON Environmental, Inc.
Burlington, Ontario

Contract No. **1425-4-CR-81-19870**
Final Report
June **1995**

Water Treatment **Technology** Report No. 9

U.S. Department of the Interior
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This report documents the research study conducted by ZENON Environmental, Inc., on behalf of the Bureau of Reclamation, to investigate a novel, transverse flow hollow fiber nanofiltration membrane and module for desalination applications. The project involved development of a high tensile strength fiber suitable for brackish water applications, production of suitable membranes, and modifications to the existing transverse flow module design for high pressure applications.

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Bureau of Reclamation
Mission Statement

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all people by encouraging stewardship and citizen participation in theii care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.

EXECUTIVE SUMMARY

Desalination of brackish waters using nanofiltration is one priority area of research identified by the U.S. Bureau of Reclamation's Desalting Technology Program. In order for membrane based desalination systems to be widely employed, further technology developments are needed to improve the cost competitiveness of the process.

ZENON Environmental, Inc. was contracted to further the development of **ZENON's** novel **Moustic™** transverse flow hollow fiber nanofiltration module for desalination applications, and assess it's potential to meet BUREC objectives. The project involved development of a high tensile strength fiber suitable for brackish water application, production of suitable membranes, and modifications to the existing transverse flow module design for high pressure applications.

The following improvements were made to the transverse flow module through the course of the project:

- A transverse flow module was constructed which could be operated at the pressures necessary for brackish water desalination.
- Suitable high tensile based fibers were developed.
- Appropriate membrane chemistries were evaluated, and a chlorine-resistant nanofiltration with suitable solute rejection characteristics was produced, and
- Methods for application evaluation of the membrane were investigated and optimized.

The high pressure nanofiltration module was tested on a synthetic brackish water and performed well with minimal pretreatment. Flux, however, was low in the configured module compared to individual fibers. Further module development is necessary to improve flow distribution and decrease channeling in the high pressure design.

To continue the development of improved nanofiltration processes for desalination of brackish water, the following alternatives are available for further evaluation and demonstration:

- Direct nanofiltration using the transverse flow concept, or adaptation of the high tensile fibers to a crossflow concept, in order to develop the most cost-effective and foulant resistant process, or
- Use an energy-efficient and cost-effective form of pretreatment prior to conventional nanofiltration, i.e. **ZeeWeed.**

Recent developments in hollow fiber technology undertaken by **ZENON** have resulted in an alternative low-pressure module design which appears ideally suited as an inexpensive form of pretreatment prior to NF. These modules have recently become commercially available, but have not been demonstrated for cost/benefit analysis on brackish water. It is therefore recommended that long term demonstration of this process be conducted, either alone or in a side-by-side comparison with the transverse flow module design. Microfiltration is receiving widespread attention for application on non-saline surface supplies to reduce turbidity and prevent passage of cysts, as well as reclamation of secondary effluents. The data from the demonstration of this two stage process would provide the information necessary for evaluation of this novel microfiltration design for other applications, in addition to the combined MF/NF scenario for brackish water.

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1.0 INTRODUCTION

1.1 Drinking Water Needs

The Office of Technology Assessment has determined that more than 50,000 communities in the United States are deficient in suitable drinking water. Much of this problem can be alleviated through the efficient application of membrane-based desalting technology. Both coastal sea and brackish water, as well as inland brackish,, and high organic source waters can be effectively purified to National Safe Drinking Water Act standards for potability by reverse osmosis and/or nanofiltration.

In order for membrane-based desalination systems to be widely employed, they must be cost-competitive. It has been widely recognized in the international water community that, although viable today, widespread use of membrane-based systems requires further technology advancement to develop the most cost-effective components and processes. The Bureau of Reclamation, through its Desalting Technology Program which was initiated in 1992, has also recognized this need.

Specific improvements in the membrane technology have been identified by the Bureau of Reclamation which are necessary for broad application of this technology. Key needs are:

1. Higher throughput membrane modules;
2. Chlorine-tolerant membranes;
3. Solids-tolerant membrane modules (to minimize cost of pretreatment);
4. Higher recovery membrane modules;
5. Membrane modules with greater chemical tolerance (for management of various organic and inorganic contaminants); and
6. Module design which results in lower energy consumption.

Zenon Environmental Inc. was awarded a contract (#1425-4-CR-81-19870) from the Bureau of Reclamation to further the development of Zenon's Moustic™ transverse flow hollow fiber nanofiltration module for desalination applications, and demonstrate its ability to meet BUREC objectives.

1 . 2 Nanofiltration

Nanofiltration (NF) separation, which has also been referred to as membrane softening, incorporates a membrane with pore sizes which can be classified between those of ultrafiltration and reverse osmosis membranes. Nanofiltration membranes are typically operated at pressures in the range of 50 to 300 psi and remove a portion of the TDS (primarily the divalent ions). Removal of salt typically ranges from 30 to 80%. Conventional nanofiltration modules are commercially used for the treatment of colored brackish groundwater supplies in Florida

Nanofiltration has been shown to remove most naturally-occurring dissolved organics such as humic and fulvic matter; however conventional module design is not suited for application to surface waters with higher turbidities and therefore higher fouiing potential. Zenon's Moustic™ transverse flow nanofiltration modules were developed and tested for application on colored surface water supplies, and shown to meet drinking water treatment criteria with reduced pretreatment requirements.. Upon further development, the hollow fiber module could also be adapted to brackish waters where higher operating pressures are required.

Direct nanofiltration is applicable in numerous situations where a brackish water supply is to be treated for production of drinking water or for reuse for agricultural purposes. In this case, nanofiltration would remove a significant portion of salts, provide essentially complete removal of most dissolved organics, as well as all bacteria and cysts which may be present. Chlorination can be applied before and/or after separation, depending upon feedwater quality and end use.

Where higher levels of dissolved salts are encountered, such as in seawater desalination, seawater intrusion, or certain mine waters, improved nanofiltration modules could provide a cost-effective form of pretreatment prior to reverse osmosis. Nanofiltration would serve to partially reduce the salt content, thereby reducing the osmotic pressure and associated operating pressures required by RO. This system configuration would reduce energy costs and extend the life of the reverse osmosis membranes.

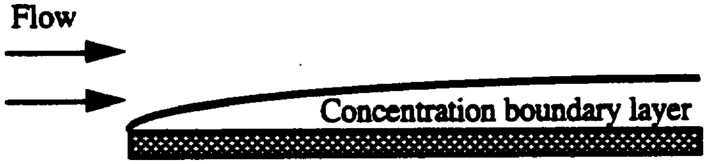
Further development of the transverse flow module has the potential to significantly reduce process costs compared to commercial modules currently used.

1.2.1 Transverse Flow Module Design

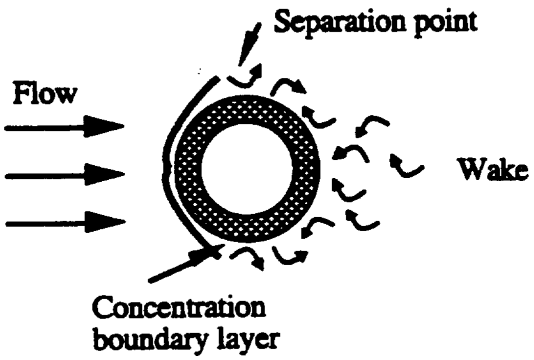
The economics and commercialization potential of the processes described above are dependent upon the development of a module design which has increased throughput, reduced fouling potential, and minimal pretreatment requirements. Prior to beginning this project, **Zenon** Environmental Inc. has developed a transverse-flow hollow fiber module referred to as **Moustic™** (**Zenon** proprietary technology), specifically designed for improved flux and reduced fouling potential. The module **was** originally developed on the premise that major benefits could be derived by improving fluid dynamics at the membrane surface in a simple manner. The transverse flow configuration potentially offers high mass transfer when compared to tangential or crossflow configurations used in traditional membrane modules. In crossflow filtration, as shown in Figure 1-1 (a), a boundary layer is allowed to develop which often limits the performance of the membrane. By contrast, Figure 1-1(b) illustrates how the transverse flow **configuration** limits the growth of the boundary layer to the upstream side of each fiber. Eddies formed at the back of the fiber help keep the surface clean.

Figure **1-1**
Comparison of Crossflow and **Transverse** Flow Configurations

(a) ***Crossflow*** configuration



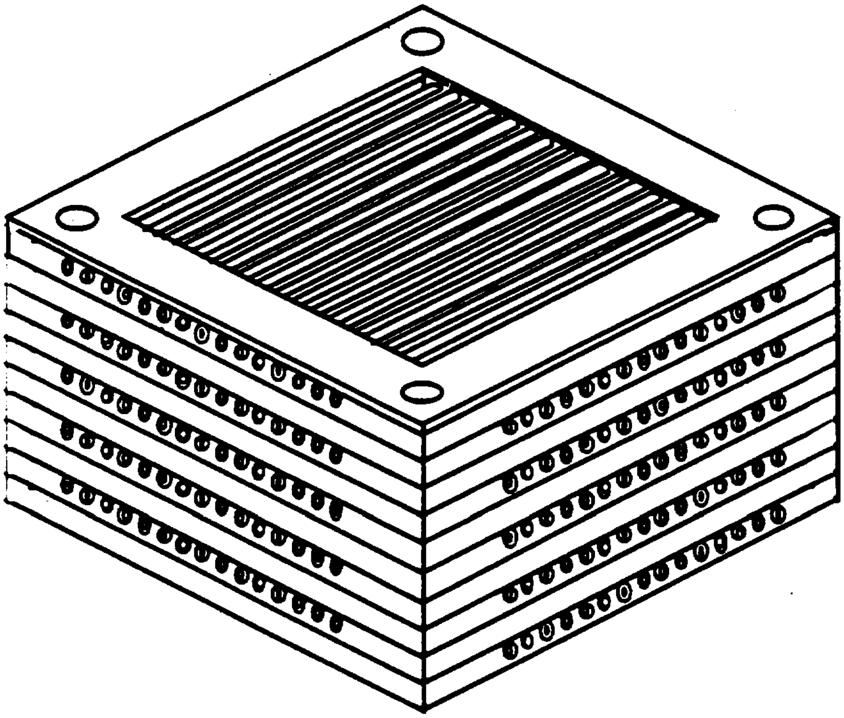
(b) Transverse flow configuration



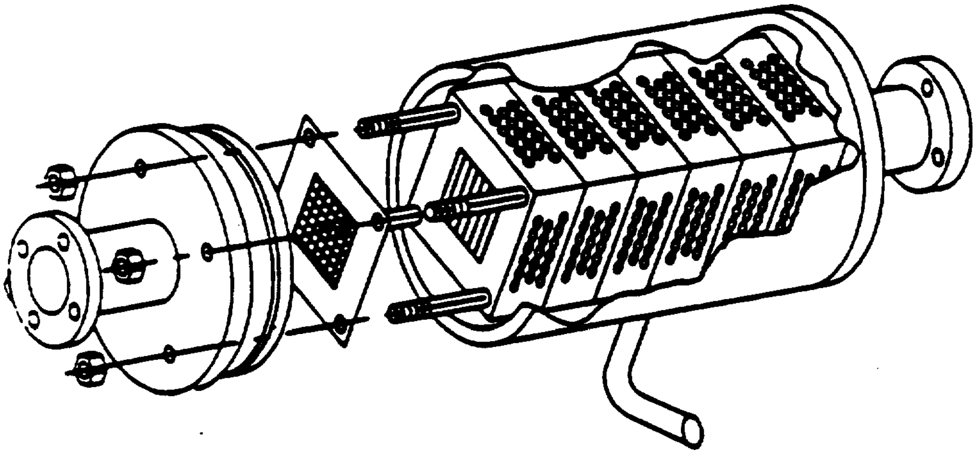
The developed module, illustrated in Figure 1-2, allows the feed to flow transversally to the axis of the hollow fibers individually tensioned in a square section (Figure **1-2(a)**). The fibers are arranged as stacked layers in alternate *directions.* The **permeate** *flows* from the outside of the fiber and into the lumen of each fiber. Each fiber is secured in a plastic frame and is open at both ends through which permeate is collected. To fabricate a module, sub-modules are arranged in series, inserted in a shell and fitted with proper headers (Figure 1-2 (b)).

Figure **1-2**
Moustic Module

(a) **Moustic™** Sub-Module



(b) **Moustic™** Module with **Shell** and Headers



The design method allows for control of both transverse and longitudinal pitches of the fibers (fibers do not touch each- other). High packing density (short pitch) can be balanced against reduced need for feed pretreatment (large pitch). Previous development of the transverse flow configuration allows a great reduction in the level of pretreatment when compared to conventional spiral-wound modules.

The transverse flow element has the following potential advantages over spiral-wound elements. Membrane fouling is significantly reduced because:

- the membrane surface is not in contact with itself or any material (such as a feed spacer),
- the hollow fiber spacing can be selected to reduce pretreatment requirements without **sacrificing** packing **density** (200 **µm pretreatment** filter for a transverse flow element as compared to **5 µm** for a typical spiral wound element), and
- the membrane has a lower susceptibility to fouling, as indicated by a mass transfer coefficient 2 to 3 times higher, for the same expense of energy.

Zenon is currently in various stages of testing pilot scale versions of the transverse flow module. **Zenon's** existing Moustic ™ Module was designed to handle operating pressures in the the range of **75-** 100 psi.

Prior to this project, **nanofiltration** membranes with **800-1,000** MWCO **were** produced by **Zenon.** Rejection of **NaCl** (using **feeds** of 3,000 ppm) was typically **30%,** with multivalent salts ($CaCl_2$, $MgCl_2$, others) exhibiting rejection > 80%. Rejections **are** similar in the presence or absence of chlorine.

Successful development of a cost-effective alternative hollow fiber module &sign with reduced fouling potential which is able to withstand higher pressures would serve to address many of the desalting technology needs identified by BUREC.

1.3 Objectives

The primary objective of the project is to further develop the module and investigate the potential technical and cost advantages of **Zenon's** alternative hollow fiber module design for **nanofiltration** applications.

Specific objectives of this project are:

- To develop an improved (higher tensile strength) **nanofiltration** hollow fiber membrane for brackish water applications (approximately 2,000 ppm total solute),
- To develop a transverse flow module for operation at higher pressures,
- To test the concept for desalting of brackish **waters,** and
- To provide a technical and economic assessment of the technology and identify potential applications of interest to BUREC.

The main applications envisaged for this membrane and module **are:**

- Desalting of brackish water (up to 2,000 ppm **NaCl)** for irrigation purposes (to less than 1,400 ppm **NaCl).**
- Total removal of **humic** and fulvic acids, as well as bacteria, cysts, and cryptosporidium for production of drinking water, along with partial removal of salts.
- Retreatment prior to RO for **desalination** of seawater.

2.0 TASK 1 FIBER DEVELOPMENT

The object of Task 1 was to develop a base fiber which:

- is suitable for operating at pressures up to 1.6 **MPa** (225 psi),
- provides a pure water flux of 200 **USgfd** at 225 psi and 25” C, and
- and is suitable for coating the **nanofiltration** barrier layer.

2.1 Introduction

Standard thin film composite reverse osmosis and **nanofiltration** membranes **have** two separate parts:

- a thin barrier layer (membrane) which serves as the **separating layer**, and
- a **microporous** sublayers (base fiber) supporting the barrier layer

It has been shown by Cadotte et al. (198 1) that polysulfone provides an excellent support for very thin, highly selective desalination membranes. In flat sheet membranes, the mechanical strength is provided by a fibrous web, and therefore, a thin support layer can be made. However, fibers must be self-supporting and in this case, need to withstand compression pressures of 300 - 400 psi. Because of this, the fiber usually has a thick wall, and this results in low permeability. As such, the formulation used in flat sheets can not be used in fiber spinning, and a new formulation with optimal characteristics needed to be developed.

Previous work has shown that a hollow fiber reinforced with fiberglass has a higher compression and collapse pressure. The dope composition, membrane thickness, and spinning conditions all affect performance, as measured by factors such as flux, compression pressure, and molecular weight cutoff **(MWCO)**. The resulting base fiber must have the appropriate MWCO, pure water flux, and compression pressure for **nanofiltration** applications.

To meet this objective, base fibers were developed from three different polymers: polysulfone (PS), sulfonated polysulfone (SPS), and polyimide (PI). The fibers were reinforced using a hollow fiberglass braid as support. In addition to strengthening the fiber, this allowed the use of dopes with lower viscosity. High viscosity dopes yield fibers with lower flux and higher compression pressure. Methodology used in fiber spinning does not allow one to use low viscosity dopes. One way to overcome this difficulty is to make a thin membrane on a support, so that most of the strength of the fiber will come from the support and the membrane only behaves as a separation layer. This would allow the coating of thinner base membranes, which in turn would **maximize** the flux while maintaining compression resistance.

2.2 Experimental Methods

2.2.1 Fiber Spinning

A simplified schematic of a fiber spinning device is shown in Figure 2-l. A reservoir containing the polymer solution is pressurized with nitrogen and the polymer is forced into the spinning jet (a tube-in-tube jet). In unreinforced fibers, the solution extruded through the spinning jet is drawn **into** a coagulation bath. The center bore of the extruded fiber is maintained open by the use of a non-coagulant fluid under pressure. The size of the extruded fiber is controlled by the pressure in the dope vessel, the extruding speed and the pressure of fluid in the center bore.

For **reinforced fibers, the** procedure is identical, except that a hollow fiberglass braid **is-used** instead of a non-coagulant bore fluid. The fiberglass reinforcement passes through the **first** jet and is coated with polymer. The second jet removes the excess polymer. The **resulting fiber proceeds** through the **coagulation** bath.

The ‘replacement of polymer solvent with water from the coagulation bath causes the viscosity of the polymer solution to **increase. The** speed of the replacement as well as the polymer formulation control the pore size of the resulting fiber. As more solvent-is replaced by water, the polymer begins to solidify in the coagulation bath and can be **further handled.**

The fiber is then directed **to** a winder by use of a self advancing godet. The fiber is wound into bobbins. The wound fiber is then **washed with** water to remove the remainder of the solvent and additives, and impregnated with preservative before drying.

2.2.2 Compression Test

A simplified chart of the test installation is shown in Figure 2-2. The compression pressure of the fiber was determined using water flux measurements. A looped fiber bundle containing 6 fibers was potted into a half inch steel fitting. The fiber bundle was connected to a water reservoir The outside of the fiber bundle was surrounded with water. The water reservoir was then pressurized with nitrogen to approximately 20 psi and the water flux recorded over a twenty minute period (measured at 5 **minute intervals). The** nitrogen pressure was increased by 20 • 50 psi every 20 minutes up to 400 psi, or when the flux started to level off and stopped increasing with pressure. The compression resistance is determined by plotting the water flux as a function of test pressure. **The** point at which the curve begins to flatten is the compression pressure of the fiber.

Figure 2-1
Hollow Fiber Spinning

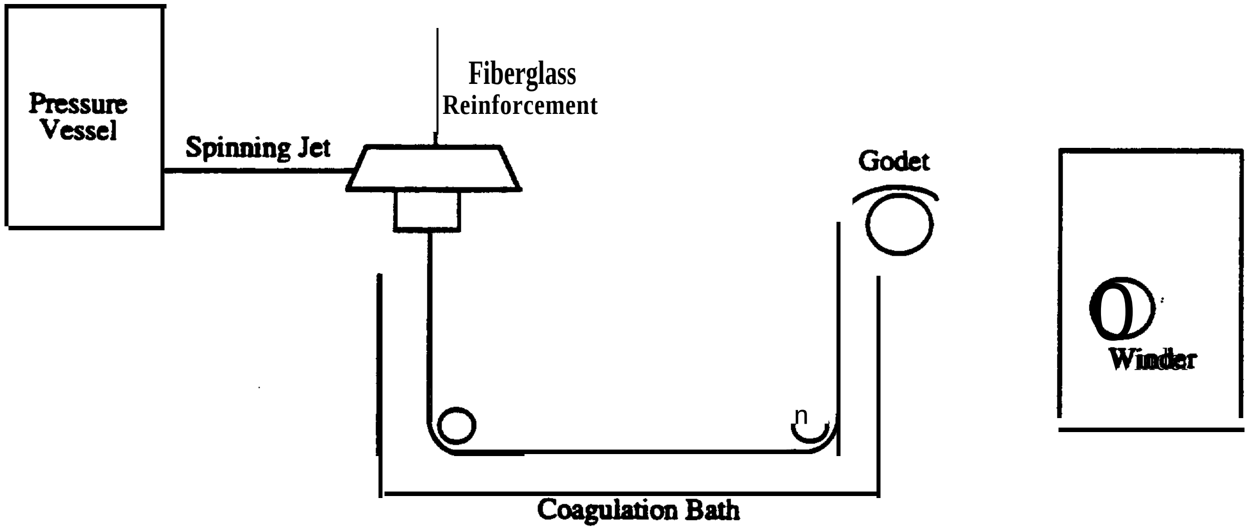
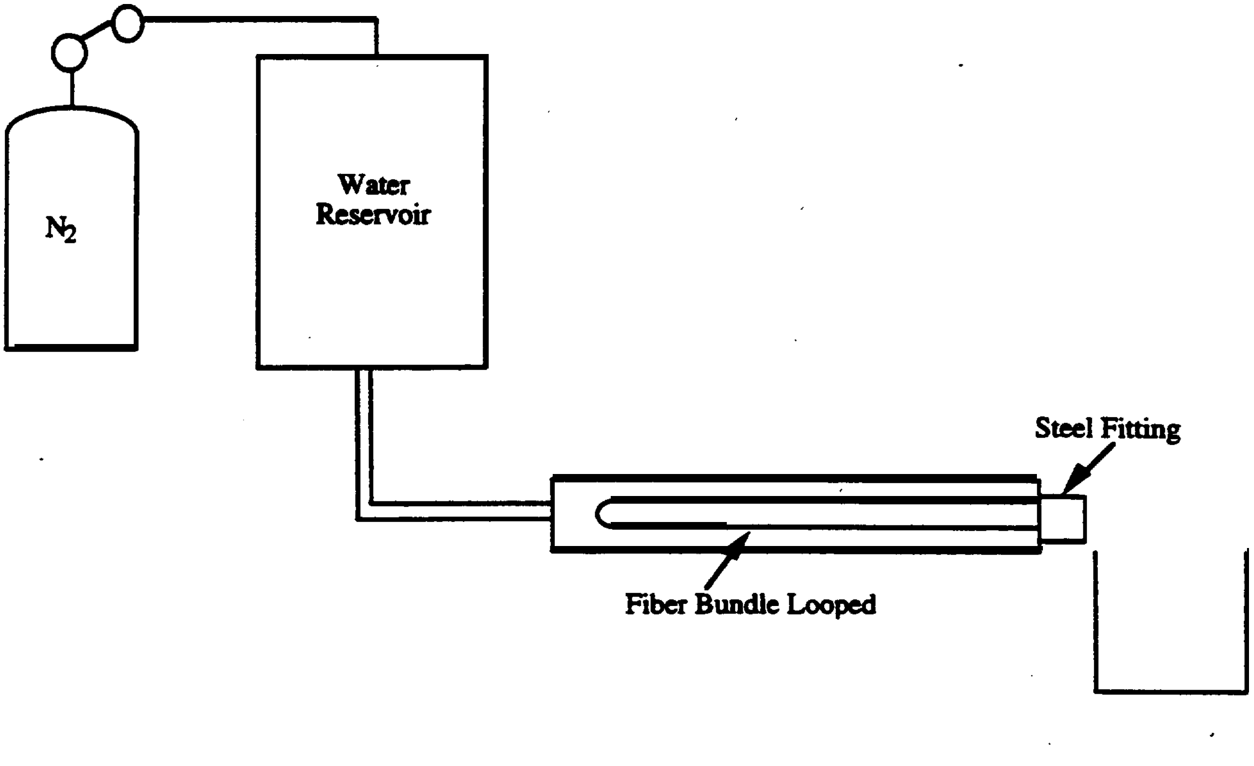


Figure 2-2
Compression Tester



2.3 Results and Discussion

The development and testing of three base fiber formulations are discussed in the following section. Raw data from various trials is given in Appendix A.

2.3.1 Polysulfone Fibers (PS)

Polysulfone is a hydrophobic polymer, commonly used by several commercial membrane manufacturers. Polysulfone has many advantages, which include being non-biodegradable, stable at extreme **pH** levels, able to operate at high temperatures, and having a high compaction resistance. One drawback of polysulfone for some applications is **its** hydrophobic nature. Another draw back is its sensitivity. **to** a broad range of solvents, which limits its usefulness in certain membrane fabrication techniques, such as solvent evaporation.

The objective was to develop a reinforced PS hollow fiber which could be evaluated for both interfacial polymerization coating and solvent evaporation coating techniques. Commercially available flatsheet **NF** membranes are based on a PS base membrane with an interfacial **polymerization** membrane coated on top.

Previous development work undertaken by **Zenon** investigated a reinforced fiber for high pressure **(RO)** applications. Since pressures would be lower for **nanofiltration,** this base membrane was modified by using a lower viscosity dope **to maximize** flux. A hollow braid with **0.3/0.9** mm **ID/OD** was used for this application, and coated with the **PS** formulation. Figure 2-3 shows that the PS fiber effectively sustained a compression pressure of **300** psi.

Figure 23
Compression Test Using Polysulfone Fiber

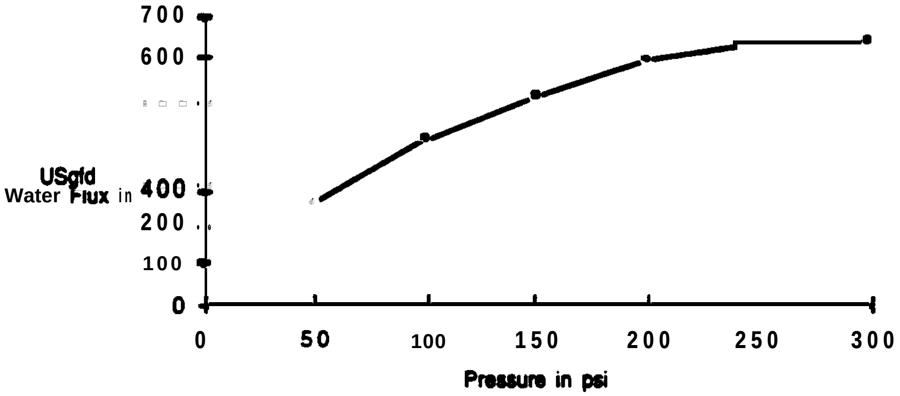


Table 2-l **summarize** s the performance characteristics of the PS fiber.

Table 2-1
Polysulfone Fiber Test Results

Base **Fibre**	Compression Pressure in psi	**Water Permeability USgfd/psi**	**%** Rejection of 10,000 MW PEG
PS	**300**	2.54	65

A pure water permeability of 2.54 **USgfd/psi,** or the equivalent of **>500** USgfd at 225 psi, was achieved. Since a **fiber** with a flux of 200 USgfd and a **90%** loss in flux after coating would produce a membrane with a flux of 20 USgfd, the high permeability of this **fiber** offers good potential for **maximizing** flux after coating.

MWCO tests showed an 65% rejection of polyethylene glycol, with a molecular weight of about 10,000 daltons. These fibers were considered acceptable for solvent evaporation coating of **Zenon's nanofiltration** chemistries (referred to as **LTMX,** and **CPS).**

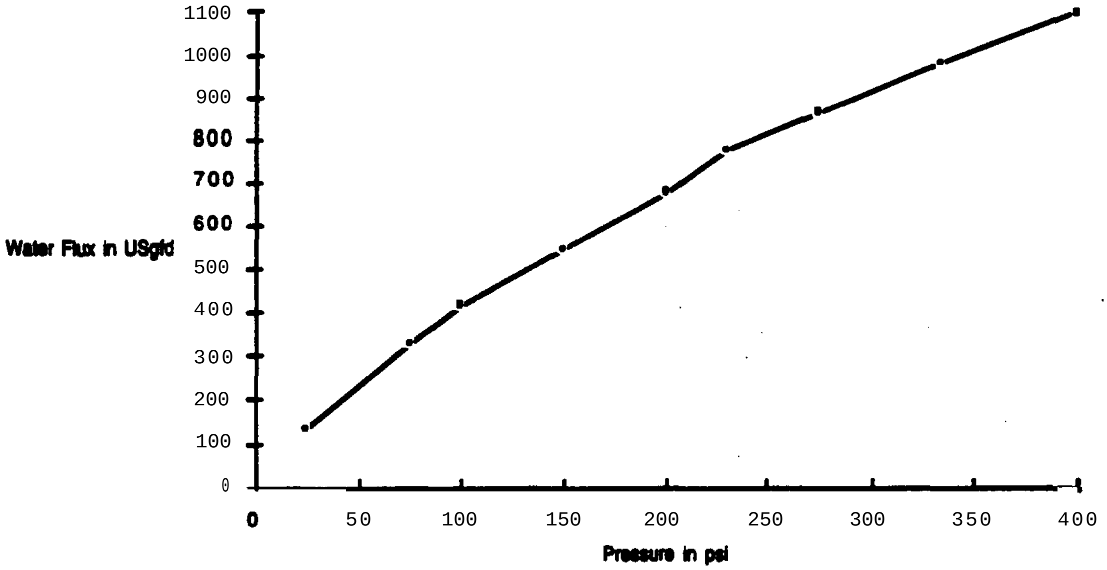
2.3.2 **Sulfonated Polysulfone Fibers (SPS)**

The second fiber developed for coating was based on a blend of sulfonated **polysulfone/polysulfone.** The objective of this task was to determine if a sulfonated polysulfone blend would increase the **hydrophilicity** and therefore water flux of the base fiber, while maintaining other required characteristics.

Sulfonated polysulfone (SPS) was selected since it is more solvent resistant and therefore more suitable for solvent evaporation of the **Zenon chlorine** resistant membrane **(LTMX).** The coating solution LTMX contains some sulphonic acid groups. It was thought that by having sulphonic acid in the base fiber, the sulphonic acid in the separating layer would react with the sulphonic acid in the base **fiber** to yield a strong crosslinked membrane. The blend containing sulfonated polysulfone will make the base **fiber** more hydrophilic in anticipation of increasing the flux, while maintaining the same amount of **polymer** resin.

Several different formulations were considered. Figure **2-4** below summarizes the compression resistance of the optimum formulation. The SPS blend fiber demonstrated a higher compression resistance than the polysulfone **fiber (>400** psi versus 300 psi).

Figure 24
Compression Test Using Sulfonated Polysulfone Blend Fiber



Performance results are **summarized** in Table 2-2 below.

Table 2-2
Sulfonated Polysulfone Fiber Test Results

Base Fibre	Compression Pressure in psi	Water **Permeability USgfd/psi**	**%** Rejection of 10,000 MW PEG
SPS (94-69-3.4)	**400**	2.15	80

This fiber has high compression resistance of **>400** psi and high permeability of 2.15 **USgfd/psi,** and is very promising for solvent evaporation coating. Although well within acceptable range, the **permeability** was slightly lower than that observed in the more hydrophobic PS fiber (2.54 **USgfd/psi).** It was also observed that the compression pressure for the SPS blend **fiber** is significantly greater, which is consistent will the flux readings.

2.3.3 Polyimide Fibers (PI)

The next **fiber** investigated was a **polyimide(PI)** formulation, **which is** suitable as a base for **coating** a selective layer by solvent evaporation.

Although polysulfone has been successfully used as a base membrane for 'coating a NF barrier layer by interfacial polymerization, its sensitivity to a broad range of solvents limits it usefulness. The only organic solvents that can be used with polysulfone are low molecular weight hydrocarbons and low molecular weight alcohols. In the solvent evaporation method used for depositing the barrier layer, a polymer is dissolved in a solvent and applied to the base membrane and the solvent is evaporated leaving a thin polymer layer on the base membrane. Several polymers which could form a better and more effective barrier layer do not dissolve in mild organic solvents. As such, we were looking for polymers which are stable to more powerful organic solvents. One such polymer is polyimide which is known to tolerate strong organic solvents such as methylene chloride and acetone.

The compression characteristics of the polyimide fiber are shown in Figure 2-5. The fiber sustained a compression pressure of 400 psi.

Figure 2-5
Compression Test Using Polyimide Fiber

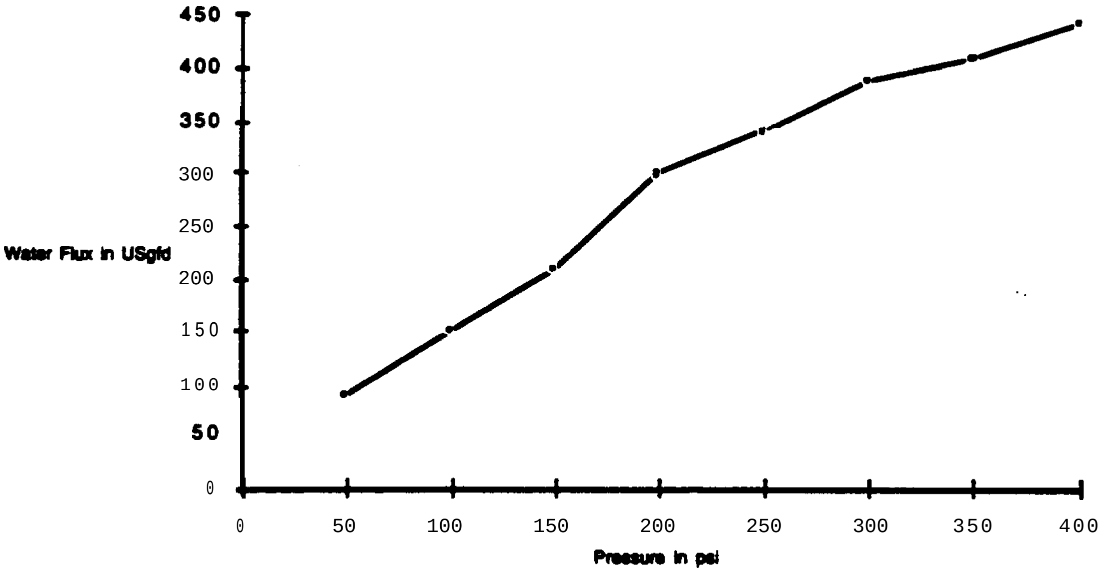


Table 2-5 summarizes the performance of the Polyimide fibers developed.

Table 2-3
Polyimide Fiber Characteristics

Base Fibre	Compression Pressure in psi	Water Permeability USgfd/psi	% Rejection of 10,000 MW PEG
PI (18-5-94)	400	1.11	84

Of the three fibers tested, the PI fiber has the lowest permeability, at 1.1 USgfd/psi; however both flux and compression pressure were considered acceptable for coating NF membranes. Scanning electron microscope photographs were taken of the fiber surfaces and are given in Appendix B. SEM photographs show that both polyimide and polysulfone fibers are defect free and suitable for coating.

2.4 Conclusions

A number of reinforced outside/in hollow fibers were produced that were capable of operation without compression or collapse at pressures up to and greater than 300 psi. All three fibers met water flux and MWCO criteria.

A reinforced fiber made with sulfonated PS had excellent flux and compression resistance (Table 2-2). This fiber is very promising for coating NF membranes.

Fiber made with PI showed promising results. However, fluxes were lower than those observed with other fibers at quivalent pressures. This observation, combined with the fact that the PI base membrane is more sensitive to high pH (required for cleaning) than the others, led to the selection of PS and SPS blend fibers for coating trials.

3.0 NANOFILTRATION MEMBRANE DEVELOPMENT

3.1 Introduction

The objective of this **subtask** was to develop a suitable **nanofiltration** membrane coating, capable of meeting the following **criteria:**

Table **3-1**
Solute Rejection Specifications

Solute	*Molecular Weight*	*Rejection (%)**
NaCl	**58**	**5-50**
$CaCl_2$	111	**70**
$MgSO_4$	120	95
Glucose	18	90
sucrose	34	98
Raffinose	500	99

* The rejections are based on a test condition of 2,000 ppm solute, pressure of 1.6 **MPa** (225 psi) and **temperature** of **77°F (25°C)**.

Although our final objective is to develop a **nanofiltration** membrane which could remove 95% sulphate ions, a membrane with **70-80%** sulphate rejection, and flux of 15-20 gallons per square foot per day **(USgfd)** at required pressures (225 psi) could be used economically to produce potable water in about 80% of the United States communities (Cescon and Hoehu, 1970). As such, our initial goal was to develop an oxidation **resistant nanofiltration** membrane with 70-8096 sulphate rejection.

The sulphate rejection properties of the membranes were determined either by using pure 2,000 ppm magnesium sulphate solution or a synthetic **brackish** sulphate feed water containing 700 ppm calcium sulphate, 400 ppm magnesium sulphate, 400 ppm sodium sulphate, and 100 **ppm** synthetic **humic** acid (fouling agent).

Two different types of thin film membrane coating methods were **investigated:**

- thin **film** composite membrane formed by solvent evaporation, and
- interfacially **polymerized** thin **film** composite membrane.

Solvent Evaporation. In this method, a coating solution is made by dissolving the polymer and other additives in a volatile solvent. The base fiber is dipped into this solution and the solvent is evaporated to give a thin film membrane.

Interfacial Polymerization. In this method, one monomer is adsorbed onto the outside of the support (or base) fiber and dipped into a solution of a second monomer and polymerization takes place at the interface. By controlling the dipping time and concentration of the first and second monomer solutions, the permeate flux and rejection of the membrane can be controlled.

Three thin film composite membranes were selected for coating trials with the reinforced hollow fibers described in the previous section. All membranes would be coated on the outside of the fiber. The three types of membranes were:

1) Zenon chlorine resistant membrane formed by solvent evaporation, designated as LTMX.

2) A commonly used formulation (aromatic diamine/triacylchloride) was used for an interfacially polymerized composite membrane. This well known formulation (FT-30) was used in order to obtain a membrane which is comparable in performance (rejection and flux) to a commercial membrane, and

3) Zenon CPS (carboxylated polysulfone) membrane chemistry developed for this application, which can be formed by either solvent evaporation or interfacial polymer&ion.

3.2 Experimental Methods

The coated NF fibers were sealed and mounted in the same way as for compression testing. Approximate surface area of the coated RO fiher bundle was in the range of 0.05 ft^2. Coated fibers were tested at pressures of 200 to 225 psi and a feed of 2,000 ppm sodium chloride was used. Experiments were usually run at 20°C.

For' each membrane chemistry, membrane formation conditions were varied, with the goal of preparing membranes with high salt (2,000 ppm solute) rejection.

Initially, commercially available flatsheets (E500 Desal), were used for trials using two interfacial polymerization membranes (diamine/triacylchloride formulation and CPS formulation). After these membranes where optimized they were coated onto the PS base fiber. The CPS chemistry was developed to be used as either an interfacial polymerization two step coating or as a solvent evaporation coating.

The base fibers developed were coated in lengths of approximately 12" long and then assembled into mini - modules. The fibers were tested in mini • module configuration of approximately 0.05 ft^2. The flux in **USgfd** and percent **rejection** of **NaCl** and **$MgSO_4$** was recorded.

The coated fibers were epoxied **into 1/2"** nylon fittings. The fibers were evenly spaced and the epoxy **was** poured into the fitting and cured overnight.

The mini-modules and coated flatsheets are mounted on the test system and operating pressures were gradually increased to reach 200-225 psi. All NF testing was done at 20°C feed **temperatures.** Raw data for coating trials is given in Appendix A.

3.3 Interfacial Polymerization Coating

To obtain an interfacially polymer&d thin film coating, **the** support film is **saturated** with a water solution containing diamines plus other additives, such as acid acceptors and **surfactants.** The **saturated film is contacted with an immiscible** solvent containing di or **triacyl** chloride reactants. A **condensation polymer forms at the interface. The film is dried to bind the thin interfacial film to the** support surface.

3.3.1 Coating of Flatsheets by Interfacial Polymerization

The **E500 Desal flatsheet** was coated with standard **interfacially polymerized** membrane **(diamine/ triacylchloride)** and the CPS **membrane,** to **optimize** coating conditions for coating onto the fibers.

In **interfacial** coating solutions. **normally** the water component is applied fir!& **and** the *excesswater* is removed. The organic **component** is then applied and the polymerization or crosslinking forms **the** selective layer.

The performance of the **CPS** chemistry on commercial **flatsheets** is given in Table 3-2. Table 3-2 shows that rejections and flux were excellent. Rejection of **$MgSO_4$** was slightly lower than the optimum target of 95% but within preliminary goals of 70 to **80%.**

Table 3-2
Interfacial Polymerization Coating of CPS Chemistry on Flatsheets
(Trial 1)

Base Membrane	Thin Film Composite	%Raffinose Rejection	%Rejection of 2,000ppm MgSO4	%Rejection of 500ppm NaCl	Flux in USgfd
E-500 flatsheet (n=3)	CPS	100	78 (s= 2.0)	77 (s=4.1)	25 (s=5.1)

n = number of observations; s = standard deviation

Further work was carried out using CPS chemistry in an attempt to increase $MgSO_4$ rejection. Reaction time was ‘increased and solids content in the coating solution was **varied** slightly. Performance was compared to coating trials using **diamine/triaclychloride** chemistry Results are given in Tables 3-3 and 3-4,

Table 3-3
Interfacial Polymerization Coating of CPS **Chemistry** on Flat Sheets
(Trial 2)

Base Membrane	Thin Film Composite	%Raffinose Rejection	%Dextrose Rejection	%Rejection of 2,000ppm MgS04	%Rejection of 500ppm NaCl	Flux in USgfd
E-500	CPS	100	90	99 99	70	4.0
		100	90		73	4.0
		loo	87	97	90	8.3

Table 3-4
Interfacial Polymerization Coating of Reference Chemistry on Flat Sheets

Base Membrane	Thin Film Composite	%Raffinosse Rejection	%Dextrose Rejection	%Rejection of 2,000ppm MgSO4	%Rejection of 500ppm NaCl	Flux in USgfd
E-500	Diamine + triacyl-chloride	100	93	99	84	6.6
		loo	90	98	80	4.8
		100	95	99	85	7.0

The rejection values obtained using the CPS chemistry were excellent and appeared to meet criteria when compared to **original** solute rejection specifications. The diamine and triacylchloride (Reference) membrane system produced rejection values that also met criteria

3.3.2 Coating of Fibers by Interfacial Polymerization

Although both **CPS** and reference coatings worked well on **flat** sheets, a different technique for coating fibers had to be developed. It is very important that the fibers remain clean during the entire coating process. The actual coating of the two components must be done in such a way as to get an even application over the entire fiber and during the crosslinking stage any movement must **be** very precise and smooth so the interface between the two components is not disrupted. The coating for interfacial polymerization was done by hand without the benefit of precise equipment.

Initially, the reference interfacial polymerization membrane was coated on the two developed fibers. The fibers were tested on **2,000** ppm $MgSO_4$ at 200 psi, and results are given below.

Table **3-5**
Interfacial Polymerization Coating of Fibers

Thin Film Composite	Base Fibre	% Rejection 2,000ppm MgSO4	Flux USgfd
Diamine & Triacylchloride (FT30)	PS	89	9
	SPS	61	13

The results show that the polysulfone fiber exhibited significantly better rejection than the sulfonated polysulfone. Despite a slightly lower flux, the **PS** fiber was considered preferable for coating trials.

3.4 **Coating** By Solvent **Evaporation**

In the solvent evaporation coating method, the fiber is dipped into a coating solution and the solvent is evaporated by heating. The surface of the fibers or **flatsheets** are first cleaned and dried and then are dipped into the coating solution and removed. Excess coating solution is allowed to run off and then the fibers or flatsheets are placed in an oven to cure the membrane and drive off the remaining solvent. The solvent evaporation membrane was coated by hand. The coated fibers were epoxied into mini-modules exactly as for the interfacial polymerization **(IFP)** coated fibers . The test procedures were the same as for IFP coating fibers.

3.4.1 Coating Flatsheets by Solvent Evaporation

Initially, commercially available flatsheets were coated with **Zenon's** membrane chemistries. The **LTMX** (chlorine-resistant) and CPS formulations were tested. Results are **summarized** in Tables 3-6 and 3-7.

Table 3-6
Solvent Evaporation Flatsheet Coating **Trials (LTMX)**

Reference#	**Thin film composite**	**%Rejection 2,000ppmNaCl**	**Flux USgfd**
71-78-1	LTMX	97.2	16.4
71-78-2	LTMX	96.1	19.8
71-80-1	**LTMX**	96.6	16.0
71-80-2	LTMX	95.6	17.5

Table 3-7
Solvent Evaporation Flatsheet Coating **Trials** (CPS)

Reference#	**Thin Film** Composite	**%Raffinose** Rejection	**%Dextrose** Rejection	**%Rejection** of 2,000ppm **MgSO4**	**%Rejection** of **500ppm NaCl**	**Flux in USgfd**
121-1	**CPS**	100	78	88	71	11.6
121-2	CPS	100	**78**	**n/a**	**76**	12.0
121-3	**CPS**	**100**	**92**	**n/a**	**76**	11.2
125-1	**CPS**	**100**	80	84	75	12.4
125-2	**CPS**	**100**	82	91	74	10.9
125-3	**CPS**	**100**	86	90	79	11.2

The CPS chemistry produced very good results by solvent evaporation coating. The CPS coated by solvent evaporation was considered suitable for fiber coating trials.

The LTMX coating solution produced rejection **values** that were excellent. **Based on** these results, the **LTMX** coating solution was selected for the majority of subsequent work on the fibers. Although the CPS coating solution demonstrated good results, the overall performance of the

LTMX membrane was superior based on flat sheet trials. CPS chemistry will, however, be tested to determine **performance** when coated on fibers. It was **also** expected that since the LTMX membrane is further developed than the CPS membrane, reproducibility would be better using **LTMX**.

3.4.2 Coating Polysulfone fibers by Solvent Evaporation

The objective of this **subtask** was to coat the selected polysulfone base fibers by solvent evaporation using **Zenon's** LTMX (and CPS) membranes to produce a NF membrane. The PS fibers were washed with alcohol to remove any preservative or dirt. The fibers were then heated to drive off the alcohol and to pretreat the fiber for coating. The fibers were then dipped in the membrane solution, drained, and placed in the oven to drive off the solvent and crosslink the membrane. Various fibers made from different formulations and diameters, which were prepared during the previous task were used.

The coated PS fibers were again tested on feeds of **2,000** ppm **NaCl** or 2,000 ppm **$MgSO_4$** and at pressures of 200 psi. Results are **summarized** in Table 3-8.

Table 3-8
Solvent Evaporation Coating **Trials** • Polyester Fiber . .

Base Membrane	**Coating** Solution	**%Rejection 2,000ppm MgSO4**	**%Rejection 1,000ppm NaCl**	**%Rejection 100ppm Raffinose**	**Flux USgfd**
20%PS/NMP **1.3mm** OD	**CPS** **n=8**	76.0 **(s=2.6)**	70.0 **(s=2.1)**	80.0 **(s=1.7)**	**5.4** **(s=0.3)**
15%PS/NMP **1.15mm** OD	**CPS** **n=4**	54.0 **(s=2.0)**	38.0 **(s=2.7)**	54.0 **(s=2.5)**	**7.5** **(s=2.**1)
20%PS/NMP **1.1mm** OD	LTMX **n=8**	78.0 **(s=4.1)**	58.0 **(s=3.2)**	68.1 **(s=3.0)**	**5.2** **(s=0.8)**
20%PS/NMP **1.3mm** OD	**LTMX** **n=8**	73.0 **(s=1.5)**	62.0 **(s=1.4)**	87.0 **(s=2.5)**	12.4 **(s=3.3)**
Small bundle of 12 fibres **20%PS/NMP** **1.3mm** OD	LTMX **n=3**	76.0 **(s=0.8)**	65.0 **(s=1.1)**	80.0 **(s=1.5)**	13.0 **(s=2.2)**

The results show that the best rejection and flux results were obtained using the 20% PS, 1.3 mm OD base fiber for both the LTMX and CPS solutions. The CPS coated fibers (20% PS, 1.3 mm OD) produced excellent rejection results but the flux was lower in every case compared to the LTMX coating solution. The LTMX coated fibers (20% PS, 1.3 mm OD) met rejection targets and demonstrated suitable flux values. These fibers were then produced in larger quantities to be used for the fabrication of a small module.

3.4.3 Coating Sulfonated PS fibers by Solvent Evaporation

Previous work undertaken by Zenon for brackish water and NF membranes has successfully used SPS for the base fiber which was then coated with the Zenon chlorine resistant membrane. Prior to this work, the NF membranes that Zenon produced were made by solvent evaporation and operated at pressures of 50 to 100 psi, and did not have fiberglass reinforcement

It was hoped that the SPS blend base could produce a higher flux than 5.5 USgfd which was obtained from the first PS /LTMX fiber module (Section 4-2) since the SPS/PS blend fibers are more hydrophilic.

The sulfonated polysulfone blend reinforced fibers were coated with the Zenon chlorine resistant membrane (LTMX). The coating procedure was very similar to the procedure used for coating the PS fibers. Results are given in Table 3-9.

Table 3-9
Solvent Evaporation Coating of Sulfonated Polysulfone Fibers

Sample #	% Rejection of 2,000ppm MgS04	Flux USgfd
1	66.3	16.2
2	60.9	20.9
3	70.9	13.0
4	74.0	12.8

The results show that LTMX coated onto SPS/PS fibers produced results comparable to the PS fibers, with fluxes slightly better and rejections slightly lower than the PS fibers. Actual testing of a SPS blend fiber module was not undertaken within the current scope of work.

3 . 5 Conclusions

Suitable methods for coating the outside surface of the reinforced fibers by interfacial polymerization and solvent evaporation were developed. Of the two fibers tested, the PS base fiber was considered superior for interfacial polymerization coating studies. The flux of 9.0 USgfd and 89% rejection of $MgSO_4$ obtained using the polysulfone fiber coated with the reference membrane (FT30) were considered very promising.

Solvent evaporation coating of Zenon chlorine resistant chemistry (LTMX) was combined with the PS base fiber. Flatsheet trials exhibited excellent rejection and flux. Both the LTMX membrane chemistry and the newly developed CPS chemistry met performance criteria when coated on flatsheets. A scanning electron microscope photograph (Appendix B) of a coated PS fiber shows some non-uniformity, however, this is due to manual coating' and would be eliminated when produced on a continuous coating line.

Rejections of coated PS fibers met preliminary criteria for brackish water, and performance was considered acceptable for further testing. The SPS blend base fiber can also be used for solvent evaporation coating of LTMX membranes. It should be noted that the fibers were coated by hand and significant improvement would be expected when precise on • line equipment is used.

Attempts should be made to further develop the coating method in order to improve the flux of the coated fibers.

4.0 NANOFILTRATION MODULE DEVELOPMENT

4.1' Introduction --

original development of the Moustic™ module involved design and testing of both round and square module designs for lower pressure (75 - 100 psi) applications. Further investigation was conducted to determine feasibility for high pressure applications (up to 800 psi) for seawater desalination, however some difficulties were encountered with module integrity under high pressures.

The objective of this phase of the project was to develop a transverse flow nanofiltration clement suitable for brackish water applications and capable of operating at pressures of up to 225 psi.

4.2 Crossflow Module Tests

In order to first confirm overall performance of the fibers in a configured module, a small module with 0.92 sq. ft. of membrane surface area, contained in a 2" PVC pipe was construct& The fibers used were 20% PS, coated with LTMX. For purpose of evaluating fiber performance, testing was conducted in a crossflow mode.

Results of testing are given in table 4-1.

Table 4-1
PS/LTMX Fiber Testing in Crossflow Module

	% Rejection Raffinose	% Rejection Dextrose	%Rejection of 2,000 ppm MgSO4	Flux (USgfd)
Crossflow Module #1	88%	74%	75%	5.5
crossflow Module #2	82%	40%	76%	10.25

Initial testing using the first module produced a permeate flux which was lower than expected at 5.5 USgfd. The polysulfone 1.3 mm OD fiber used to coat the LTMX membrane was re-tested for RO water flux. At 150 psi the water flux was only 0.33 USgfd/psi compared to 2.54 obtained in earlier tests. It was suspected that changes occurred during fiber storage as a result of low glycerol level in the fiber due to high humidity conditions. In order to improve the fiber storability,

modifications were made in the glycerol impregnation stage.

More **PS** base fiber was made, and the amount of glycerol was monitored during storage. A second small module was **constructed,** with 1.05 **sq.** ft. of **membrane** surface area within a **2"** diameter pipe. Module **#2** showed improved results, despite a lower than expected dextrose rejection. Flux improved to 10 **USgfd.**

Testing was then carried **out to** approximate **performance** on a brackish **water supply.** Testing was carried out using a synthetic **feed,** with the following composition:

$CaSO_4$	**700ppm**
$MgSO_4$	**400ppm**
Na_2SO_4	**400ppm**
Synthetic Humic Acid	**100ppm**

The results of testing are given in Table 4-2.

Table 4-2
Crossflow Testing of PS Fiber with LTMX Coating on Synthetic Brackish Feed
(Crossflow Module #2)

Elasped Time in hours	**Flux USgfd**	**%Rejection of Solute**	color **Permeate APHA**	**Color Feed APHA**
0.0	10.3	45.0	16	1,500
2.0	5.0	44.0	17	1,500
4.0	5.0	62.0	12	1,500
5.0	5.4	66.3	14	1,245
6.0	5.3	66.3	13	1,150
21.0	4.9	66.3	14	990
24.0	5.2	66.0	14	969
25.0	5.6	64.1	14	n/a
26.0	5.2	60.1	14	n/a
28.0	4.9	64.6	14	720

In this multi-solute **solution,** rejection was lower than that shown for MgS04 alone. This may he due to concentration **polarization,** fouling or presence of monovalent ions. If the low rejection was due to concentration **polarization** due to module configuration., it was anticipated that this problem would be removed in transverse flow module configuration.

Since dissolved **organics** can be present in brackish water supplies, synthetic **humic** acid was also added. Despite excessive levels of greater of 1,000 APHA (measured on diluted sample), rejections of greater than 98% were achieved. Color levels in drinking water supplies would not likely be much greater than 200 APHA, and at the observed 98% rejection, color levels in the permeate from a highly colored supply would be typically less than 5 APHA.

4.3. Transverse Flow Module Development

Previous work indicated that the weak link with the Moustic™ transverse flow modules in higher pressure applications was the potting epoxy in the cartridge walls.

In the first stage of testing, current modules were stressed. The existing design incorporates round modules which are wrapped with a mesh material and then covered with fiberglass. The cartridge and pressure vessel test apparatus are shown in Figures 4-1 and 4-2.

Figure 4-1
Transverse Flow UF Cartridge (Fiberglass Wrapped)

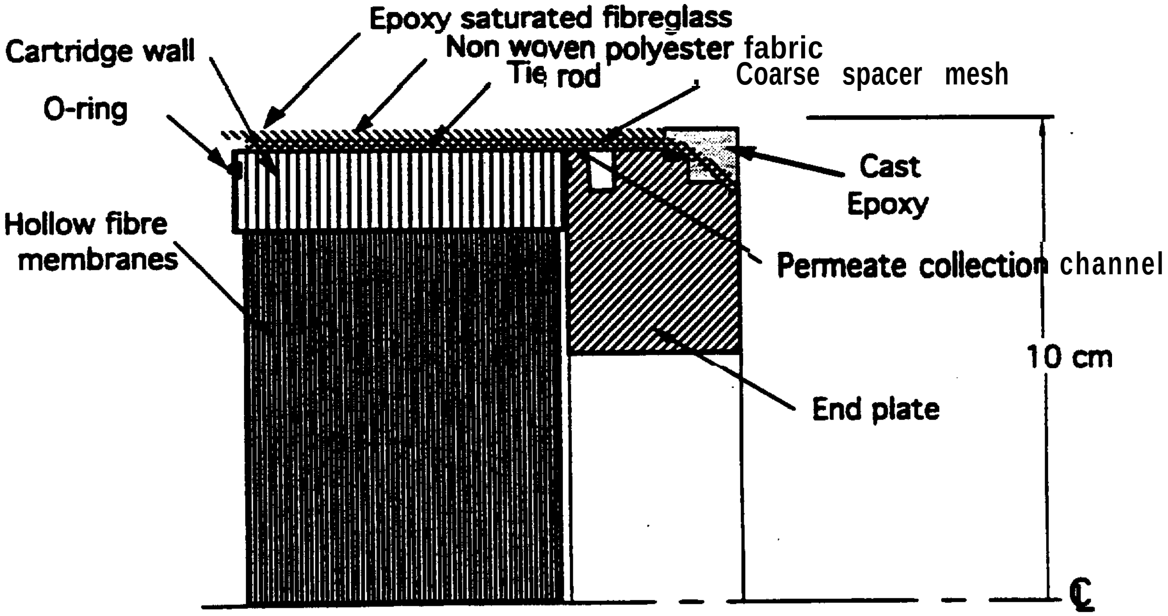
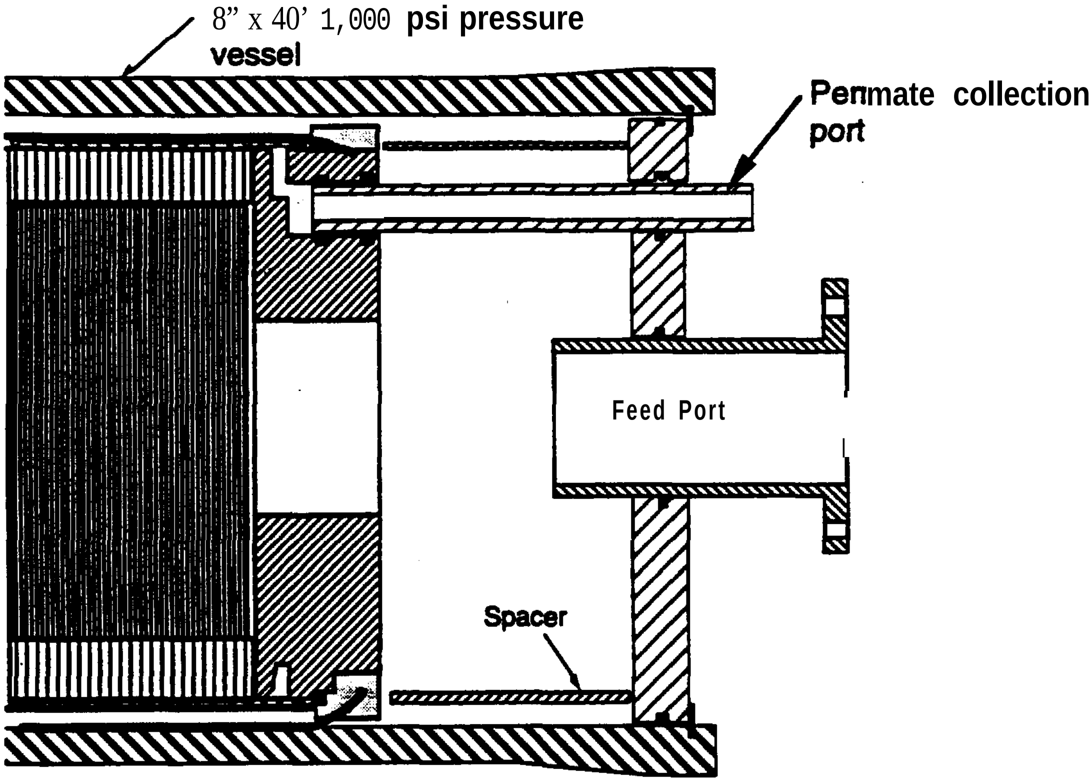


Figure 4-2
Membrane Cartridge in Pressure Vessel Test Apparatus



Under initial pressurization tests, the **permeate** exited through the mesh material, and the module leaked at 100 psi due to the module epoxy cracking.

4.3.1 High Pressure Transverse Flow Module #1- Combined Pressure Vessel/Module Design

The modified first version of the high **pressure,** transverse flow module **incorporated** the pressure vessel and module into one unit. Each high pressure unit, in the form of a square, would be bolted together by means of a flange. Scaling between each module was accomplished by means of an **"O"** ring seal.

Several issues must be considered in design:

1. **stress** concentration,

2. high construction cost,
3. differing epoxy, stainless steel rigidity, and
4. delamination of epoxy and stainless steel bond.

In order to test the epoxy under high pressure, a 2" block of epoxy was made. The block of epoxy was made with a layer of urethane to seal with the permeate header An injection moulded permeate header was used. The epoxy and permeate header was pressurized from the outside.

The primary function of the urethane was to prevent a reaction between the epoxy and the Polyethylene Ethyl Glycol (PEG). It's secondary function was as a sealing material around the permeate header.

The first test block produced a small leak when it was pressurised from the outside. Results are shown in Table 4.3. Increasing the pressure to 250 psi produced an implosion of the permeate header.

Table 43
Module **#1 Pressure Tests - Run #1**

Time	Pressure	Leakage	Comments
15 minutes	85 psi	**1 ml**	
		0 ml	
13 **minutes later**	**150** psi	**20 ml**	air lock
15 minutes	200 psi	46ml	
15 minutes	250 psi	167ml	
30 minutes	0 psi		steady flow'

A second block using a harder urethane was tested in the expectation that it would not deform as much under high pressure. It would also allow a higher bolt tension to be used and therefore produce a better seal. The moulded header was replaced by a machined header with thicker wall sections to withstand the high pressure.

Table 4-4
Module **#1** Pressure Test - Run **#2**

Time	Pressure	Leakage
		0 ml
30 minutes	100 **psi**	**0 ml**
30 minutes	200 psi	**0 ml**
120 **minutes**	250 psi	**0 ml**
24 hours	400 psi	**0 ml**

As shown in Table 4-4, the harder urethane provided a better seal. When placed under **400** psi water pressure there was no leak. The harder urethane showed some deformation over time so that when pressure was dropped to atmospheric pressure, the seal was broken. This was due to loss of bolt tension because of deformation of the urethane. The machined header showed no signs of permanent deformation.

In summary, the urethane did not provide an effective long term seal at high pressures. There is also a concern that the urethane may not perform well under elevated **temperatures.** using epoxy to seal the permeate header is effective but permanent, and therefore prevents sealing of individual **fibers** that may be damaged or defective.

After **performing** stress calculations for the pressure vessel/module design it was decided that a simplified alternative was needed to avoid the problems associated with a combined **module-**pressure vessel design. A smaller module that would fit an 8" pressure vessel was needed.

4.3.2 High Pressure Transverse Flow Module # 2 • Separate Pressure Vessel/Module Design

The second version of the transverse flow module has the pressure vessel and the module separated. The only part of the module that is under pressure is the **permeate** side. This design greatly simplifies construction. A standard 8" pressure vessel was used to house the module. Figures 4-3 and 4-4 **illustrate** the pressure vessel and module design.

Figure 4-3
Pressure Vessel Design **(Module #2)**

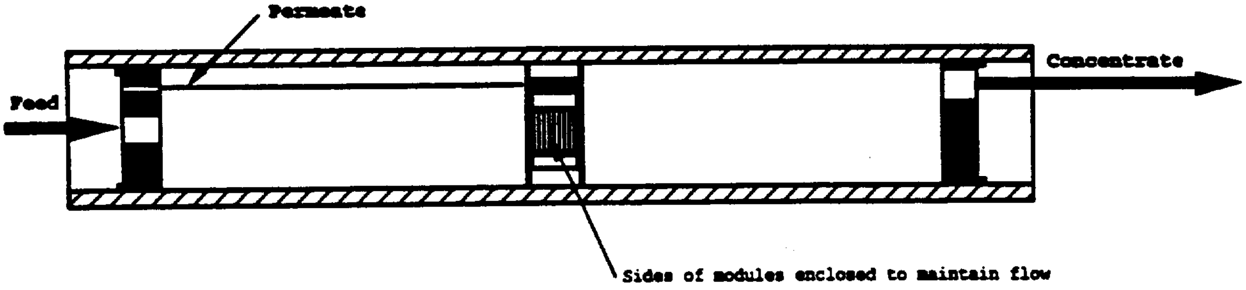
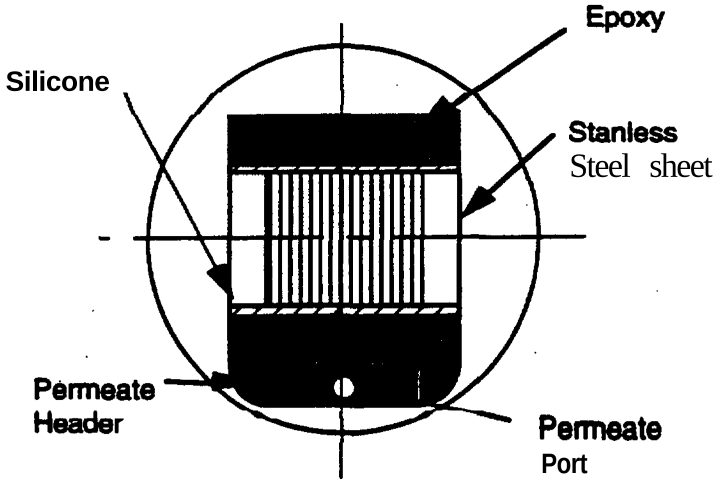


Figure 4-4
High-Pressure Mini Module Design (Module #2)



Fiber sheets where potted with epoxy at each end. One end of the fibers was sealed and the other **end was left open. A machined header was epoxied at the open end to collect the permeate.**

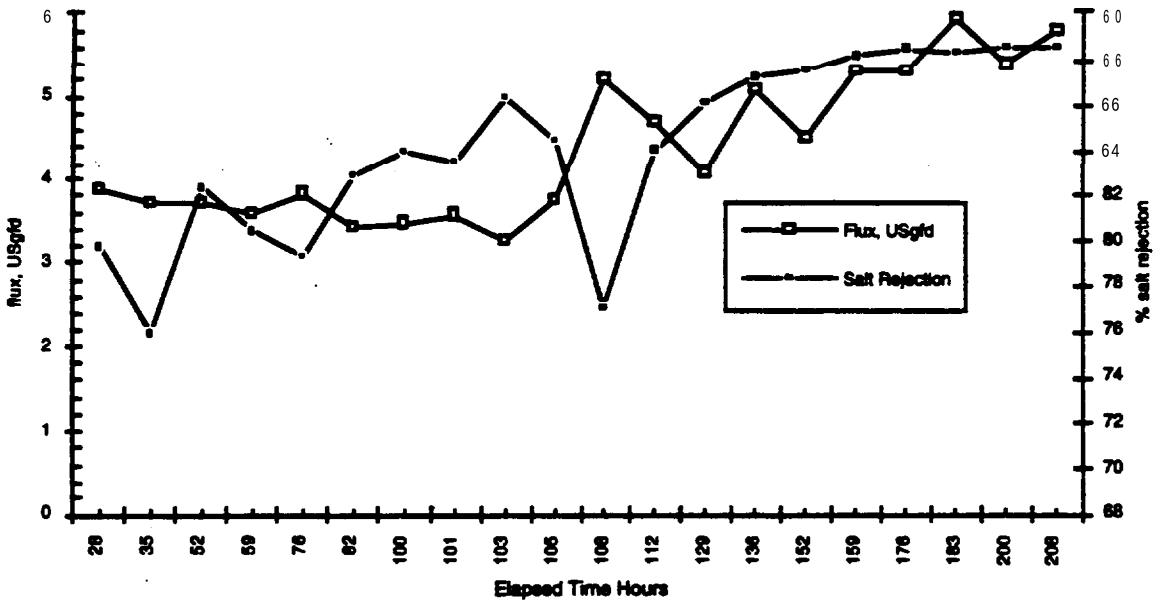
It was decided to remove the urethane after the moulding process and to permanently seal the **permeate header** to the module with epoxy. The module was bolted between two 8” diameter sheets with a 180 mm by 180 mm square hole. In an attempt to maintain the necessary flow distribution, the open sides of the module were blocked. This was accomplished by placing two stainless steel sheets on both sides of the module. Incorporating the stainless steel side support into the module design would improve the handling of the module and protect the fibers **from** damage. In this configuration, sealing of the module to the permeate header was accomplished by an epoxy seal. **An “O” ring seal may be a better alternative but this would require threaded inserts be placed in the epoxy.**

4.4 Transverse Flow Module Test

A module **(#2)** was fabricated and used to conduct long-term testing on synthetic brackish water. **The** module was placed in in the pressure vessel and tested on a **feed** containing calcium **sulphate** (700 **ppm),** magnesium sulphate (400 ppm), sodium sulphate **(400** ppm) and synthetic **humic** acid (100 ppm). The test was carried out at 200 psi and 2.5 liter per minute feed flow (Reynolds number of 14) over a period of over 200 hours.

The module design successfully sustained an *Operating* pressure of 200 psi over the course of the test period of 205 hours. The results of testing (flux and salt rejection vs. time) are illustrated in Figure **4-5. The** flux values were corrected to 20°C.

Figure **4-5**
Performance of **Transverse** Flow Module **#2** on Synthetic Brackish Water



Salt rejection was initially 80% and after 205 hours of **operation,** increased to 90%. These values are better than obtained in crossflow module tests and are acceptable for brackish water **desalination.** The flux, however, was very low (3.8 **USgfd)** at the start and improved slightly over the course of the trial to 5.8 **USgfd.** Overall, the flux from the module was low compared to the values obtained for single fibers. The fact that the flux increased slightly over time indicates that the low flux may be due to **channelling** of flow caused by air trapped in the module. As the air was purged from the system, the flux improved. The increase in flux could also be the result of plugging of leaks in the baffles with **foulant humic** acid, which would improve the flow distribution in the module.

4.5 Conclusions and Recommendations

The polysulfone fibers coated with LTMX membrane chemistry developed in earlier tasks were fabricated and used for testing in both crossflow and transverse flow module configuration. Rejection of magnesium sulphate was within target criteria and flux, although lower than the target, was considered acceptable for further testing on synthetic brackish feed. Rejection of total solute was in the range of 65%, and rejection of synthetic humic acid (measured as color) was approximately 98%.

Two alternative transverse flow module designs were constructed and tested for performance at the target pressure of about 200 psi. A combined pressure vessel with enclosed module was designed and constructed using the developed nanofiltration membranes, and was successful in sustaining an operating pressure of 200 psi over 200 hrs of continuous operation.

The initial flux of the crossflow module was higher than the transverse flow module, but dropped drastically within 24 hours. Although the flux in the transverse flow module was low, it did not drop significantly over a period of 205 hours, which indicates that the transverse flow module is less prone to fouling. These results reconfirm Zenon's earlier demonstrations of low pressure transverse flow nanofiltration for colored water applications, and again illustrates the potential advantages in terms of reduced pretreatment requirements.

It is likely that channelling is the primary cause of low flux in these tests of the transverse flow module. The channelling is due to the design of the prototype module, since it incorporates a square module in a round pressure vessel. Although it was originally assumed that adding circular baffles in the front and back of the square module would prevent channelling, results indicate that further development of the module design is required to eliminate this problem

Another concern in the present module construction is that the packing density is relatively low. The packing density could be improved by further work to reduce the size of the header and increase the size of the pressure vessel, thus resulting in an increase in the size of the module itself.

5.0 TECHNICAL & ECONOMIC EVALUATION

5.1 Module Design and Commercialization Potential

The major features of the Moustic™ design are lower **operating** costs resulting **from:**

- A unique combination of high mass transfer and low pressure drop, and
- A unique combination of low pretreatment requirements and high packing density.

The original low-pressure transverse flow module design (**Moustic™**) offers several advantages over conventional spiral wound elements, in terms of pretreatment requirements and reduced fouling potential.

These advantages were demonstrated in previous work on colored surface water supplies, where pretreatment requirements were shown to be **significantly** reduced in a side-by-side comparison with spiral modules (**Zenon**, 1993). A cost analysis indicated that the transverse flow module in full commercial production would be **cost** competitive with spiral modules. Independent testing and **economic** analysis for treatment of highly colored supplies (**Wiesner**, et. al., 1993) also showed that the **transverse** flow module was competitive with alternative membranes and **treatment** trains capable of meeting drinking water quality criteria and **DBP limits.**

In order to adapt the module to higher pressure operation suitable for brackish water **treatment**, the following improvements have been made to the low-pressure transverse flow module. design through the course of this testing **program:**

- A transverse flow module was **constructed** which could be operated at the **pressures necessary** for brackish water **desalination** (225 psi),
- Suitable high tensile base fibers were developed,
- Appropriate membrane **chemistries developed** and tested, and a chlorine-resistant **nanofiltration** membrane with suitable solute rejection **characteristics** was **produced**, and
- Methods for application of the membrane were investigated and **optimized.**

The flux, however, in configured module tests was significantly lower than required for **cost-**competitive application. Flux was low in both crossflow and transverse flow configurations, indicating that further improvements in module design and membrane application are needed. Fibers were coated manually, and automatic coating equipment would improve coating **consistency** and reproducibility. In the current transverse flow configuration, the low flux observed during **these trials** is likely due to air trapped in the module flow **channelling associated** with high pressure module design.

A detailed study (Appendix D) was previously undertaken to compare the performance of the **FilmTec** • NF 70 module with **Zenon** low pressure transverse flow module on synthetic colored water feed. Comparing flux levels after 600 hours of operation, the transverse flow modules ranged between **30-40** gfd (0.38 • 0.50 **gfd/psi)** and spiral-wound modules were at 10 gfd (0.133 **gfd/psi).** Over more than 5,000 hours of continuous testing, the transverse flow modules exhibited higher fluxes than **FilmTec** NF 70 spiral modules. This was a result of a better module configuration and higher molecular weight cutoff of the transverse flow modules.

Flux/psi data at low transmembrane pressures for the crossflow module **#2** is given in Table A-8 (Appendix A). As the **transmembrane** pressure increased, the flux **increased** 2.52 gfd at 100 psi to 5.5 gfd at 200 psi (approximately linear). Rejection also increased from 59.2% at 100 psi to 75.5% at 200 psi.

The results of high pressure module tests indicate several areas where further improvements are **necessary** to make the concept **commercially** viable:

- Test data indicates that **the** current module maintained structural integrity under higher pressures. Further testing is necessary to demonstrate long term high pressure performance of this configuration.

- A **preliminary** assessment indicates that a minimum flux of 15 • 20 **USgfd** is necessary to be competitive with commercially available NF modules. This could be accomplished by further **optimization** of module design to **minimize channelling,** as well as improvements in coating application and packing density. **Channelling** could be reduced by constructing a circular module which could tightly fit into the pressure vessel. The packing density will be higher in a circular design than in a square module, and this could be further improved by increasing the size of the pressure vessel.

- The most significant cost component in manufacture of the the current module is associated with cutting and potting of fiber **ends.** Longer fiber length would therefore substantially decrease membrane cost per unit area. One way to **maximize fiber** length is to orient them parallel to the axis of the module instead of transverse. There are **commercially** available MF and UF membranes in which the filtration mode is from the outside to the inside of the fiber, with crossflow (parallel to module axis) feed. These modules, however, do not tolerate a very high suspended solids content in the feed, nor do they tolerate high velocities without fiber breaking. Higher velocities would allow higher suspended solid in the feed. The fibers developed for transverse flow are extremely strong and in a crossflow configuration flow velocity could be very high without causing fiber breakage.

- An analysis of surface area/volume ratios for **different** module types was conducted (Appendix C) and results show that the ratio for the high pressure transverse flow module tested is lower than commercially available spiral and hollow fiber modules. This is due to the large headers in the current design. This will be addressed in the next phase of module development.

5.2 Potential Applications

Membrane technology in general is receiving increasing attention for various water treatment applications. Membrane application has been growing for municipal supplies, where over 146 **Mgal/day** of desalting treatment capacity was installed in the United States by **1992. (Bessler,** 1993). Regulatory directives are key driving factors, and membrane separation is now being applied for compliance with the Surface Water Treatment Rule requirements for **filtration** of **drinking** water supplies.

Desalting of brackish sources for drinking water, irrigation, reclamation, groundwater recharge and industrial uses is becoming more economically competitive due to technology improvements and increasing water costs, particularly in the Western U.S. The "National Desalting and Water Treatment Needs Survey" (**Bessler,** 1993) identified several key areas were emerging membrane processes offered significant potential for co**mmercial** application in the near-term. These include:

- Membrane softening (for brackish applications),
- **Organics** removal, and
- Specific ion **removal** (nitrate and fluoride)

The results of this project identify two alternative approaches which are available for treatment of brackish water sources by **nanofiltration:**

1) Develop modules to treat the water directly, or
2) Use a costeffective low **pressure** microfilter to removal solids prior to treatment by conventional **nanofilters.**

Direct Nanofiltration

We have shown that the transverse flow module can handle higher solids than crossflow **filtration** and performs well with minimal pretreatment. For brackish water, we have shown that a transverse flow module which could withstand pressure up to 300 psi could be fabricated. In addition to removal of salts, testing has shown that the nanofiltration module effectively removed color and **THM/DBP** precursors from the brackish feedwater. Further development and testing of the high pressure module would provide the data necessary to demonstrate cost effectiveness. Alternately, the high tensile fibers used for transverse flow could be further adapted to crossflow configuration in order to improve tolerance to suspended solids and reduce pretreatment requirements over conventional modules.

MF pretreatment prior to NF

Conventional spiral **nanofiltration** modules require a high degree of pretreatment for application on waters with high or variable turbidity. The transverse flow module was developed to **minimize** pretreatment requirements, reduce fouling and reduce costs, and has achieved success on low pressure applications. In order to meet the same objective of **reducing** pretreatment requirements and overall costs of nanofiltration for brackish water, an alternative module configuration **(ZeeWeed™)** which has been recently developed by **Zenon** and is ready for demonstration scale application offers great potential. **Zenon** has developed a new low cost **microfilter** module which operates under vacuum and has been shown to effectively handle extreme solids, at low energy costs. **The** raw brackish feed water could be treated with this module to remove suspended solids, with subsequent treatment by nanofiltration (spiral or hollow fiber) modules to remove dissolved solids. **The microfilter** permeate will be essentially free of turbidity, and in the case of surface waters or **groundwaters influenced** by surface waters, cysts and cryptosporidium. Fouling of commercial high pressure nanofiltration can be **significantly** reduced, and overall cost savings are promising.

6.0 RECOMMENDATIONS FOR FURTHER WORK

Development and demonstration of module designs which reduce pretreatment requirements, fouling potential and energy requirements are critical to expanding commercial applications of **membrane** technology. As the technology continues to develop, alternative module designs rapidly emerge.

Zenon's continuing efforts towards development of innovative and cost-effective **nanofiltration** modules and systems address several of Reclamation's research needs, as described below:

- **Zenon's** original low pressure transverse flow **nanofiltration** mcxiules **(Moustic™)** have been shown to be effective for removal of dissolved **organics** (along with partial softening) of **non-**saline water sources for production of drinking water Long-term demonstration is needed to provide a comprehensive cost analysis.

- Initial efforts towards development of a high-pressure transverse flow module and high tensile fiber have been successful and offer several potential treatment scenarios for brackish water desalting.

- Alternative hollow fiber designs for **microfiltration** modules also offer potential for efficient pretreatment, prior to conventional **nanofiltration.** This scenario has the potential to **decrease the NF** fouling potential, and reduce overall operating costs.

The commercial application of the transverse flow requires further development and design improvements for high pressure applications, and **Zenon** would like to continue to pursue this promising module design as well as alternative applications of the high tensile strength fiber. Recent efforts in the **ZeeWeed™ module** design indicate that this module has the most *potential* for greatest commercial **success and impact in the short term.** Itistherefore recommended that the next phase of testing proceed towards evaluation of **microfiltration** pretreatment prior to spiral **nanofiltration** for desalting of brackish supplies, either alone or in a side-by-side comparison with a further **improved** high-pressure **nanofiltration** module.

The vacuum based hollow fiber design developed by **Zenon (ZeeWeed™)** has **been tested at** pilot scale in several rigorous wastewater applications. These **microfiltration** modules are now commercially available, however the technical and economic advantages for brackish water pretreatment have not been investigated. Modules are available for testing, and a long term pilot demonstration on brackish water supplies could be mobilized **immediately.** The data would be used to generate long term operating and cost data in or&r provide a comprehensive cost assessment.

Microfiltration as a stand-alone process is receiving widespread attention for application on non-saline surface water supplies to reduce turbidity, as well as reclamation of secondary effluents. The microfiltration data generated from such a demonstration would also provide information on the competitiveness of this design in other water treatment applications, as well as brackish water

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APPENDIX A

RAW TEST DATA

Table A-I

Base Fiber Formulation • Polysulfone

Formulation #	Formulation Description	%Rejection of 10K PEG
94-82	20%PS, 80%NMP , OD = 1.3mm	n/a
94-86	15% PS, 80%NMP, OD = 1.15mm	65
95-8	20% PS, 80%NMP, OD = 1.3mm	92
95-I 51-I 95-151-2	20%PS, 80%NMP, OD = 1.3mm	84
95-151-3 95-151-4	20% PS, 80%NMP, OD = 1 .lmm	80
95-151-5 95-I 51-6	15% PS, 80%NMP, OD = 1 .15mm	65

Table 2-I in the final report used sample 94-86

Table A-2
Base Fiber Formulation • SPS

Formulation #	Formulation Description
94-69	30% solids; 19%PS, 7.5% SPS, 3.5% LiCl, 70%NMP
94-83-2	28% solids; 18% PS, 6.5%SPS, 3.5% LiCl, 72%NMP
95-13	28% solids; 18% PS, 6.5%SPS, 3.5% LiCl, 72%NMP

Table A-3
Pure Water Flux of Polysulfone Fibers at Various Pressures (20°C)

94-82

Pressure in psi	Water Flux in usgfd					
	94-82-1	94-82-2	94-82-3	94-82-4	94-82-5	94-82-8
30	5.3	0.0	3.5	107.0	7.2	35.9
60	5.3	3.9	3.5	leak	n/a	38.2
100	7.0	6.7	3.5	leak	9.6	40.6

94-86

Pressure in psi	Water Flux in usgfd	
	94-86-1	94-86-2
50	331.6	165.6
100	522.0	279.5
150	641.0	375.0
200	738.0	450.0
250	783.0	466.0
300	810.0	495.0

95-8

Pressure in psi	Water Flux in usgfd		
	95-8-1	95-8-2	95-8-3
20	0.0	0.0	0.0
40	12.0	6.3	7.5
70	23.4	15.0	16.9
120	46.8	37.6	37.6
160	54.0	48.9	45.1
250	79.3	67.7	67.7
400	104.0	84.6	88.4
600	144.0	124.0	131.0

Figure 2-3 in the final report used sample 94-88

Table A-3
Pure Water Flux of Polysulfone Fibers at Various Pressures (20°C)

Run # 94-151

Pressure in psi	Water Flux in usgfd					
	94-151-1	94-151-2	94-151-3	94-151-4	94-151-5	94-151-6
24	72.1	73.6	148.8	127.0	89.3	136.2
48	144.0	147.0	191.5	191.0	179.8	187.8
80	180.4	184.0	213.0	234.0	312.4	274.9
128	270.0	257.5	340.0	298.0	588.5	388.7
180	380.2	404.2	447.0	423.7	718.0	519.3
280	432.5	498.8	553.3	554.8	808.1	595.9
400	487.8	552.1	574.5	880.0	927.8	784.0
550	521.5	899.0	880.0	787.5	1047.7	931.8
800	522.0	738.0	880.0	873.0	1108.0	1054.5

Table **A-4**

Pure Water Flux at Various Pressures (20°C)

94-69

Pressure in psi	Water Flux in usgfd		Pressure in psi	Water Flux in usgfd	
	94-69-1	94-69-2		94-69-3	**94-69-4**
20	93.7	106.0	25	128.0	126.5
33	154.5	174.0	75	314.0	300.0
SO	223.0	250.0	100	405.5	383.5
70	298.0	337.0	150	530.5	495.5
90	368.5	415.5	200	672.0	611 .O
120	487.0	539.0	230	758.0	708.5
150	547.0	637.0	275	849.0	794.0
172	333.5	362.5	335	965.5	892.0
200	362.5	390.2	400	1081.5	996.0
			455	917.0	855.0

Fiiure 24 in final report **used** samples **94-69-3,4**

94-83-2 / **95-13**

Pressure in psi	Water Flux	Pressure in psi	Water flux in usgfd		
	94-83-2		95-13-l	**95-13-2**	**95-13-3**
50	102.7	23	70.4	98.1	**85.0**
100	183.4	45	100.8	150.0	**144.5**
150	256.7	100	201.5	295.0	**289.0**
200	332.6	160	257.5	283.5	**282.0**
250	349.7	260	288.5	365.5	**344.0**
		360	314.0	412.5	**387.5**
		480	361 .O	469.0	**445.0**

Tables **A-4B**

Reference #	**%Rejection** of **10K** PEG
94-69-I	88%
94-69-2	85%
94-69-3	80%
95-13-I	89%
95-13-3	84%

Table 2-2 in final report used sample 94-69-3

Table A-5A

Pure Water Flux of PI Fibers at Various Pressures (20°C)

18-S-94

Pressure in psi	Water Flux in USgfd
50	90
100	150
150	210
200	3oa
250	340
300	390
350	410
400	444

Figure 2-5 in the final report

Table A-SB

Reference #	%Rejection of 10K PEG
18-5-94	88%
18-5-94	80%

Table 2-3 in the final report

Table A-6
Coating Trials - All Fibers

Reference Number	Base Membrane	Thin Film Composite	%Rejection of 2,000ppmMgSO4	%Rejection of 500ppm NaCl	Flux In Usgtd
94-75-I	SPS/PS	17LT	27		3.4
84-75-2	SPS/PS	17LT	29		3.5
94-79-1	SPS/PS	17LT	52		32.9
94-79-2	SPS/PS	17LT	54		32.6
94-78-3	SPS/PS	20LTM	26.5		19.5
94-79-4	SPS/PS	20LTM	24		12
94-79-5	SPS/PS	20LTM	38.5		15.1
94-79-6	SPS/PS	POLTM	17.6		13.8
94-85-1	15%PS	FT30	80		‘6.8
94-85-2	15%PS	FT30	89		0
84-87-I	SPS/PS	FT30	61		13
94-87-2	SPS/PS	FT30	broke		
94-87-3	SPS/PS	LTMX	29		21.5
94-87-4	SPS/PS	LTMX	2s		20.1
84-89-I	Ultem	POLTM	14.2	36	22
94-89-2	SPS/PS	POLTM	36	26	10
94-91-1	PS	NF40	4	13.4	33.5
94-91-2	PS	NF40	4	22	36.18
94-91-3	PS	NF40	3	13.8	50.25
94-95-1	PS	CPS(SD)	6		36
94-95-2	Ultem	CPS(SD)	50.6	25	38.5
94-95-3	PS	CPS(IFP)	3		36
94-95-4	PS	CPS(IFP)	12.7		30

Table A-6 (Continued)

Reference Number	Base Membrane	Thin Film Composite	%Rejection of 2,000ppmMgSO4	%Rejection of 500ppm NaCl	Flux In Usgfd	%Rejection a Raffinose	%Rejection of Dextrose
94-96-I	Ultem	CPS(SD)	15.7	27.9	18.3	20	
94-98-2	Ultem	CPS(SD)	34.1	60.6	4.6	85	
94-98-3	SPS/PS	CPS(SD)	21.1	29.8	22.9	20	
94-90-4	SPS/PS	CPS(SD)	40.5	73.1	17.3	20	
94-102-1	E500	CPS(SD)	77.9	77.2	12.3	100	
94-102-2	E500	CPS(SD)	71.1	63	12.3	100	
94-102-3	E500	CPS(SD)	67.3	62	12.3	90	
94-104-1	E500	CPS(IFP)	77.8	76.5	26.3	100	
94-104-2	E500	CPS(IFP)	76	73.5	29.5	100	
94-104-3	E500	CPS(IFP)	80.2	81.6	19.6	100	
94-108-1	15%PS	CPS(SD)	25.4	33.3	9.8		
94-108-2	15%PS	CPS(SD)	30.7	30.5	9.6		
94-111-1	15%PS	FT30(IFP)	69		14.5	78	
94-111-2	15%PS	FT30(IFP)	69		15.2	81	
94-111-3	E500	FT30(IFP)	99	84	6.6	100	93
94-111-4	E500	FT30(IFP)	98	80	4.0	100	90
94-111-5	E500	FT30(IFP)	99	85	7	100	95
94-117-1	E500	CPS(IFP)	99	70	4	100	90
94-117-2	E500	CPS(IFP)	99	73	4	100	90
94-117-3	E500	CPS(IFP)	97.3	90.4	0.3	100	87
94-121-1	E500	CPS(SD)	88	71	11.6	100	78
94-121-2	E500	CPS(SD)		76	12	100	78
94-121-3	E500	CPS(SD)		76	11	100	92

Table A-6 (Continued)

Reference Number	Base Membrane	Thin Film Composite	%Rejection of 2,000ppmMgSO4	%Rejection of 500ppm NaCl	Flux in Usgfd	%Rejection of Raffinose	%Rejection of Dextrose
94-125-1	E500	CPS(SD)	84	75	12.4	100	80
94-125-2	E500	CPS(SD)	91	74	10.9	100	82
94-125-3	E500	CPS(SD)	90	79	11.2	100	86
94-126-I	30%PS	CPS(SD)	n/a	22.7	45.6	n/a	n/a
94-126-2	30%PS	CPS(SD)	n/a	22	61.2	n/a	n/a
94-126-3	30%PS	CPS(SD)	n/a	16.7	168	n/a	n/a
94-127-1	30%PS	CPS(SD)	31.5	33	12.7	n/a	n/a
94-127-2	30%PS	CPS(SD)	21	18.3	21.7	n/a	n/a
94-127-3	30%PS	CPS(SD)	20	24.8	30	n/a	n/a
94-128-1	30%PS	CPS(SD)	28	n/a	13.1	n/a	n/a
94-128-2	30%PS	CPS(SD)	37.5	n/a	14.2	n/a	n/a
94-132-I	20%PS,1.3	CPS(SD)	76	72	9	87	n/a
94-132-2	20%PS,1.3	CPS(SD)	75	72.3	8.3	82.4	n/a
94- 132-3	20%PS,1.3	CPS(SD)	72	68.3	10.5	76.5	n/a
94-134-1	20%PS,1.3	CPS(SD)	57	n/a	8	n/a	n/a
94-134-2	20%PS,1.3	CPS(SD)	n/a	n/a	5.3	n/a	n/a
94-I 34-3	20%PS,1.3	CPS(SD)	67	62	7.2	60	n/a
94-135-I	20%PS,1.3	CPS(SD)	68	60.7	6.2	56	n/a
94-1 35-2	20%PS,1.3	CPS(SD)	76	88.3	5	68	n/a

Table A-6 (Continued)

Reference Number	Base Membrane	Thin Film Composite	%Rejection of 2,000ppm $MgSO_4$	%Rejection of 500ppm NaCl	Flux in Usgfd	%Rejection of Raffinose	%Rejection of Dextrose
94-137-I	20%PS,1.3	CPS(SD)	81.2	75	6.5	84	n/a
94-137-2	20%PS,1.3	CPS(SD)	77	70.4	5.0	71.4	n/a
94-137-3	20%PS,1.1	CPS(SD)	77.5	08.4	6.7	70.2	n/a
94-139-I	20%PS,1.15	CPS(SD)	54.7	35.9	10.3	55	n/a
94-139-2	20%PS,1.15	CPS(SD)	56.5	41.9	7.5	54.5	n/a
94-148-1	20%PS,1.3	CPS(SD)	76	69.1	5.1	02	n/a
94-148-2	15%PS,1.15	CPS(SD)	54	37.7	6.5	56.5	n/a
94-148-3	20%PS,1.3	CPS(SD)	76	69.8	5	80	n/a
94-148-4	15%PS,1.15	CPS(SD)	52.2	36.5	5.8	50.7	n/a
94-140-5	20%PS,1.3	CPS(SD)	74.5	69.6	[illegible].3	79.5	n/a
94-149-1	20%PS,1.1	LTMX	70	57.5	5.2	65.5	n/a
94-149-2	20%PS,1.3	LTMX	73	61.6	12.1	85	n/a
94-155-1	20%PS,1.1	20%PS,1.1	72.4	53.0	6.8	66	n/a
94-155-2	20%PS,1.1	LTMX	75	58.2	4.6	n/a	n/a
94-155-3	20%PS,1.1	LTMX	85	62	5.1	71	n/a
94-157-1	20%PS,1.1	20%PS,1.1	83	63.9	4.9	71	n/a
94-157-2	20%PS,1.1	20%PS,1.I	80	50.4	5.2	n/a	n/a
94-157-3	20%PS,1.1	20%PS,1.I	77	55.6	5.4	n/a	n/a
94-157-4	20%PS,1.1	20%PS,1.1	70.5	54.6	4.1	n/a	n/a

Table A-7
Performance of Transverse Flow Module #2

Date dd-mmm-yy	Time AM:PM	Elapsed Time	Permeate rate (ml/min.)	Permeate rate (ml/min.) corrected (25°C)	Flux (25°C) gfd.	Permeate Cond.	Feed Cond.	Feed Temp. °C	Salt Rejection
12-Jan-95		2.00	4.6	4.1	6.6	0.370	0.695	30	47%
13-Jan-95		6.00	3.5	3.1	5.0	0.550	1.715	30	68%
16-Jan-95	4:15 PM	12.00	3.5	3.1	5.0	0.544	1.715	30	68%
17-Jan-95	8:30 AM	28.25	2.0	2.4	3.8	0.311	1.536	17	80%
17-Jan-95	3:30 PM	35.25	1.8	2.2	3.5	0.349	1.449	15	76%
18-Jan-95	8:00 AM	51.75	1.8	2.3	3.7	0.268	1.513	15	82%
18-Jan-95	3:00 PM	58.75	1.8	2.2	3.5	0.300	1.531	16	80%
19-Jan-95	8:00 AM	75.75	1.9	2.3	3.7	0.299	1.415	15	79%
19-Jan-95	2:00 PM	81.75	2.0	2.1	3.4	0.270	1.570	22	83%
20-Jan-95	8:00 AM	99.75	3.1	3.1	3.4	0.267	1.660	24	84%
20-Jan-95	11:00 AM	101.25	2.2	2.2	3.5	0.254	1.735	24	86% 83%
		102.75	2.1	2.1	3.4	0.244			
20-Jan-95	1:00 PM	104.75	2.3	2.2	3.5	0.244	1.568	24	84%
23-Jan-95	11:15 AM	107.75	3.2	3.2	5.1	0.402	1.750	24	77%
23-Jan-95	3:30 PM	112.00	2.9	2.9	4.6	0.280	1.742	24	84%
24-Jan-95	8:00 AM	128.50	2.5	2.5	4.0	0.259	1.861	24	86%
24-Jan-95	3:30 PM	136.00	3.1	3.1	5.0	0.237	1.850	24	87%
25-Jan-95	7:45 AM	152.25	3.4	3.5	4.5	0.229	1.822	26	87%
25-Jan-95	3:00 PM	159.40			5.6	0.226	1.905	26	88%
26-Jan-95	8:00 AM	176.40	3.3	3.2	5.1	0.222	1.924	25	88%
26-Jan-95	3:00 PM	183.40	3.6	3.6	5.8	0.217	1.860	24	88%
27-Jan-95	8:00 AM	200.40	3.4	3.3	5.3	0.221	1.928	25	89%
27-Jan-95	3:30 PM	207.90	3.6	3.5	5.6	0.221	1.928	25	89%
30-Jan-95	3:30 AM	215.40	3.9	3.8	6.0	0.203	1.998	27	90%
31-Jan-95	8:00 AM	231.90	3.5	3.5	5.6	0.201	1.980	25	90%
31-Jan-95	3:00 PM	238.90	3.6	3.6	5.8	0.195	1.991	26	90%

Operating Pressure 225 psi

Table A-8
Low Pressure Module Testing

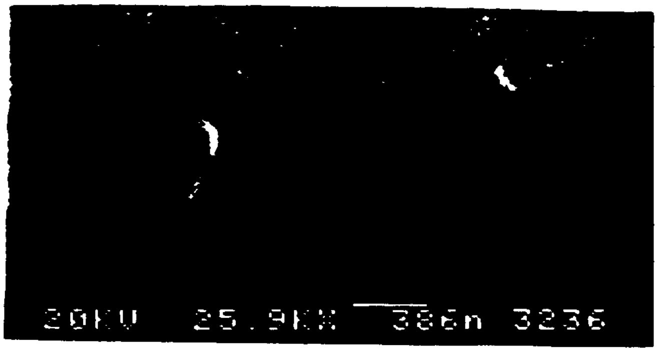
Module had 0.92 sq ft of membrane
All testing was at 20°C feed temperature

Test Pressure	Flux USgfd at 20°C	Percent Rejection	Flux/psi
200	5.5	75.5	0.0275
150	4.4	66.7	0.0293
100	2.52	59.2	0.0252

APPENDIX B

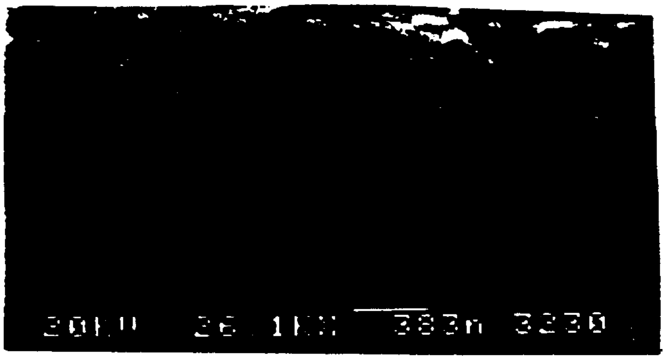
SCANNING ELECTRON MICROSCOPE PHOTOGRAPH

SEM PHOTOGRAPHS



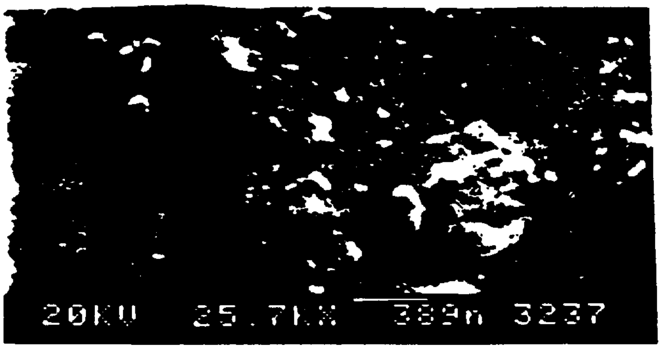
Polyimide [illegible]

Polyimide Base Fiber



Sample PS

Polysulphone Base Fiber



NF Coated Fiber (**Polysulphone** Base Fiber)

APPENDIX C

SURFACE AREA/VOLUME ASSESSMENT

Appendix C

Surface area/volume ratio for different module types were calculated and are given below:

FilmTec NF45 flat sheet spiral:	$240\text{ft}^2/\text{ft}^3$
Dupont B6410 - hollow fiber:	$1023\text{ft}^2/\text{ft}^3$
Zenon low pressure - fiber NF module:	$122.7\text{ft}^2/\text{ft}^3$
Zenon high pressure - transverse flow: NF module (module used in this study)	$16\text{ft}^2/\text{ft}^3$

APPENDIX D

COMPARATIVE STUDY • LOW PRESSURE NF TRANSVERSE FLOW MODULE (MOUSTIC) VS FILMTEC SPIRAL

Appendix D

Comparative Study - Low Pressure NF Transverse Flow Module (Moustic) vs FilmTec Spiral Module

This study was carried out earlier under a project undertaken for Fort Belvoir (contract #DAAK70-92-C-0034 and the relevant report excerpts are attached.

3 . TASK I "LONG-TERM COMPARATIVE EVALUATION"

3.1 Introduction

The objectives for Task I were accomplished by long-term comparison of transverse flow and spiral-wound nanofiltration (NF) modules operating on synthetic feed. After discussion with Fort Belvoir's representatives, two NF spiral modules with similar chemistries to the RO modules used in the ROWPU units were ordered from FilmTec and Fluid systems. Two transverse flow NF elements were fabricated at Zenon.

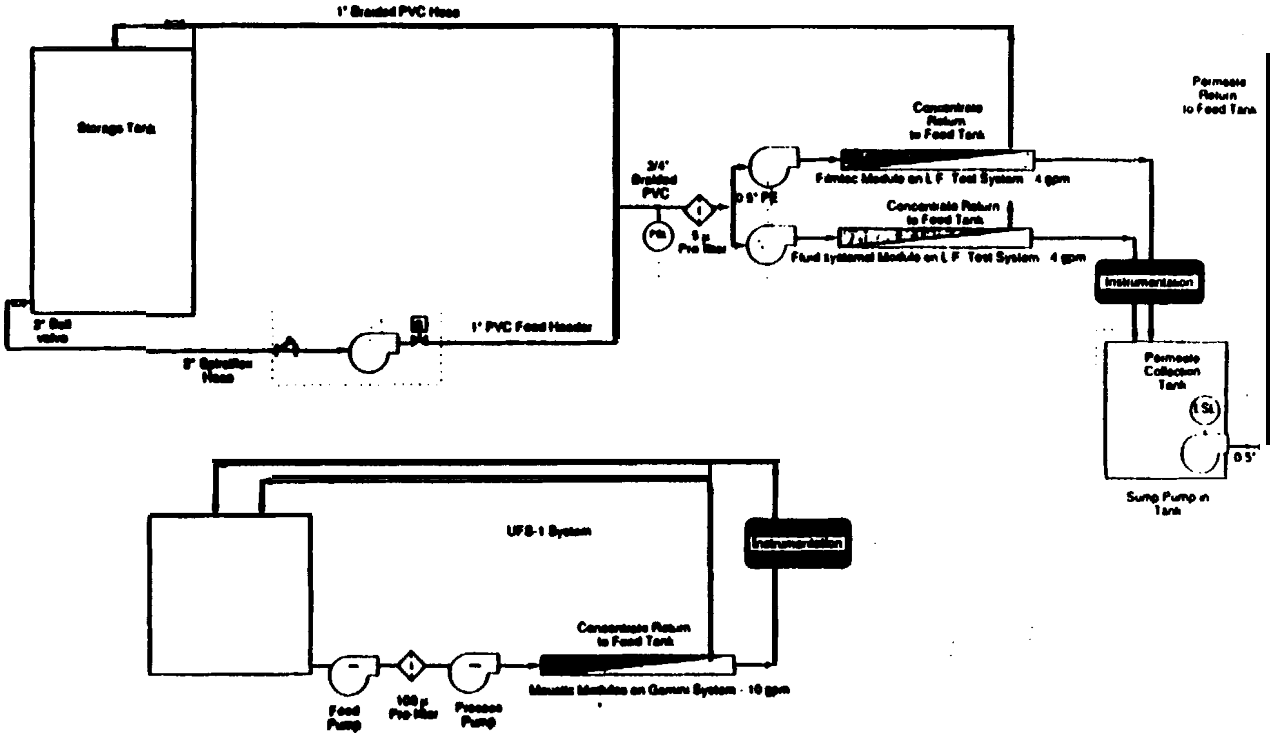
3.2 Experimental Methods

All long-term comparative'studies were performed on the pilot systems built by Zenon. The arrangement of the test systems is shown in Figure 2.

Each system included membrane modules, storage tanks, feed and process pumps, prefilters, instrumentation and other components required far long-term studies. In most experiments, the systems were set up with the spiral modules and the transverse flow modules being on separate feed tanks. This was done in order to avoid filtering the feed to the transverse flow modules through a 5 µm filter which was used to prefilter the feed to the spiral modules. Instead, the transverse flow modules were prefiltered with a 200 µm filter. In the tests, as explained below, the feed streams for both spiral and transverse flow modules were prefiltered through the 200 µm filter.

In order to simulate natural waters, a pure strain of Chlorella vulgaris, a typical polluted water filter clogging algae, was obtained from the Cultures Collection at the University of Toronto. The algae was cultivated in-house using sequentially larger batch sizes to yield the large amounts required for the pilot studies. Typical algae levels (4-16 ppm) in eutrophied lakes were determined and algae was added to the feed tanks at those levels.

Figure 2 **Simplified Flow Chart** of **Test Systems**



REVISION	DATE	DESCRIPTION	BY	APPROVE
2	Sept 1991			
1	Aug 1991			

ZENON ENVIRONMENTAL INC.
Burlington Ont

SCALE	DRAWN A [illegible] DATE	CHK'D DATE	APP'D DATE
CUSTOMER			CONTRACT #
TITLE MOE CW Test System Setup			DRAWING #

In most experiments, testing was conducted using a synthetic feed of salt (500 ppm), color (50 APHA) and a 50/50 mixture of Fire and Stratton clay (100 NTU). In some experiments, higher levels of color (150 APHA) and turbidity (300 NTU) were the test conditions. The following parameters were used to monitor feed composition: total and suspended solids, color, conductivity, TOC, SDI, etc. Temperature, flux, pressure, pH and conductivity were monitored continuously using on-line instrumentation. Sensors were calibrated weekly against known standards. Manual readings were taken every few days as another independent source. The results are discus& in the next section.

3.3 Results and Discussion

The comparative evaluation of the transverse flow and the spiral modules was initiated in October 1992, after the pilot system. was built and the feed composition chosen. The results of the pilot study are presented in Tables 2 and 3 and in Figures 3 through 5.

The results from the first month (725 hours for spiral modules and 600 hours for transverse flow modules) of testing indicated that the transverse flow modules exhibited a higher flux than the spirals. The higher flux may have been due to several phenomena: the configuration may have been less susceptible to fouling, and/or as a result of the higher molecular weight cutoff (MWCO) of the transverse flow membrane. The lower MWCO of the spiral modules is shown through the significantly higher salt rejections (57% for the FilmTec, 90% for the Fluid Systems vs. 30-35% for the uansverse flow modules).

Comparing flux levels after 600 hours of operation, the transverse flow modules ranged between 30-40 gfd and the spiral-wound modules were at approximately 10 gfd. The overall trend was slightly downward. Several shutdown periods were incurred on the transverse flow system during the initial testing which resulted in flux restoration (a.k.a. relaxation cleaning). The shutdown period of the longest duration occurred at the 240 hour mark This resulted in the highest observed flux recovery. The transverse flow modules operated almost continuously since that shutdown; whereas the spiral modules were shut down every day for 5 minutes or so to change the prefilter cartridge. During this shutdown period, a certain amount of relaxation cleaning appeared to occur as the concentrate was very dark the first few seconds of startup and turbidity levels in the feed tank increased.

Table 2. Comparative Study: Spiral Elements Humic Acid, 500 ppm NaCl, 50/50 mix of Fire and Stratton Clay Pre 5μm Filter SDI = 200, Post Filter SDI = 100					Module 1 Filmtec NF-70 (2.5"x 40")						Module 2 Fluid Systems NF (4"x40")					
Date	Hourmeter (hs)	Temp (°C)	Feed Color [APHA]	Feed Turbidity [NTU]	Feed Pr (psi)	Flux 1 (L/min)	Flux 1@75°F (gfd)	Color [Apha]	Turb [NTU]	Rej [%]	Feed Press [psi]	Flux 2 (L/min)	Flux 2 @75°F (gfd)	Color [Apha]	Turb [NTU]	Rej [%]
9/30/92 11:40	0	23	41		75	2.04	32	0		65	75	3.39	16	0		84
10/1/92 8:35	21	26	37		75	2.12	31	0		63	75	3.4	15	0		93
10/2/92 8:30	45	24	33	40	75	1.8	27	0	0.05	75	75	3 4	16	0	0 13	91
10/5/92 8:30	117	23	30	44	75	1.24	19	0	0.08	76	75	3.16	15	0	0 11	91
10/6/92 8:30	141	25			75	1.16	17				75	3.08	14			
10/7/92 9:40	166	24	22	46	75	1.04	16	0	0.05	76	75	3	14	0	0 12	91
10/8/92 9:00	189	26	41	86	75	0.86	12	0	0.08	76	75	2.84	13	0	0 12	91
10/9/92 9:30	214	28	32	40	75	0.8	11	0	0.08	76	75	2.84	12	0	0 12	91
10/13/92 9:15	310	27	21	50	75	0.76	11	0	0.08	77	75	2.4	11	0	0 12	92
10/14/92 9:15	334	27	60	84	75	0.82	12	0	0.08	73	75	2.72	12	0	0 12	90
10/15/92 8:40	357	27	22	46	75	0.8	11	0	0.1	69	75	2.58	11	0	0.1	90
10/16/92 8:35	381	27	41	94	75	0.8	11	0	0.1	65	75	2.58	11	0	0.1	90
10/19/92 16:00	460	26	67	102	75	0.83	12	0	0.08	63	75	2.4	11	0	0 12	90
10/20/92 8:45	477	27	32	83	75	0.76	11	0	0 1	61	75	2.32	10	0	0 12	90
10/21/92 8:45	501	27	55	86	75	0.7	10	0	0.08	57	75	2.1	9	0	0.08	89
10/22/92 13:30	530	28	47	120	75	0.7	10	0	0.08	57	75	2.1	9	0	0.08	89
10/23/92 11:55	552	27	78	140	75	0.69	10	0	0.08	57	75	2.2	10	0	0 08	89
10/26/92 9:20	622	28	57	200	75	0.78	11	0	0.1	58	75	2.5	11	0	0.08	89
10/27/92 8:30	645	28.5	60	130	75	0.76	10	0	0.08	58	75	2.36	10	0	0 1	89
10/28/92 13:45	674	28.5	55	112	75	0.75	10	0	0.08	58	75	2.2	9	0	0.08	89
10/29/92 9:35	694	27	48	112	75	0.72	10	0	0.08	58	75	2.39	11	0	0.08	89
10/30/92 16:10	725	28	51	98	75	0.7	10	0	0.08	57	75	2.2	9	0	0.08	89
11/1/92 11:10	766	28			75	0.69	10	0	0.08		75	2.06	9			
11/3/92 10:50	815	28	58	120	75	0.67	9	0	0.08	57	75	2.2	9	0	0 08	89
11/6/92 10:25	887	27	62	90	75	0.55	8	0	0.08	57	75	1.76	8	0	0 08	89
11/9/92 10:30	959	25	75	88	75	0.53	8	0	0.08	57	75	1.88	9	0	0 08	90
11/11/92 14:00	1010	27	53	88	75	0.53	7	0	0.08	55	75	1.88	9	0	0.08	90
11/13/92 15:30	1060	28	55	82	75	0.53	7	0	0.08	54	75	1.88	9	0	0.08	91
11/16/92 15:30	1132	27	51	80	75	0.54	8	0	0.08	54	75	1.88	8	0	0 08	91
11/18/92 16:40	1181	27	49	60	75	0.53	7	0	0.08	53	75	1.85	8	0	0.08	91
11/20/92 14:20	1227	27	41	77	75	0.51	7	0	0.08	53	75	1.76	8	0	0.08	91
11/23/92 16:20	1301	27	47		75	0.54	8	0		55	75	1.7	8	0		90
11/25/92 9:00	1341	25	51		75	0.54	8	0		50	75	1.65	8	0		90
11/25/92 14:15	1347	28	48		75	1.6	22	0		55	75	2.4	11	0		92
11/27/92 10:45	1391	28	55		75	1.2	17	0		60	75	2.4	11	0		88
11/30/92 11:00	1463	26	62	30	75	1.15	17	0		62	75	2.35	11	0		88
12/4/92 11:30	1560	26	58		75	0.9	13	0		65	75	2.1	9	0		86
12/7/92 14:50	1635	24	62	52	75	0.88	13	0		65	75	2.1	10	0		92
12/9/92 10:25	1655	24	65	43	75	0.89	13	0	0.08	64	75	2.1	10	0	0.09	93
12/11/92 9:50	1726	24	34	35	78	0.93	14	0	0.07	63	78	2.4	11	0	0 07	92
12/13/92 14:10	1779	24	35	25	78	0.8	12	0	0.07	60	78	2.4	11	0	0 08	91
12/14/92 11:12	1800	24			78	0.76	12				78	2.28	11			
12/15/92 9:50	1821	24	28	16	78	0.76	12				78	2.34	11	0	0.06	90
Feed Tanks Switched																
12/16/92 9:35	1846	16			75	0.505	9				75	1.54	9			
12/16/92 14:30	1851	16			75	0.58	11				75	1.6	9			
12/17/92 8:45	1869	16			76	0.57	11				77	1.6	9			
12/18/92 14:00	1898	16	18	78	75	0.56	10	0	0.12	66	74	1.58	9	0	0.1	92
12/21/92 15:50	1972	15	271	74	75	0.5	10	0	0.12	64	75	1.5	9	0	0.12	92
12/22/92 14:10	1995	16	151	76	75	0.48	9	0	0.12	63	75	1.4	8	0	0 12	92
12/23/92 9:25	2014	16	92	60	75	0.456	8	0	0.12	61	75	1.35	8	0	0.12	91

Table 2 - (continued)

12/30/92 11:30	2184	17	52	112	75	0.39	7	0	0.12	64	75	1.31	7	0	0 12	92
1/2/93 10:50	2255	16			75	0.39	7				75	1.31	6			
1/4/93 10.50	2303	17			75	0.39	7	0	0.1		75	1.25	7			
1/11/93 13:40	2474	16	65	45	80	0.465	8	0	0.1	70	80	1.2	7	0	0 09	93
1/12/93 15:45	2500	16	62	115	75	0.44	8	0	0.12	66						
1/13/93 16:00	2524	16	150	116	75	0.45	8	0	0.12	65	75	1.26	7	0	0 11	90
1/15/93 14:00	2570	16	79	92	75	0.435	8	0	0.12	66	75	1.23	7	0	0 12	90
1/17/93 11:00	2615	16	62	90	75	0.422	7	0	0.12	67	75	1.21	6	0	0 12	90
1/18/93 12:10	2641	16	60	95	75	0.42	7	0	0.11	66	75	1.21	7	0	0 13	91
1/21/93 17:00	2717	17	66	75	75	0.4	7	0	0.12	67	75	1.1	6	0	0 12	93
1/25/93 15:25	2812	17	61	78	75	0.34	6	0	0.12	68	75	1.02	6	0	0 12	91
1/27/93 10:15	2856	16	57	84	75	0.34	6	0	0.12	68	75	1.025	6	0	0 12	91
2/5/93 16:15	3077	15	35	39	75	0.35	7	0	0.12	66	75	1.04	6	0	0 12	90
2/9/93 15:30	3172	14	41	60	75	0.34	7	0	0.12	65	75	0.995	6	0	0.12	90
2/11/93 11:35	3216	14	61	90	75	0.335	7	0	0.12	64	75	0.97	6	0	0.12	90
2/12/93 14:15	3243	13	69	92	75	0.32	6	0	0.12	65	75	0.95	6	0	0.12	90
2/15/93 16:20	3317	16	69	95	75	0.345	6	0	0.12	67	75	1.03	6	0	0.12	92
2/16/93 14:40	3339	16			75	0.34	6	0	0.12		75	1.02	6			
2/17/93 14:10	3363	16	52	70	75	0.33	6	0	0.12	65	75	1.01	6	0	0.12	91
2/19/93 14:10	3411	15	45	66	75	0.32	6	0	0.12	64	75	0.98	6	0	0 12	91
3/2/93 16:30	3676	15	39	62	75	0.34	6	0	0.12	65	75	0.96	6	0	0 12	90
3/5/93 17:00	3749	15	57	72	75	0.3	6	0	0.12	64	75	0.89	5	0	0.12	90
3/10/93 11:20	3864	14	52	81	75	0.29	5	0	0.12	64	75	0.88	5	0	0.12	90
3/13/93 11:00	3935	14	49	71	75	0.29	5	0	0.12	65	75	0.885	5	0	0.12	90
3/19/93 16:45	4085	16	41	79	75	0.3	6	0	0.14	63	75	0.84	5	0	0.12	91
3/22/93 16:45	4157	16	43	74	75	0.29	6	0	0.12	64	75	0.84	5	0	0.12	90
3/24/93 15:45	4204	16	45	69	75	0.275	5	0	0.12	63	75	0.85	5	0	0.12	91
3/26/93 15:00	4251	16	61	72	75	0.27	5	0	0.12	62	75	0.845	5	0	0.12	91
System Washed, Feed Composition Changed																
4/6/93 10:30	4253	16	156	296	75	1.5	26	0	0.12	96	75	1.92	11	0	0.12	95
4/6/93 11:45	4254	16			75	1.2	21	0			75	1.69	9	0		
4/6/93 12:45	4255	16			75	1.17	21	0			75	1.69	9	0		
4/6/93 14:00	4256	16			75	1.17	21	0			75	1.69	9	0		
4/9/93 8:45	4299	24	110	261	75	1.1	17	0	0.12	94	75	2	9	0	0.12	94
4/12/93 16:20	4403	26	100	243	75	1.26	17	0	0.12	92	75	2.4	10	0	0 12	92
4/14/93 10:50	4445	15	135	270	75	0.9	15	0	0.12	91	75	1.5	9	0	0.12	91
4/16/93 8:45	4491	16	140	282	75	0.73	14	0	0.12	90	75	1.44	8	0	0 12	91
4/19/93 14:30	4569	12	125	247	75	0.6	12	0	0.12	87	75	1.275	8	0	0.12	91
4/21/93 8:45	4611	14	151	280	75	0.63	12	0	0.12	90	75	1.3	8	0	0.12	91
System Washed, 200 Micron Prefilter Installed																
4/27/93 16:10	4614	22	152	286	96	2.7	43	0	0.12	78	95	3.75	19	0	0.12	95
4/27/93 16:30	4614	22			96	2.62	40				95	3.61	18			
4/27/93 16:50	4614	22			98	2.33	37				95	3.2	16			
4/28/93 8:45	4630	22	137	249	98	0.88	14	0	0.12	70	96	2.4	12	0	0.12	94
4/29/93 10:35	4656	23	120	215	98	0.7	11	0	0.12	69	97	2	10	0	0.12	93
4/30/93 10:00	4679	23	136	268	100	0.63	10	0	0.12	68	98	1.84	9	0	0.12	94
5/3/93 13:50	4755	24	35	61	100	0.54	8	0	0.12	65	100	1.53	7	0	0.12	90
5/5/93 11:45	4801	25	139	272	99	0.43	6	0	0.12	64	96	1.353	6	0	0 12	90
5/7/93 8:45	4846	26	154	305	99	0.45	7	0	0.12	64	97	1.39	6	0	0.12	90
5/10/93 10:30	4920	25	199	250	96	0.43	6	0	0.13	65	96	1.32	6	0	0.12	90
5/12/93 15:55	4973	25	140	230	97	0.32	5	0	0.12	65	96	1.04	5	0	0.12	90
5/14/93 13:20	5019	22	130	255	99	0.3	5	0	0.12	64	94	0.95	5	0	0.12	90
5/18/93 12:00	5113	21	141	290	99	0.29	5	0	0.12	62	96	0.88	4	0	0.12	90
5/21/93 9:00	5182	21	155	296	99	0.275	4	0	0.12	63	98	0.86	4	0	0.12	90
5/25/93 16:45	5286	22	48	121	98	0.26	4	0	0.12	60	98	0.82	4	0	0.12	90
5/28/93 14:35	5356	25	141	269	100	0.25	4	0	0.12	60	98	0.8	4	0	0 12	89
5/31/93 11:15	5425	23	111	227	100	0.21	3	0	0.12	60	98	0.8	4	0	0.12	88

Table 3. Comparative Study: Transverse Flow Elements Humic Acid, 500 ppm NaCl, 50/50 mix of Fire and Stratton Clay Flow Rate = 10 GPM, Feed SDI = 200					Module 1 UF-20 Coated XK-041-D92						Module 2 Old Ceramet, Cleaned MC-3 UF-20 Coated XK-048-F92					
Date	Hourmeter (hs)	Temp (°C)	Feed Turbidity (NTU)	Process Feed Color (APHA)	Feed Pr (psi)	Flux 1 (mL/min)	Flux 1 @75°F (gfd)	Color (Apha)	Rej (%)	Turb. (NTU)	Feed Press (psi)	Flux 2 (mL/min)	Flux 2 @75°F (gfd)	Color (Apha)	Rej (%)	Turb (NTU)
9/30/92 10:50	0	23		44	80	720	47	0	28		80	860	63.53	0	40	
10/1/92 8:35	20.04	21		25	78	580	38	0	27		78	760	60.51	0	46	
10/2/92 8:30	43.86	22	86	28	80	460	30	0	27	0.1	80	660	49.95	0	44	0.08
10/5/92 8:30	85.25	22	84	34	80	460	32	0	26	0.08	80	700	52.98	0	43	0.08
10/6/92 8:40	109.33	22			80	450	30				78	620	46.93			
10/7/92 8:40	133.72	21	42	67	80	430	28	0	26	0.1	80	620	48.10	0	40	0.08
10/8/92 8:45	157.41	21	60		80	420	29	0	25	0.1	80	620	48.10	0	40	0.08
10/9/92 13:10	179.14	22	88	58	80	430	28	0	25	0.1	80	640	48.44	0	39	0.08
10/13/92 13:25	186.25	19	94	54	80	660	47	0	25	0.18	80	640	52.29	0	38	0.1
10/14/92 8:30	194.52	19	92	49	80	680	47	0	20	0.2	80	700	57.19	0	33	0.18
10/15/92 10:20	219.31	18	82	29	80	550	40	0	29	0.18	80	600	50.27	0	33	0.14
10/16/92 9:00	241.73	18	90	34	80	550	40	0	20	0.16	80	620	51.95	0	33	0.14
10/16/92 16:15	242.39	19	99	72	80	730	52	0	19	0.2	80	900	73.53	6	25	0.26
10/19/92 9:00	307.22	18	70	41	80	500	37	0	27	0.12	80	640	53.62	1	34	0.28
10/20/92 9:10	331.29	18	82	35	80	600	37	0	28	0.12	80	630	52.78	0	33	0.25
10/21/92 15:40	349.07	19	110	72	80	510	36	0	27	0.12	80	720	58.83	0	31	0.26
10/22/92 13:20	369.75	19	90	69	80	480	34	0	29	0.12	80	600	49.02	0	33	0.26
10/23/92 8:50	389.22	20	84	65	80	440	31	0	28	0.14	80	540	43.04	0	33	0.2
10/26/92 8:45	462.15	20	85	40	80	415	29	0	26	0.08	80	540	43.04	0	36	0.17
10/27/92 15:30	484.26	20	88	39	80	440	31	0	26	0.1	80	560	44.63	0	34	0.2
10/28/92 8:30	501.3	20	94	35	80	440	31	0	28	0.12	80	580	46.23	0	35	0.38
10/29/92 9:05	525.84	20	108	32	80	410	29	0	30	0.11	80	560	44.63	0	34	0.1
10/30/92 14:35	555.39	19	109	49	80	400	29	0	30	0.12	80	520	42.49	0	35	0.1
11/1/92 11:05	599.9	19			80	380	28				80	500	40.65			
11/3/92 10:50	647.67	19	109	62	80	370	26	0	30	0.12	80	510	41.67	0	34	0.1
11/6/92 8:30	718.32	19	100	45	80	325	23	0	32	0.1	80	480	39.22	0	34	0.1
11/9/92 9:50	790.85	19	98	32	80	330	24	0	32	0.1	80	460	37.58	0	34	0.1
11/11/92 14:00	842.75	22	96	46	80	330	22	0	32	0.1	80	470	35.57	0	34	0.1
11/13/92 15:15	892.02	22	92	64	80	330	22	0	32	0.1	80	470	35.57	0	34	0.1
11/16/92 13:25	962.12	21	88	61	80	300	20	0		0.1	80	440	34.13	0		
11/17/92 9:00	981.75	21			80	300	20	0	32		80	440	34.13	0	33	0.1
11/18/92 16:05	1000.75	23	87	65	80	280	19	0	31	0.12	80	410	30.29	0	30	0.12
11/20/92 13:15	1042.37	19	82	68	80	230	16	0	30	0.13	80	280	22.86	0	30	
11/23/92 16:10	1114.69	24			80	225	14	0			80	200	14.42	0	25	
11/25/92 9:00	1155.63	24	49	64	80	180	12	0	25		80	220	15.87	0	48	
11/25/92 14:20	1155.63	27	48	68	80	480	29	0	40		80	510	34.29	0		
11/26/92 16:10	1167.75	24			80	360	24	0			80	390	28.13	0		
11/27/92 10:45	1176.54	23		65	80	320	21	0	35		80	325	24.01	0	35	
11/30/92 10:50	1202.07	23	60	60	80	250	18	0	25		80	260	19.21	0	29	
12/4/92 11:15	1274.24	23	88	68	80	720	47	0	33		80	640	47.28	0	33	
12/7/92 14:45	1363.46	22	48	75	80	330	22	0	37		80	300	22.71	0	35	
12/8/92 10:20	1383.46	22	49	80	80	330	22	0	38	0.11	80	300	22.71	0	33	0.02
											New Module Installed					
12/9/92 10:25	1385	22	88		80	325	22				80	750	50			
12/11/92 8:45	1426	22	88	39	80	325	22	0	35	0.1	80	580	38	0	33	0.07
12/13/92 14:00	1479	22	98	38	80	320	21	0	34	0.1	80	390	26	0	33	0.07
12/14/92 11:00	1500	21			80	270	18				80	340	23			
12/15/92 8:53	1521	22	89	38	80	260	17	0	33	0.15	80	320	21	0	33	0.13
Feed Tanks Switched & Washed																
12/16/92 8:50	1546	20			80	695	48				80	960	67			
12/16/92 16:20	1553	23			80	560	36				80	890	58			
12/17/92 8:40	1569	23			80	520	34				80	650	42			
12/18/92 14:00	1599	23	120	24	80	400	26	0	31	0.12	80	540	35	1	33	0.14

12/21/92 15:50	1672	22	118	189	80	340	23	2	31	0.12	80	440	29	3	32	0.14
12/22/92 14:10	1695	22	110	125	80	320	21	1	33	0.12	80	420	28	2	33	0.14
12/23/92 9:30	1714	22	130	64	80	300	20	0	33	0.12	80	400	26	2	33	0.14
12/30/92 11:25	1884	21	110	48	80	280	20	0	32	0.12	80	360	24	1	31	0.12
1/2/93 10:45	1955	20			80	280	18				80	305	21			
1/4/93 10:45	2003	21			80	240	16				80	290	20			
1/11/93 13:40	2174	21	72	55	80	265	18	0	35	0.18	80	292	20	0	32	0.17
1/12/93 15:45	2200	21	74	49	80	240	16	0	32	0.16	80	280	19	2	30	0.18
1/13/93 16:00	2225	24	72	51	80	290	18	0	31	0.15	80	330	21	2	28	0.18
1/15/93 14:00	2271	22	82	67	80	290	19	0	31	0.15	80	330	22	1	29	0.18
1/17/93 11:00	2316	24	78	58	80	280	18	0	31	0.16	80	315	20	1	29	0.16
1/18/93 12:10	2341	23	75	55	80	275	18	0	31	0.19	80	310	20	1	30	0.19
1/21/93 17:00	2418	22	70	45	80	290	19	0	31	0.15	80	315	21	2	32	0.16
1/25/93 18:25	2512	22	72	49	80	280	19	0	31	0.16	80	320	21	2	31	0.16
1/27/93 10:15	2555	22	64	45	80	295	19	0	31	0.16	80	330	22	2	30	0.16
2/5/93 16:15	2777	21	60	35	80	280	19	0	30	0.16	80	330	22	1	30	0.16
2/8/93 15:30	2872	20	40	42	80	280	20	0	29	0.15	80	325	23	0	28	0.16
2/11/93 11:35	2916	21	82	73	80	270	19	0	29	0.14	80	315	21	0	27	0.15
2/12/93 14:10	2943	19	80	61	80	260	19	0	30	0.14	80	300	21	1	27	0.16
2/15/93 16:00	3017	21	72	65	80	255	17	0	30	0.14	80	300	20	0	26	0.18
2/16/93 14:30	3030	21			80	255	17				80	300	20			
2/17/93 14:10	3063	20	61	40	80	255	18	0	29	0.14	80	295	21	0	26	0.15
2/19/93 14:15	3111	19	58	45	80	240	18	0	29	0.14	80	280	21	0	26	0.15
3/2/93 14:50	3375	19	59	39	80	200	15	0	30	0.14	80	230	17	0	27	0.14
3/5/93 17:00	3450	18	64	52	80	185	14	0	28	0.15	80	220	16	0	26	0.16
3/10/93 11:20	3564	16	70	47	80	190	14	0	28	0.14	80	210	16	0	26	0.14
3/13/93 10:45	3635	14	88	52	80	175	14	0	28	0.14	80	200	16	0	26	0.14
3/18/93 16:30	3785	15	81	60	80	150	12	0	35	0.12	80	190	15	0	35	0.12
3/22/93 15:55	3857	19	78	45	80	160	11	0	35	0.12	80	200	14	0	34	0.12
3/24/93 15:40	3904	19	74	44	80	155	11	0	36	0.12	80	190	14	0	34	0.12
3/26/93 15:00	3952	18	78	46	80	155	11	0	35	0.12	80	190	14	0	35	0.12
System Washed, Feed Concentration Changed																
4/6/93 10:20	3953	20	302	148	80	650	45	1	26	0.14	80	700	49	3	24	0.16
4/6/93 11:45	3954	20			80	440	31				80	520	38			
4/6/93 12:45	3955	20			80	385	27				80	480	33			
4/6/93 14:00	3957	20			80	370	26				80	470	33			
4/8/93 8:40	3999	22	242	98	80	240	18	0	31	0.12	80	320	21	1	30	0.14
4/12/93 13:00	4100	22	282	125	80	220	16	0	33	0.12	80	260	17	0	31	0.12
4/14/93 10:45	4145	22	280	140	80	210	14	0	33	0.12	80	250	17	0	31	0.12
4/16/93 8:45	4191	22	288	145	80	200	13	0	34	0.12	80	250	17	0	32	0.12
4/19/93 14:15	4268	22	235	115	80	190	13	0	34	0.12	80	240	16	0	32	0.12
4/21/93 8:40	4311	22	288	146	80	190	13	0	35	0.12	80	235	16	0	32	0.12
System Washed																
4/27/93 16:10	4463	22	296	152	80	700	46	1	25	0.14	80	800	53	3	23	0.17
4/27/93 16:30	4463	22			80	660	44			0.12	80	780	50			
4/27/93 16:50	4463	22			80	600	40			0.12	80	700	46			
4/28/93 8:40	4479	22	248	137	80	370	25	0	32	0.12	80	460	30	1	30	0.14
4/29/93 10:35	4505	23	215	120	80	340	22	0	32	0.12	80	410	26	1	30	0.14
4/30/93 10:50	4529	23	269	130	80	320	21	0	32	0.12	80	400	26	1	30	0.14
5/3/93 13:40	4604	24	61	35	80	300	19	0	33	0.12	80	350	22	0	31	0.12
5/5/93 11:30	4650	25	272	139	80	290	18	0	34	0.12	80	340	21	0	31	0.12
5/7/93 8:40	4695	26	305	154	80	300	18	0	35	0.12	80	350	21	0	31	0.12
5/10/93 10:35	4769	25	250	199	80	280	17	0	33	0.14	80	325	20	0	31	0.14
5/12/93 16:00	4823	25	230	148	80	260	16	0	34	0.12	80	300	18	0	31	0.12
5/14/93 13:20	4868	22	255	139	80	230	15	0	34	0.12	80	260	17	0	32	0.12
5/18/93 10:20	4961	21	280	141	80	220	15	0	35	0.12	80	250	17	0	32	0.12
5/21/93 9:00	5032	21	296	155	80	215	15	0	35	0.12	80	240	16	0	33	0.12
5/25/93 16:46	5135	22	121	48	80	205	14	0	36	0.12	80	220	15	0	33	0.12
5/28/93 14:35	5205	25	288	141	80	200	12	0	36	0.12	80	210	13	0	33	0.12
5/31/93 11:15	5274	23	227	111	80	190	12	0	37	0.12	80	200	13	0	34	0.12

Figure 3.
Fluxes of Spiral and Transverse Flow **Modules** vs. Time:
Overall Picture
Total *Numbers* *of Pn-Filters Replaced: 2 • for Transverse Flow Modules,* ***114*** **• for** *Spiral Modules*

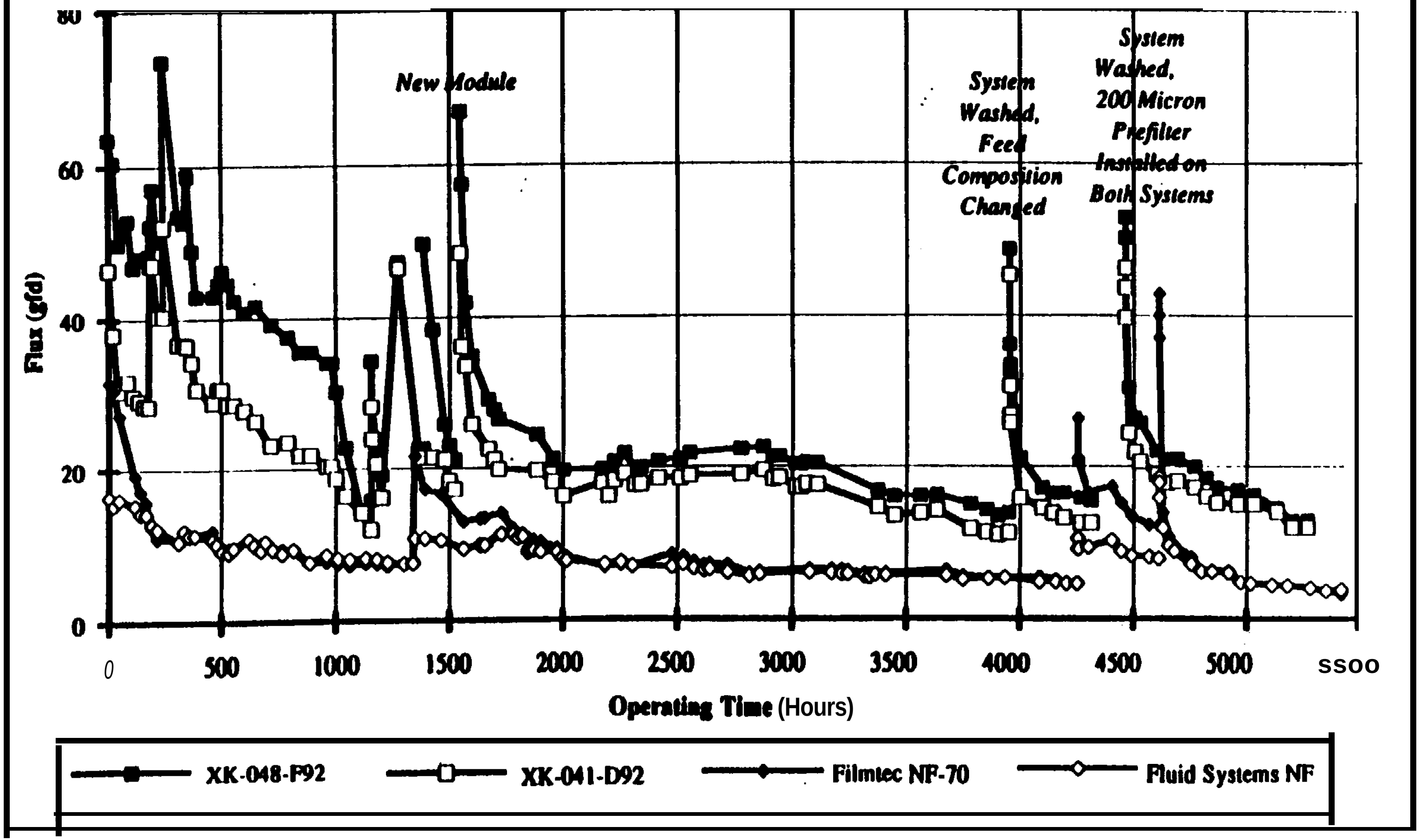


Figure 4
Fluxes of Spiral **and Transverse** Flow **Modules** vs. Time:
Increased Feed Concentration

Numbers of *Pm-Filters* ***Replaced:*** *0 -for* ***Transverse***
Flow ***Modules, 6- for Spiral Modules***

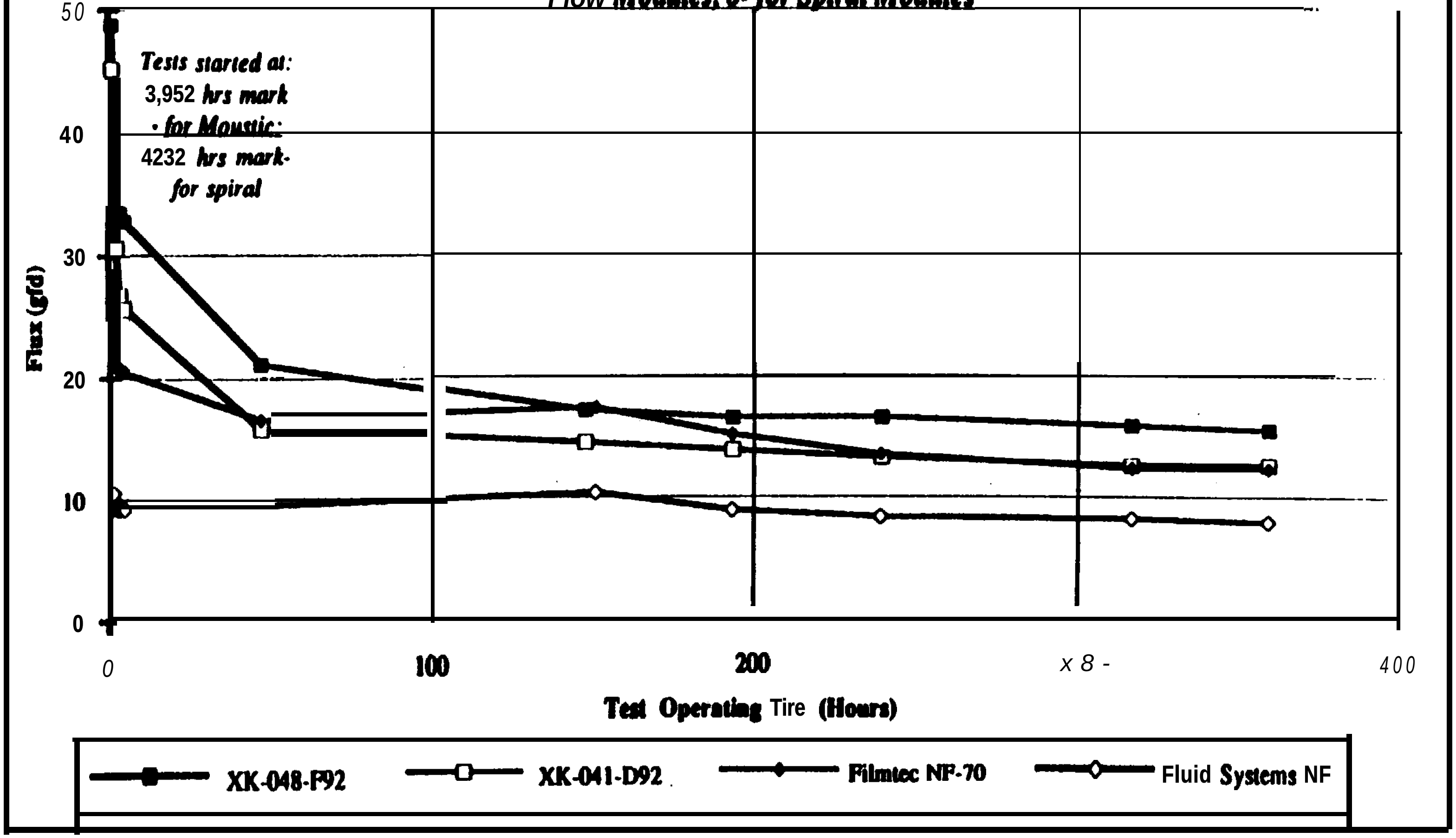
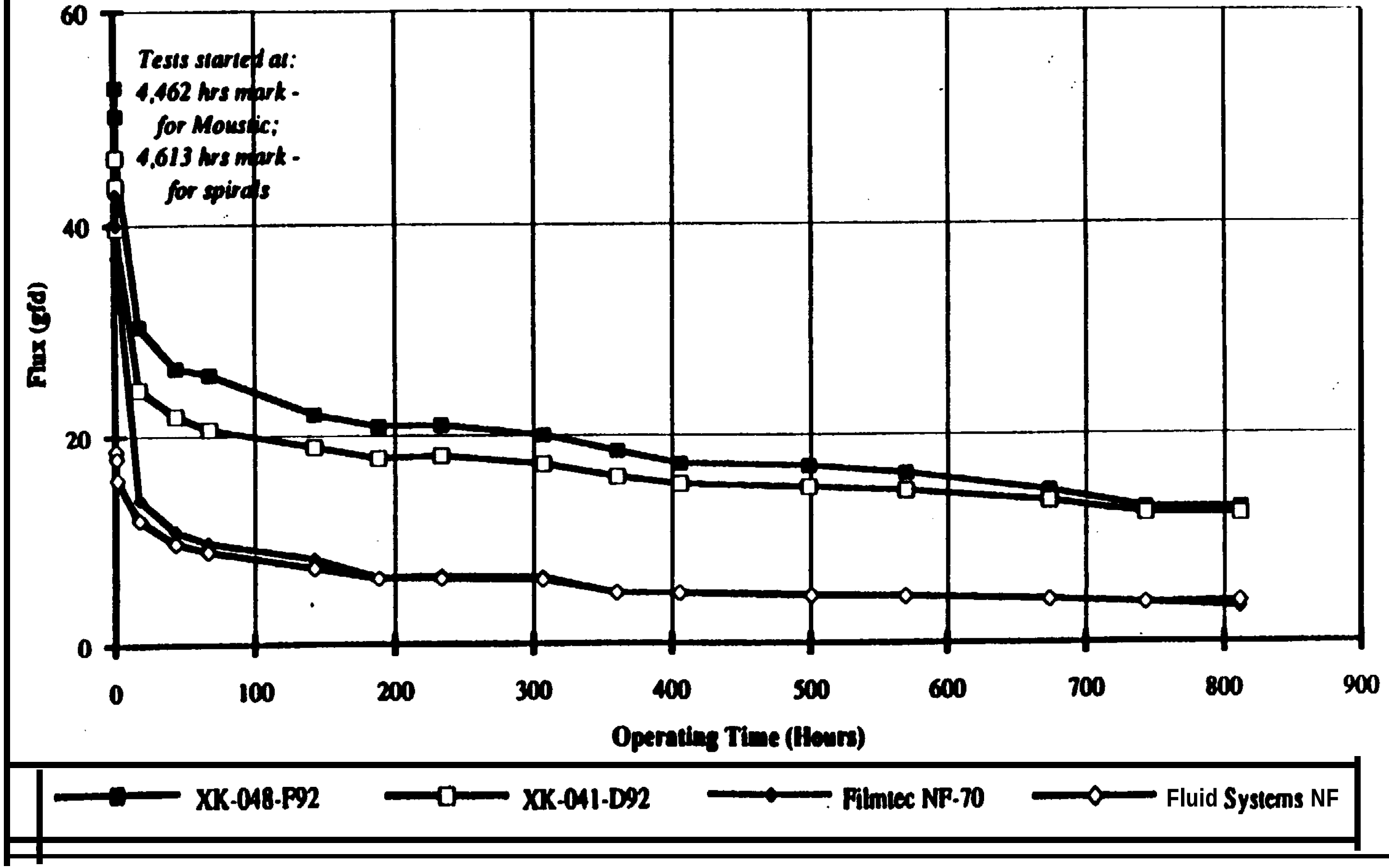


Figure 5.
Fluxes **of** Spiral Transverse **Flow Modules** vs. **Time:**
200 **µm Pre-Filters on** Both Systems



During the second month of testing, a pseudo steady state was reached. The spiral modules exhibited a flux of 8 gfd at 20°C; whereas fluxes for the transverse, flow modules declined from 42 gfd to 30 gfd, and 26 gfd to 19 gfd at 20°C, respectively. At the 1,000 hour mark, the transverse flow modules were switched over to a different system as the previous system was scheduled for field testing. Due to accidental dead end operation, severe flux decline was observed. Successive chemical cleaning cycles did not prevent a rapid flux decline from recurring and several different causes were investigated. One of the two modules (XK-048-F92) was replaced with a new module to determine whether the fibres were irreversibly fouled during the dead end mode of operation. This did not appear to be the case, as the flux decline on the new module occurred at the same rate as the previously cleaned modules. It was postulated that the algae concentration in one tank was significantly higher than in the other. A chlorophyll analysis indicated that algae concentrations in the spiral feed tank were significantly lower than in the transverse flow feed tank (1 mg/l vs. 29 mg/l). The feed tanks were thus switched to test this hypothesis. There seemed to be minor differences in the rate of flux decline. The spiral modules suffered a significant flux decline (from 12 to 9 gfd, a 23 % decline). After a few days feed water was transferred from one tank to the other to equalize feed concentrations. After 450 hours of operation at these conditions, the flux of the spiral modules was 7 gfd; whereas the transverse flow modules were at 16 and 20 gfd for the old and new modules respectively.

In January 1993, permeate fluxes were almost unchanged for both spiral and transverse flow modules. The average flux was 6.5 gfd for the Fluid Systems NF module and 7 gfd for the FilmTec NF-70 module. At the same time, spirals were only one third of the fluxes for transverse flow modules (19 gfd for XK-041-D92 and 21.5 gfd for XK-048-F92, respectively). It must be stressed that transverse flow modules exhibited higher fluxes despite the fact that their feed contained more colloidal particles than that for spiral modules.

In February, permeate fluxes of both transverse flow modules decreased to approximately 75% of the January levels. At the same time, it was found that turbiity and color of the feed dropped between February 16 and March 2. It is possible that the lower color and turbidity resulted in a higher light penetration through the water and lead to the growth of algae. To confirm this hypothesis, samples of the feed were submitted to the chlorophyll A analysis. The results of the analysis, however, did not confirm algae growth.

In March, permeate fluxes of both transverse flow and spiral modules continued to decrease. The fluxes dropped to 11 and 14 gfd for transverse flow modules and to 5 gfd for both spiral modules. In spite of the significant overall decrease, transverse flow modules still demonstrated higher permeate fluxes.

By the end of March, the mark *"4,000 hours of continuous testing" was* passed for spiral modules and almost achieved for transverse flow (Moustic$^{\text{TM}}$) modules. As shown on Figure 3, both transverse flow and spiral elements were subjected to fouling which resulted in decreasing permeate fluxes. The transverse flow elements exhibited a higher permeate flux. This may be a result of a better module configuration and a higher molecular weight cutoff (MWCO) of Moustic$^{\text{TM}}$ elements. It appears to be difficult to give a more definite explanation since the membranes tested were not fully comparable.

Pretreatment requirements are an important parameter characterizing the performance of a membrane element The less pretreatment required, the easier to operate a membrane system. This is especially important for military applications where maintenance must be minimized. From this view point, the performance of transverse flow elements was much better. After almost 4,000 hours of testing, the 200 micron prefilter was replaced only twice, it., when the system was cleaned. At the same time, 5 micron prefilters used for spiral elements required replacement two to four times a week. As a result, one hundred and fourteen 5 micron prefilter cartridges had to be used and later disposed of as they could not be regenerated. Moustic$^{\text{TM}}$ operation is a significant cost savings in terms of the number of filters and also system uptime (productivity).

In March, after "4,000 hours of work" was nearly achieved for transverse flow *modules* and exceeded for spiral modules. It was decided, however, to continue testing the modules at more challenging conditions. The client was informed about these plans and gave approval. It was decided to wash both systems before the feed composition was changed, in order to have permeate fluxes as close as possible to their initial values at the beginning of the entire test. Two sets of experiments were performed.

The first test set was carried out on both spiral and transverse flow elements at a *higher feed color* and *turbidity*. For this purpose, a new feed solution was prepared by dissolving sodium chloride, humic acid, and a mixture of fire and Stratton clay. The target parameters of the new feed were as follows: NaCl concentration • 500 ppm, color • approximately 150 APHA, turbidity •

approximately 300 NTU. No algae was added to the feed since it was found earlier that algae would not grow under the test conditions. The elements were tested for approximately 400 hours. The results arc presented in Figure 4.

The fouling which occurred for both types of membrane elements was significantly higher than in previous tests. In these tests, transverse flow modules exhibited an even greater flux decline than the spiral modules.' This phenomenon could be explained due to the fact that Moustic™ modules, on the one hand, and spiral modules, on the other hand, were operated at different pretreatment conditions. When the feed concentration was increased, it did not affect the spirals since 5 micron prefilters removed almost all suspended solids. In the case of the transverse flow modules, 200 micron prefilters allowed a much greater passage of suspended particles, therefore resulting in increased membrane fouling. It was concluded, therefore, that pretreatment conditions should be identical in order to obtain more comparable data. It must be added that, like in previous tests, 5 micron prefilters required a frequent replacement; whereas 200 micron prefilters were not replaced.

In *the second test set, both types* of membrane elements were operated using *200 micron prefilters . These* tests were necessary in order to study how the membranes would perform at identical pretreatment conditions. The test results ate presented in Figure 5. The permeate fluxes of spiral modules dropped to 30% of their initial values after approximately 24 hours for FilmTec NF-70 and 190 hours for Fluid Systems. In comparison to this, it took respectively 500 and 3,750 hours in previous tests when 5 micron prefilters were used. At the same time, the rate of fouling for Moustic™ modules did not change since the same 200 micron prefilters were used in all tests. After 400 hours of testing, the permeate fluxes decreased to 26% and 12% for spiral modules and to 32% for both Moustic™ modules, compared to the initial fluxes. These results indicate that, under identical pretreatment conditions, the fouling rate for Moustic modules is significantly lower than that for spiral ones.

It was concluded that long-term comparative pilot studies accomplished their objectives in the evaluation of transverse flow elements. On May 31, 1993, pilot studies were completed. At the end of the tests, cumulative test time was 5,425 hours for spiral-wound elements and 5,274 hours for transverse flow elements.