NOVEL DISK MODULES FOR MEMBRANE SEPARATION PROCESSES (U)

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DOE Contract No. DE-AC09-89SR18035

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WSRC-RP-93-1541

Keywords: Membrane Fouling, Bacteria,
F/H ETI, Reverse Osmosis,
Rochem, Spiral-Wound,
Water Flux, Salt Rejection,
Decontamination Factor

December 6, 1993

CC: TIM, 703-43A, Rm. 26 (4)

To: R. H. Hsu, 773-43A

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ABSTRACT

Biologically active feed streams generally cause large declines in the performance of conventional reverse osmosis membrane systems. Both treated water quality and flow rate can be adversely affected. Extensive cleaning procedures are generally necessary to restore the system to pre-fouled conditions.

The Rochem Disc Tube™ [reference: Rochem Separations Systems (1991)] is a novel membrane filtration module designed for use with reverse osmosis, nanofiltration, ultrafiltration, and micro-filtration membranes. The Disc Tube™ module is composed of a series of stackable membrane disks separated by spacer disks and will be described in detail in this report. The open channel feed path, short feed and permeate flow lengths, and modular construction are features which provide advantages over more traditional module designs. The design of the Disc Tube™ allows the unit to run, even on very silty waters or biologically active streams, with minimal pretreatment.

A Disc Tube™ module was tested side-by-side with a spiral-wound module on a biologically active inorganic simulant. Data are presented showing the performance improvements possible from using the Disc Tube™. The Disc Tube™ exhibited much better performance, both in terms of water flux (over 30% higher) and salt rejection (less than 1% loss as compared to 2-3% loss for a spiral-wound

module). Salt passage was essentially unchanged for the Disc Tube™, whereas the spiral-wound module experienced a 30-50% increase in salt passage.

Additionally, the Disc Tube™'s performance could be restored by a single cleaning in 1% NaOH at 35°C and 200 psi. The spiral-wound module required a second cleaning using 8 g/l of Filmtec Alkaline Cleaner™.

INTRODUCTION

Membrane fouling has always been a problem, limiting the usefulness and applicability of membrane systems. Traditionally, physical/chemical pretreatment of the water has been used to reduce the fouling potential. Pretreatment costs can be as high as the operating cost of the membrane system, depending on the pretreatment level required.

The reverse osmosis (RO) system at the Effluent Treatment Facility (ETF) at the Savannah River Site, Aiken, South Carolina has experienced fouling from trace quantities of inorganics (Al, Fe, and Si) and $1.E5-1.E7/ml$ bacteria. The bacteria are primarily produced in an upstream Hg-removal resin bed/activated carbon bed process. The bacteria adhere to the colloidal inorganics that are in the membrane feed at their solubility limits (having been precipitated and removed upstream by a ceramic microfilter system).

The resulting bacterial/inorganic foulant adheres to the membrane surface and results in high feed pressures and poor salt rejection. The feed pressure increases because the membrane system at the ETF is designed to produce a constant rate of treated water, or permeate. This is accomplished by increasing the membrane feed pressure whenever permeate flow drops. The system normally operates at 400 psi and the pressure has been noted on occasion to rise to 750 psi within minutes. Salt rejection typically drops from 97-98% (design value) to 90-95%. A loss of 3-7% may not sound large, but the amount of dissolved solids in the treated water increases by 250-300%.

These performance losses have been attributed to bacteria present in the feed, and several potential solutions have been proposed and demonstrated here at the Savannah River Technology Center (SRTC). Most of the solutions deal with feed pretreatment and only reduce the magnitude of the problem without actually correcting it. Another potential fix to the problem will be discussed now.

Advanced hybrid plate-and-frame modules have been developed [reference: Rochem Separations Systems (1991)] that increase the applicability of membrane systems by using hydrodynamics rather than pretreatment to prevent membrane fouling. The membrane module is designed with a 3" feed flow path. The feed channel height is unobstructed and measures about 0.04". The short, open nature

of the flow path means that the membrane module can accept feeds that would severely foul conventional spiral-wound or tubular membrane systems.

This paper will discuss the use of Disc Tube™ modules on biologically active inorganic simulant. This simulant was chosen to closely resemble the membrane feed at the ETF. The performance of the Disc Tube™ module is compared to results obtained from using a spiral wound module on the same simulant. The Disc Tube™ exhibited much better performance, in terms of permeate flux, salt rejection and membrane cleaning.

The paper will start with a discussion of the Disc Tube™ module and its hydrodynamics. The advantages and disadvantages of the design will be discussed next. Finally, the experimental methods and results of side-by-side testing of the Disc Tube™ and spiral-wound modules will be discussed.

DESCRIPTION OF THE ROCHEM MODULE

The Disc Tube™ Module

The original version of the Disc Tube™ was developed and patented in 1987 (U.S. Patent #4,698,154). The module was designed for use in seawater desalination. The Disc Tube™ was designed to eliminate the fouling problems experienced with previously developed plate-and-frame, tubular, and spiral wound modules.

The Disc Tube™ has a simple modular design. The components are shown in Figure 1. The disk shown in the center picture is 8" in diameter. Flat membrane sheets are cut into octagons 7.5" in diameter. Two octagons are assembled backing-to-backing with a permeate carrier between. The edges are then sealed using an ultrasonic welding process to form a membrane cushion. No other cushion diameters are used. The membrane cushions are stacked between a series of injection-molded plastic spacer discs. The spacer discs have an O-ring on each side to seal the feed from the permeate. A 1.25" hole is cut in the center of the cushion to allow permeate flow from between the spacer discs and a central tie rod which assembles the module.

A stainless steel end plate is attached to the tie rod, and a set of spacer discs and membranes are stacked on the tie rod. After the membranes and discs are in place, a second stainless steel end plate is put on the tie rod. The end plates have chevron hydraulic

seals that expand when the module is pressurized to seal against the fiberglass pressure vessel. A membrane module can contain up to 170 membrane cushions depending on the length of the tie rod. The total membrane area associated with 170 cushions is about 75 ft².

The unique design of the Disc TubeTM allows for the processing of waters which cannot typically be processed by spiral-wound or hollow-fiber modules. The Disc TubeTM can be run on water with a turbidity of greater than 4 NTU (nephelometric turbidity units). The design of the Disc TubeTM allows the unit to run, even on very silty waters, with minimal pretreatment. Typically only a multimedia filter and ten micron cartridge filter are used. The main purpose of the prefilters is to protect the pump and system hardware.

The Disc TubeTM system has been used on a variety of aqueous waste streams around the world. Specifically, the application has targeted landfill leachate clean up. Several references can be found detailing the use of the Disc TubeTM to remediate landfill leachate [e.g., Peters (1991)].

Module Hydrodynamics

The Disc TubeTM is hydrodynamically designed to improve the performance of existing membranes. The open channel flow path, frequent reversals of flow and fully turbulent flow work together to create a module with excellent characteristics.

The solution flow path through the membrane is shown in Figure 2. The feed water flows in through the end plate and down to the far end of the module through an annular ring between the pressure vessel and the spacer discs. The water flows across the bottom of the first spacer disc and up through a series of slots near the center of the disc. The water flows up until it contacts the membrane near the inside edge of the cushion. An O-ring seal forces the water to flow radially toward the outer edge of the membrane cushion. When the water reaches the outer edge of the cushion it contacts the raised lip of the spacer disc, which forces the water to reverse direction and flow radially back toward the center of the module on the second side of the membrane cushion. Near the center of the module, the water contacts the O-ring and is forced up through the slots in the spacer disc. The flow pattern repeats over each membrane cushion along the entire length of the module. The concentrate is removed from the module on the same end plate as the feed enters. The permeate passes through the membrane and passes to the inside of the O-ring seals by the carrier sheet. The water then flows up through channels along the tie rod and is removed from the module at the same end as the feed and concentrate.

The Disc TubeTM module has a fully-open feed channel flow path. There are no woven spacers on the feedwater side of the module.

The feed path is the open space between the spacer discs and the membrane cushion. The minimum clearance between the disc and membrane is one millimeter. This clearance is maintained by a series of raised dots on the spacer disc surface. These dots have two primary uses, first to support the membranes and ensure a flow path. This is most important during the onset of flow in the module. Once flow has begun, the membranes float and flutter between the spacer discs and are not in continuous contact with the dots. The second function of the dots is to increase the turbulence in the module. This is accomplished because the dots provide bluff bodies and shedding vortices. The dots promote mixing of the feed solution as it flows across the surface of the membrane.

Figure 2. Diagram of Disc Tube Module Flowpath.
[Source: Rochem Separation Systems (1991)]

The frequent flow reversals in the module increase the turbulence in the module and reduce concentration polarization in the module. The 2.5 inch path length between reversals and mixing of the solution does not allow the build up of a highly concentrated boundary layer at the membrane surface. The highly turbulent flow increases back diffusion from the membrane surface and also keeps suspended particles from settling out. This reduces concentration polarization and membrane fouling and hence results in higher flux rates.

The short flow path in the Disc Tube™ module greatly reduces the solute build-up characteristic in spiral-wound and tubular modules. Contrast the 2.5 inch flow path in the Disc Tube™ module to the 40 inch flow path of a spiral wound module or 10 foot flow path typical in tubular modules. The solids contained in a given volume of solution are in contact with each Disc Tube™ membrane for $2.5/40 = 6.25\%$ the distance traveled in a spiral wound membrane. The 2.5 inches is the distance the solids must travel in the Disc Tube™ prior to being remixed and subsequently traveling along another membrane sheet. The solution undergoes 340 flow reversals from the time it enters the Disc Tube™ module, as compared to zero reversals in the spiral wound module.

When all of the module's hydrodynamic conditions are considered together, the Disc Tube™ provides the best design available for the support of membranes. The open channel design resists plugging and allows the passage of suspended material in the feed and reduces precipitate formation inside the module. The Disc Tube™'s ability to process highly turbid solutions means that there are many nucleation points and membrane scaling is less likely.

Disc Tube™ Module Advantages/Disadvantages

There are several advantages to this type of design. The primary advantage is absence of spacer material in the feed channel as in the case of the spiral-wound modules. This allows the module to process much dirtier feeds, with the restriction on particle size being the 1 mm channel opening.

This open-channel design allows the module to process waters with a high silt density index (SDI) value. SDI is defined by the following expression:

$$SDI = 100 * \frac{(1 - \frac{T_s}{T_f})}{5} \quad (1)$$

The SDI test is performed by filtering a fixed volume of water through a Millipore 0.45μ filter at 30 psi. The time required is denoted by T_f . The filtering process continues for five minutes.

Another fixed volume of water is filtered and the time required is denoted by T_s .

The Disc TubeTM module can process feeds with 5 minute SDI values of 16 (the maximum value is 20). Water with an SDI value of 16 would severely foul conventional spiral-wound modules.

Another advantage of the open channel design is that biologically active feeds can readily be processed. The absence of the spacer material eliminates "dead spaces" that are available for bacteria to attach and grow in the spiral-wound module. The pillows "float and flutter" in the feed solution being processed, which increases their resistance to fouling. Also, due to the lack of spacer material, cleaning the Disc TubeTM module is easier.

Another attractive feature of the Disc TubeTM module is that only the membrane pillows would need to be disposed of when membrane replacement becomes necessary. This would result in a minimization of the waste volume generated over disposal of spiral-wound or tubular modules in use today.

The main disadvantage to the Disc TubeTM design is that the membrane packing density is significantly less than in a spiral-wound module. A standard Disc TubeTM module is 8" in diameter and 40" long, with about 75 ft² of membrane area. Spiral-wound modules are physically the same size, but have 280 ft² of membrane area. Thus more Disc TubeTM modules would be required to process a given flow.

Cost is also a consideration with the Disc TubeTM module. A single Disc TubeTM element will cost about \$6,000; whereas, spiral-wound elements will cost less than \$2,000. Of course, large purchases of Disc TubeTM elements may substantially reduce the cost/module. Costs could be potentially offset by increased availability and run time between cleanings, reduced probability of membrane replacement, and improved performance due to biofouling reduction.

The reduced surface area and module cost are partially offset by the fact that the Disc TubeTM module can operate at 1,400 psi, versus 1,000 psi for standard spiral-wound modules. According to Rochem officials, the Disc TubeTM elements have been modified to operate at 2,100 psi, which would further offset the reduced area by allowing the modules to operate at 2-3 times the pressure that spiral-wound modules are operated. Higher operating pressure increases the permeate flow per unit area of the membrane, thus increasing the efficiency of the module by 2-3 times. Higher pressure operation would result in some additional capital and operating costs (e.g., larger pumps, thicker piping, etc.), but would make the modules competitive with standard spiral-wound modules.

Another factor that would offset the Disc TubeTM module's cost is that only the set of membrane pillows need be replaced, rather

than the whole module. The cost of the pillows would be approximately \$2,500. Also, different membrane types can be inserted into the Disc TubeTM modules to handle changes in the feedwater to the modules or changes in the application that the Disc TubeTM modules were intended for. Thus, no equipment changes or retrofitting would be required.

EXPERIMENTAL PROCEDURE

The goal of this work was to evaluate the performance of a Disc TubeTM module when processing the effluent from the granulated activated carbon (GAC) beds at the ETF. The effluent contains trace quantities of metal hydroxides and bacteria/bacterial byproducts. This stream readily fouls the spiral-wound modules in use, and frequently results in large losses in salt rejection and water fluxes.

A series of tests were conducted to evaluate whether the Disc TubeTM module would perform better than the existing spiral-wound modules in use at the ETF. These tests involved processing solutions containing metal (Al, Fe) hydroxides, Si, and salt. Tests were also done with 1.0E7/ml bacteria present. Chemical cleaning of the fouled membrane was performed with a caustic wash at 35°C and 200 psi. The unit was then rinsed and a standard salt test (2,000 mg/l NaNO₃) was performed to determine performance restoration.

A sample run cycle, along with pertinent calculations, is shown in Figure 3. The permeate is diverted to drain and the concentrate returns to the feed tank. The feed becomes more concentrated. This simulates the movement of the feed solution through the membrane system. The tank is then refilled and additional reagents and bacteria (if needed) are added to replenish any solids that may have been deposited on the membrane's surface.

In addition to salt rejection, the quantity "DF" or decontamination factor is also used in the subsequent discussion. The nuclear industry generally refers to a process' efficiency by its DF. Decontamination factor, or DF, is related to salt rejection by:

$$DF = \frac{1}{1-R} \quad (2)$$

and salt rejection, R, is defined by:

$$R = 1 - \frac{C_p}{C_f} \quad (3)$$

where C_p and C_f are the average permeate and feed concentrations, respectively.

The value of DF increases rapidly for $R > 95\%$. For example, for rejection values of: 90%, 95%, and 99%, the corresponding DF values are: 10, 20, and 100, respectively.

Another measure of membrane performance is salt passage. Salt passage is given by the following expression:

$$\text{Salt Passage} = \frac{C_{\text{perm}}}{C_{\text{feed}}} \quad (4)$$

Where C_{perm} and C_{feed} are the permeate and feed salt concentrations, respectively. Low salt passage values indicate good membrane performance; high values indicate poor performance. As an example, salt rejections of 90%, 95%, and 99% yield salt passages of 0.1, 0.05, and 0.01, respectively.

The quantity "% water recovery" is used to allow different rates of membrane fouling to be compared properly. The flow-averaged DF is used to estimate the overall performance of a three-stage membrane system from single-module data.

The results obtained with the Disc Tube™ module could not be compared directly to the spiral-wound module data. This is because the Disc Tube™ module contained standard-rejection seawater membranes, and the spiral-wound module contained a high-rejection seawater membrane. The high-rejection membrane has inherently higher DFs and lower water flux, and thus a direct comparison would be very misleading.

These differences were overcome by normalizing the permeate flow and flow-averaged DFs. The normalized permeate flow is computed by dividing the value at any time (J_w) by the starting flow value (J_{w0}), as shown below:

$$\text{Normalized Permeate Flow} = \frac{J_w}{J_{w0}} \quad (5)$$

The flow-averaged DFs are normalized by dividing the DFs with bacteria present by the values obtained for a bacteria-free solution:

$$\text{Normalized Flow-Averaged DF} = \frac{DF_{\text{with bacteria}}}{DF_{\text{bacteria-free}}} \quad (6)$$

RESULTS AND DISCUSSION

Results of Processing Bacteria-Containing Feeds

The Disc Tube™ module was evaluated on simulants with and without bacteria to determine susceptibility of this design to bacterial fouling. The results are given in Figures 4 and 5. It can be seen that approximately 5% greater flux loss occurred after processing three bacteria batches or cycles than was observed for the bacteria-free solution. Salt passage was 20-40% lower when bacteria were present (see Figure 5). The salt DF in the presence of bacteria was about the same as in the bacteria-free solution. In fact, the DF was slightly higher when bacteria were present. All DF values ranged between 15-24 at 0% recovery and dropped to 8-15 at 90-95% recovery.

The Disc Tube™ module performed much better than the spiral-wound module on bacteria-containing solutions. It can be seen in Figure 6 that the flux loss observed when bacteria were present were much smaller than measured for the Filmtec unit. Typically, the addition of bacteria resulted in no more than a 5% increase in flux loss (as compared to bacteria-free operation) in the Rochem system. Compare this to 10-15% for the Filmtec spiral-wound module. Additionally, the Disc Tube™ module had 10-15% higher normalized flux values than were obtained when the Filmtec module was used. This indicates that bacterial fouling had a much larger impact on the spiral-wound module than on the Disc Tube™ equipment.

The presence of bacteria resulted in little change to the salt passage for the Disc Tube™ module. It can be seen in Figure 7 that the salt passage was 30-50% greater for the spiral-wound module. This is due to the improved fluid mechanics of the Disc Tube™ module. Correspondingly, higher normalized DFs were sustained with the Disc Tube™ module. Biofouling reduced the Disc Tube™ DFs by a maximum of 15%; whereas, DFs with the spiral-wound modules were reduced up to 45%.

An increase of 10-15% in system productivity would result in significant savings. System downtime for cleaning would be reduced. Also, the run time between cleanings would increase.

The lack of appreciable bacterial fouling with the Disc Tube™ module indicates superior performance to the standard spiral-wound element. This type of performance could enable the ETF membrane system to operate as designed (both in terms of water quality and quantity) by using the Disc Tube™ modules to augment the present system.

Results of Cleaning the Rochem Module

Results of the cleaning studies involving both the Disc Tube™ and spiral-wound modules are given in Figures 8 and 9. It is obvious that the Disc Tube™ module was much easier to clean after contact-

ing the metals and bacteria solutions. A single caustic cleaning completely restored the salt passage to pre-fouled conditions, as shown in Figure 8. This was not the case with the spiral-wound membrane, as shown in Figure 9. Approximately 30-50% higher salt passage values remained after the membrane was cleaned with NaOH. A subsequent Filmtec Alkaline Cleaner step was necessary to restore performance.

CONCLUSIONS AND RECOMMENDATIONS

The Disc Tube™ system is an advanced module design for the treatment of waters difficult to treat with conventional membrane systems. The open channel design promotes turbulent flow and makes the system highly resistant to fouling and scaling. The module is easily cleaned if it becomes fouled, resulting in a system with high efficiencies over a long period.

The Disc Tube™ membrane module demonstrated superior performance to that observed when using a standard spiral-wound module. The membrane successfully processed a solution of bacteria and metals with minimal fouling (in terms of both flux and DF). In side-by-side testing against a spiral-wound module, the Disc Tube™ exhibited 30% higher water flux and 50-70% lower salt passage. Also, the Disc Tube™ module could be cleaned with a single NaOH wash, as opposed to a two-step cleaning procedure with the spiral-wound module.

The Disc Tube™ is a proven membrane technology that is versatile and robust enough to handle a broad spectrum of commercial applications. In particular, the Disc Tube™ system can handle streams that would have permanently and severely fouled conventional membrane systems.

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$$\% \text{ WATER RECOVERY} = \text{TOTAL PERM} / \text{FEED VOLUME}$$

$$\text{FLOW-AVERAGED PERM. CONC.} = \frac{(\text{PERM FLOW}) * (\text{PERM CONC}) * \text{TIME}}{\text{TOTAL PERM}}$$

$$\text{FLOW-AVERAGED DF} = \text{FEED CONC} / \text{FLOW-AVERAGED PERM CONC}$$

$$\text{SALT REJECTION, } R = 1 - \text{FLOW-AVERAGED PERM CONC} / \text{FEED CONC}$$

Figure 3. Description of an Experimental Run Cycle and the Computation of % Water Recovery and Flow-Averaged DF.

Figure 4. Effect of Bacteria on Permeate Flow for the Rochem Module.

Figure 5. Effect of Bacteria on Salt Passage for the Rochem Module

Figure 6. Water Flux Improvements Resulting From Using the Rochem Membrane Module

Figure 7. Comparison of Salt Transport Through the Disc Tube(TM) Module to the Spiral Wound Module.

Figure 8. Effect of Caustic-Cleaning on Disc Tube membrane Module Performance.

Figure 9. Salt Passage as a Function of Caustic Cleaning for the Spiral-Wound Module.

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