EVALUATION OF CLEANING SPIRAL WOUND MEMBRANE ELEMENTS WITH THE TWO-PHASE FLOW PROCESS

Novaflux Technologies, Inc.
Princeton New Jersey

Agreement No. 01-FC-81-0740

Desalination and Water Purification Research and Development Program Report No. 101

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A protocol to achieve the cleaning of 8-inch spiral elements using the Novaflux two-phase flow patented method has been established and validated. The technology has demonstrated capability of significantly improving the flux of 8-inch spiral elements, and decreasing pressure drop between the two ends of the modules to acceptable levels. In addition, the two-phase flow process was systematically validated for cleaning 2.5-inch and 4-inch spiral elements in series using a short 10-minute cycle.

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Mission Statements

U.S. Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

Bureau of Reclamation

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.

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1. Executive Summary

The feasibility of utilizing the new two-phase Novaflux Process™ for cleaning spiral wound RO elements was validated for two types of applications, namely: clean-out-of-place (COP) and cleaning-in-place (CIP). The two-phase flow process is based on passing a mixture of a cleaning liquid and air having a high gas/liquid volumetric ratio at a high velocity through the feeding channels of spiral wound elements to clean them in a short period of time. The process is significantly more efficient compared to conventional liquid circulation methodologies, utilizing only a fraction of the cleaning liquid.

An apparatus for performing COP cleaning was designed, constructed and used to study the cleaning of single 8-inch RO elements. Cleaning parameters, including: liquid/gas ratio, gas velocity, gas pressure and cleaning chemistry of the liquid used to form the two-phase flow mixture were systematically evaluated. Based on this part of the study, a final cleaning cycle was developed where an overall cleaning time of less than 30 minutes could be accomplished. Hydranautics 8-inch elements were used for testing and cycle development during this part of the study. These elements were obtained from a drinking water preparation facility in New Jersey that utilized groundwater as the primary source. These elements were used for over 1 year and were fouled with silt, inorganic minerals and biofilm.

To study the two-phase cleaning of spiral elements in series under controlled fouling conditions, a pressure vessel with two 2.5 x 40 inch elements in series was used to study the cleaning in place configuration. The RO vessel was supplied with micro-filtered water having 5,000 ppm TDS and 100 TSS where fouling could be accomplished in only a few hours. A two-phase flow cleaning cycle was developed that has resulted in an average of 30-40% improvement in flux in < 10 minutes, restoring it to over 80% of the manufacturer's published specification values. These results confirmed that the two-phase flow cleaning could be used in several applications, including both small and medium size water treatment systems, and in situation where cleaning of RO elements is impossible or impractical with conventional cleaning methodologies. The feasibility of CIP for cleaning RO spiral elements with size of 4" and 8" elements connected in series along with air requirements needed to perform the two-phase cleaning has been completed in this study.

2. Background and Introduction to Potential Solution

The main objective of this program was to define the operating parameters and to validate the cleaning of RO spiral elements using the two-phase flow process invented by Novaflux Technologies. The potential benefits of the Novaflux Process™ are: i) rapid and efficient membrane cleaning, ii) low-pressure drop of elements connected in series, iii) high flux and output levels, iv) minimal discharge of cleaning chemicals, and v) low consumption of water needed for membrane cleaning operations. If the two-phase cleaning process is applied at an optimized frequency, the average flux can be maintained at significantly higher levels compared to current membrane cleaning practice. Notably, due to the ability of the Novaflux two-phase process to quickly and effectively clean RO elements in a short time, it appears possible to extend the reverse osmosis separation/treatment step to applications deemed impossible in the past.

2.1 Description of the two-phase flow Novaflux cleaning process

Novaflux Technologies, Inc. has developed and patented a membrane cleaning process in which a small volume of a safe cleaning and/or de-scaling solution is mixed with an air stream through a nozzle to form a two-phase mixture having a high air-to-liquid ratio in the range between 50:1 and 6,000:1. The droplet size of the cleaning solution is in the 25-400 microns range. When such two-phase mixture is injected into membrane feeding channels at velocities greater than 30-40 ft/sec it effects the cleaning of such feeding channels. This process has proven to effectively clean spiral elements in a short period of time, usually minutes. This new cleaning process constitutes a dramatic improvement over conventional liquid circulation cleaning methods [8-10]. The two-phase flow process is especially applicable to spiral RO membranes since surface cleaning of the membrane is sufficient to restore flux. Since this cleaning process is effective in removing accumulated solids from the membrane surface, it can further decrease the pressure drop of elements arranged in series. The latter usually arises from the accumulation of solid deposits in membrane feeding channels.

The two-phase flow dynamics regime that is optimal for cleaning with the Novaflux Process™ is a special case/variant of the annular mist regime, where several criteria need to be satisfied [2,8-10]. In the regime that is optimal for cleaning, hydrodynamic instability needs to be present at the surface to be cleaned causing liquid droplets to form, strike the surface to effect cleaning, coalesce with other droplets, and then reform due to the high gas velocity employed in the process. The process of forming and reforming liquid droplets along the surface to be cleaned is repeated, until the cleaning of the entire surface is achieved. Droplets reformation is influenced by the dimension and geometry of the passageway to be cleaned, liquid surface tension, liquid viscosity, velocity of gas and liquid/gas ratio. The localized shear and impact stresses generated during the droplet impact or during the removal of liquid droplets from the surface are two- or three orders of magnitude higher than the bulk shear normally computed in classical fluid mechanics. Further, the chemistry of the cleaning solution used in the process must satisfy certain criteria, notably it must assist in lowering the adhesion between the foulant and membrane surface and support maintaining high velocities during cleaning, without complications due to foaming.

For the case of two-phase flow traveling down a spiral wound membrane element, the spacer creates complicated variations in the process at the surface of the membrane. Elaborate modeling may be needed to define flow patterns of droplets in this case. This modeling is outside the scope of the present study. Minimum threshold of gas velocities must be achieved for cleaning to be effective with this process. Because of this requirement, the amount of gas needed to make the two-phase flow must be satisfied.

Key variables for the two-phase cleaning process:

Based on our prior experience in cleaning tubing and medical devices, we have established a set of optimal criteria that have been used in this study. The following parameters have been previously optimized for cleaning narrow passageways and will be explored in the context of membrane cleaning. Some additional optimization will possibly be required to arrive at optimal cleaning conditions for the case of spiral-wound membrane element.

a. Liquid to gas ratio - Typical liquid to gas volumetric ratios of successful two-phase mixture are in the range of 1:50 to 1:6000. If too much liquid is used, slug flow occurs, and it is difficult to achieve sufficient velocities required for droplet formation and reformation, and to effect high shear stresses at the surface to be cleaned. Too little liquid cannot achieve good cleaning in a reasonable period of time, simply because there are not enough droplets to impact the wall. The liquid/gas ratio is adjusted such that the optimal droplet regime is created in the passageway to be cleaned.

b. Turbulence **-** Turbulent flow enhances reformation of the liquid droplets and also aids in directing droplets to impact the surface to be cleaned, and thus effecting the cleaning of the entire surface. In most of the cleaning applications that have been explored, turbulence has been found to be a critical variable.

c. Surface tension **-** Surfactants are normally added to the cleaning solution to modify the surface tension. Lowering of the surface tension assists in creating droplets and in promoting the wetting of the surface to be cleaned. An essential function of the surfactant is its ability to lower the adhesive strength of the foulant to the surface, which ultimately translates to faster and more efficient cleaning by the two-phase process.

d. Viscosity **-** If the viscosity is too high, the liquid will remain attached to the wall, which is deleterious to cleaning. Additives that result in increasing liquid viscosity are not desirable for this application.

e. pH **-** The optimum pH of the cleaning solution depends on the nature of the material to be removed. For the removal of organic deposits, an alkaline solution is normally preferred. However, for removing inorganic deposits scale, an acidic solution is preferred.

f. Pulsating flow **-** Pulsating flow can be useful in creating localized secondary flows, causing droplets to interact with the surface to be cleaned. Surges of two-phase flow will clean debris that has been dislodged during the cleaning process; this action aids in flushing such debris from the surface.

3. System Description

3.1 Off-line cleaning or cleaning out of place (COP) test rig used for 8-inch RO elements

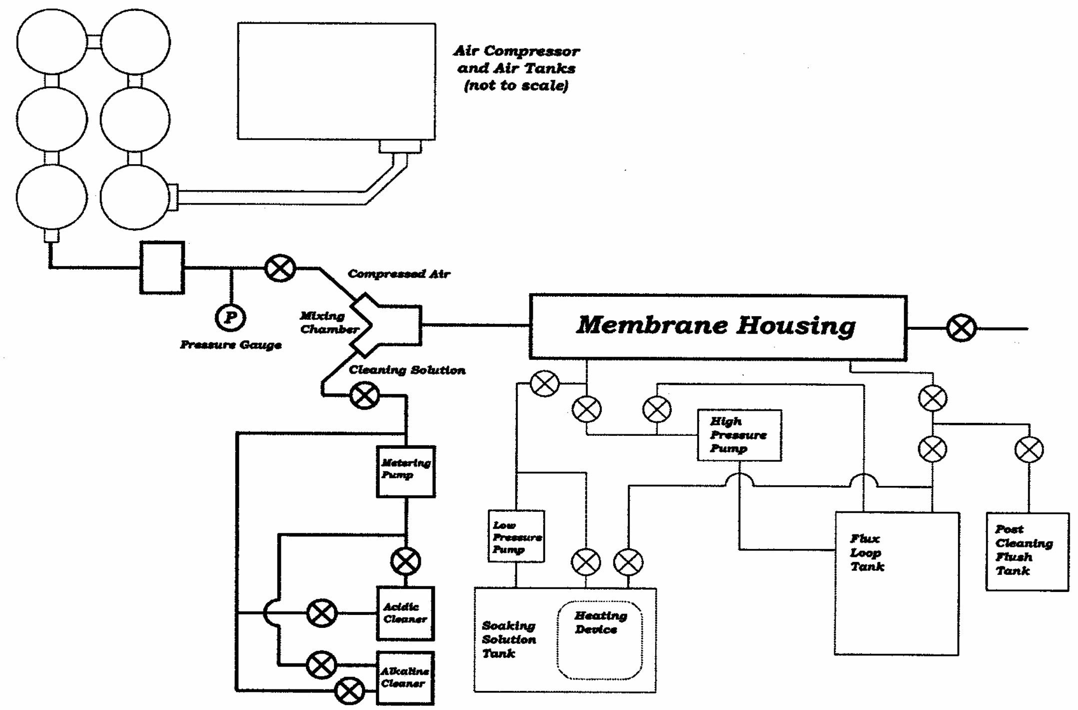
A test rig constructed to carry out the initial cleaning tasks of this program was designed and constructed. The apparatus had three major loops: soaking loop, cleaning loop and flux measurement loop. The cleaning system used in the study was controlled manually. In order to effectively apply the two-phase flow for cleaning RO membrane elements, we had to modify an RO pressure-vessel housing and to redesign the end caps, and their associated adapters. A de-mister was designed and constructed to condense the two-phase flow generated at the outlet of the RO element being cleaned. Details of the system are described as follows:

a. Cleaning loop and cleaning cycle: The main components of the cleaning loop include a 50 HP compressor, two air filters, six 240 gallon air tanks, a regulator, a pressure gage, a metering pump, an acidic cleaning solution tank, an alkaline cleaning solution tank, a high pressure RO housing that can accommodate an 8" RO element, an exhaust de-mister, and related manual valves and low pressure hoses.

The high pressure RO housing is secured on a swiveling table allowing the cleaning to be performed at angles between 0-90^o. The custom-machined end-caps and demister mentioned above are also essential components of the cleaning loop.

In a typical cleaning cycle, the air is set at 45 psi and the rate of the cleaning solution is typically set at 0.1 ~ 0.2 gallons per minute, with the aid of a metering pump. The cleaning solution used can be either acidic or alkaline depending on the type of fouling. The cleaning agents are delivered with the aid of a special nozzle, located at one side of the element, which is then mixed with air to form the two-phase flow mixture needed to clean the spiral element. A cleaning cycle normally lasts about ten minutes. The air/liquid exhaust is then directed to the demister where air is separated from the two-phase mixture and discharged – see Figure 1.

b. Soaking loop and soaking cycle: The soaking loop consists of a soaking solution tank, a 6000W heater and temperature controller, a low-pressure pump, RO membrane housing that accommodates an 8" RO filter, and the associated manual valves. During soaking, the temperature is set at 50 °C. The soaking solution is circulated through the RO element using a low-pressure pump – see Figure 2. Soaking was sometimes necessary when the condition of the elements is poor, or if the elements have been dried. Because the fouled 8" RO elements obtained from US Filter were always dry, they had to be soaked to soften the foulants. The soaking solution could be the same as the cleaning solution, or can be just clean water.



(a)

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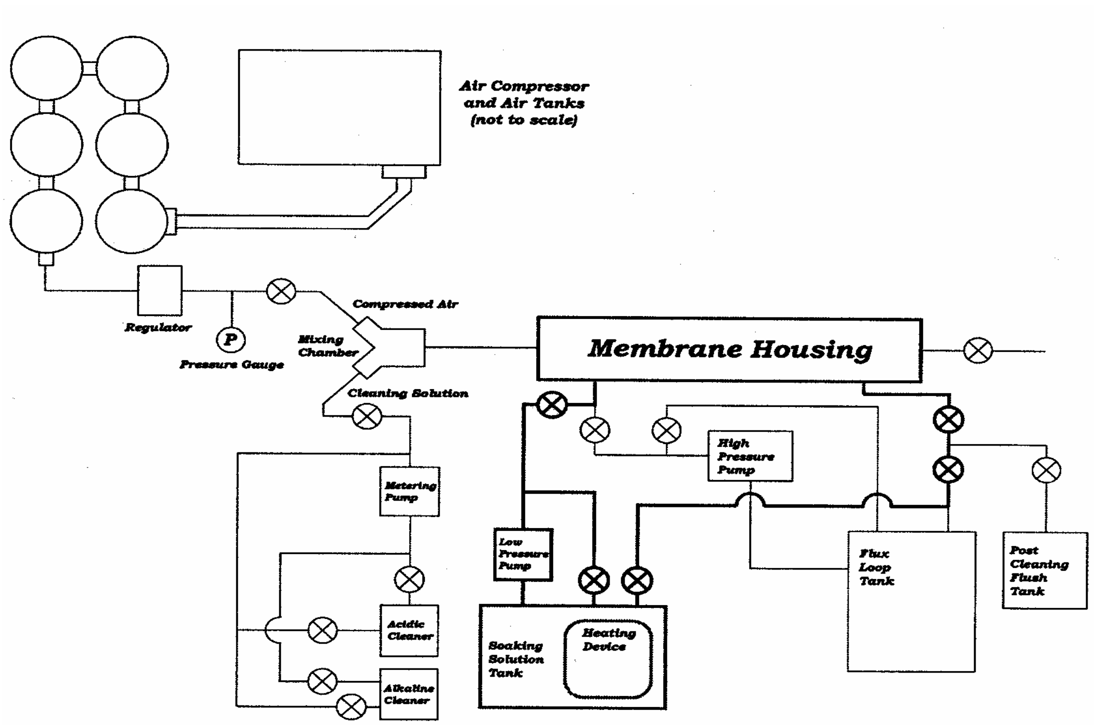
Figure 1.—(a) Schematic of an 8-inch COP process showing the cleaning loop and cleaning cycle (shown in bold); (b) Photograph of the actual system used in the study.



(a)

(b)

Figure 2.— (a) Schematic of an 8-inch COP process showing the soaking loop and soaking cycle (shown in bold); (b) Photograph showing the entire system including soaking, cleaning and flux measurement loops.

c. ***Flux measurement loop:*** The main components of the flux measurement loop include: a flux loop tank, a post-cleaning flush tank, a high-pressure pump, six manual valves, two pressure gages, and a high pressure RO housing that accommodates an 8" RO element. The hoses connecting these main components could sustain a pressure up to 300 psi. The system is rinsed with clean water in the flux loop tank for about 10 minutes so that the dirty water does not return to the flux loop tank. The high-pressure side effluent from the membrane housing is directed to post-cleaning flush tank for disposal. Flux measurement is performed right after the system is rinsed. The RO feed pressure is set at 200 psi during rinsing and 250 psi during flux measurements. Flux is measured at the product port located at the stainless steel end-cap – see Figure 3.

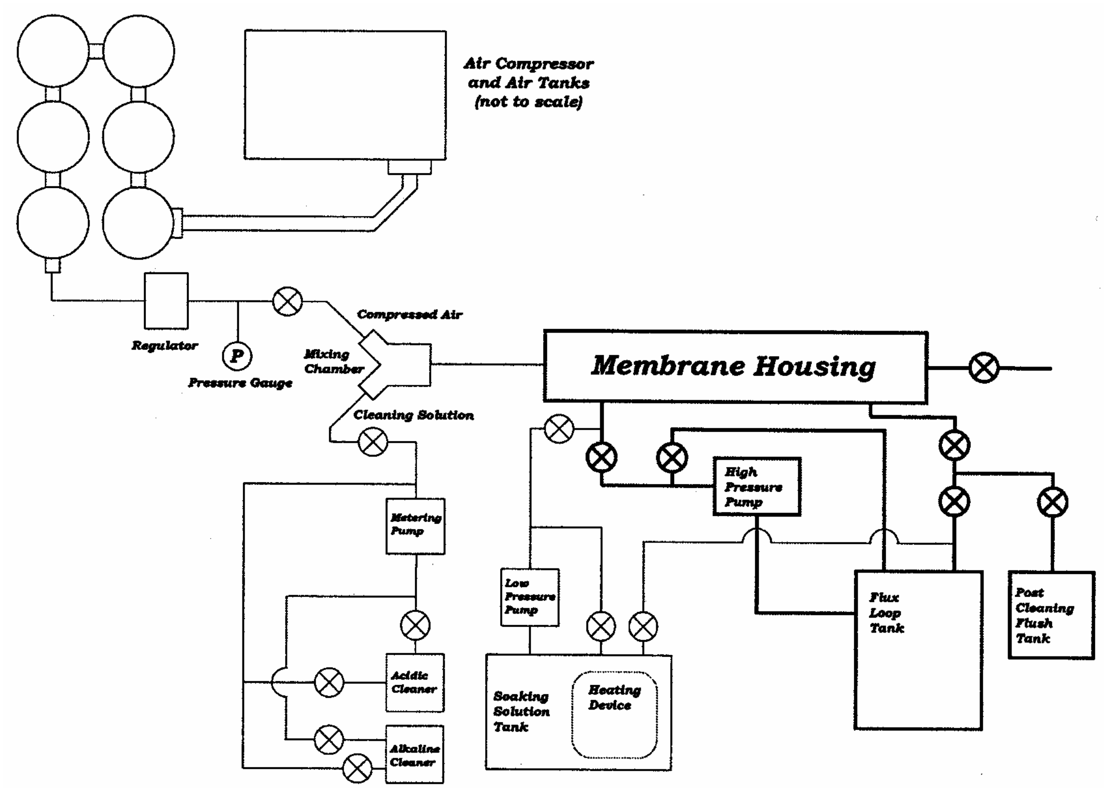
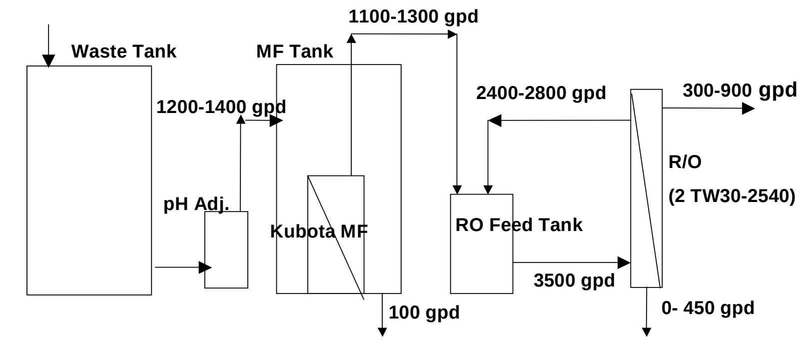


Figure 3.—Schematic of an 8-inch COP process showing the flux measurement loop (shown in bold).

3.2 Cleaning in place (CIP) system for two RO elements in series

Our multiple RO element test system consisted of a submersed Kubota FC-25 microfilter to pre-treat waste stream, and this pretreated water was used as influent for a single RO vessel (made by Osmonics) with two FilmTec TW30-2540 elements in series. The RO separation stage was operated at 30% recovery with concentrate re-circulating to the feed water. This system produced RO water from a high TSS, high TDS, high protein and fat dairy processing waste stream - see Figure 4. The average RO feed TDS was >5,000 ppm during the study.



	Waste Feed	Kubota feed	MF/Kubota Permeate	R/O Feed	RO Permeate	Concentrate recycle	Blowdown
Flow (gpd)	1280	1280	1180	3571	**0.8-2.4 lpm**	2391	180
pH	11.5	8-9	8-9	8-9.5	**8.5-10.2**	7-8	7-8
TDS (ppm)	7-8000	7-8000	7-8000	7000-14,000	**80-350ppm**	9000-18,000	9000-18k
Susp.Solids	>10,000				**<20 ppm**		
Dissolved O2					**> 6 ppm**		

Figure 4.—Test skid/Typical results.

When feeding the RO vessel with microfiltered pretreated water, a typical membrane cleaning cycle includes a two-phase flow cleaning step using air set at 50 psi which is mixed with either acidic or alkaline cleaning solution and delivered to RO feeding channels for about ten minutes. After this two-phase cleaning step, the RO elements are then rinsed with RO product water for another ten minutes. Detailed RO flux, TDS, pH and temperature data were documented during a 3-month study. The water quality of the micro-filtration feed, RO pretreated influent and RO products were measured daily over a period of 5 weeks. A detailed drawing of the system used in this part of the study is given in Figure 5.

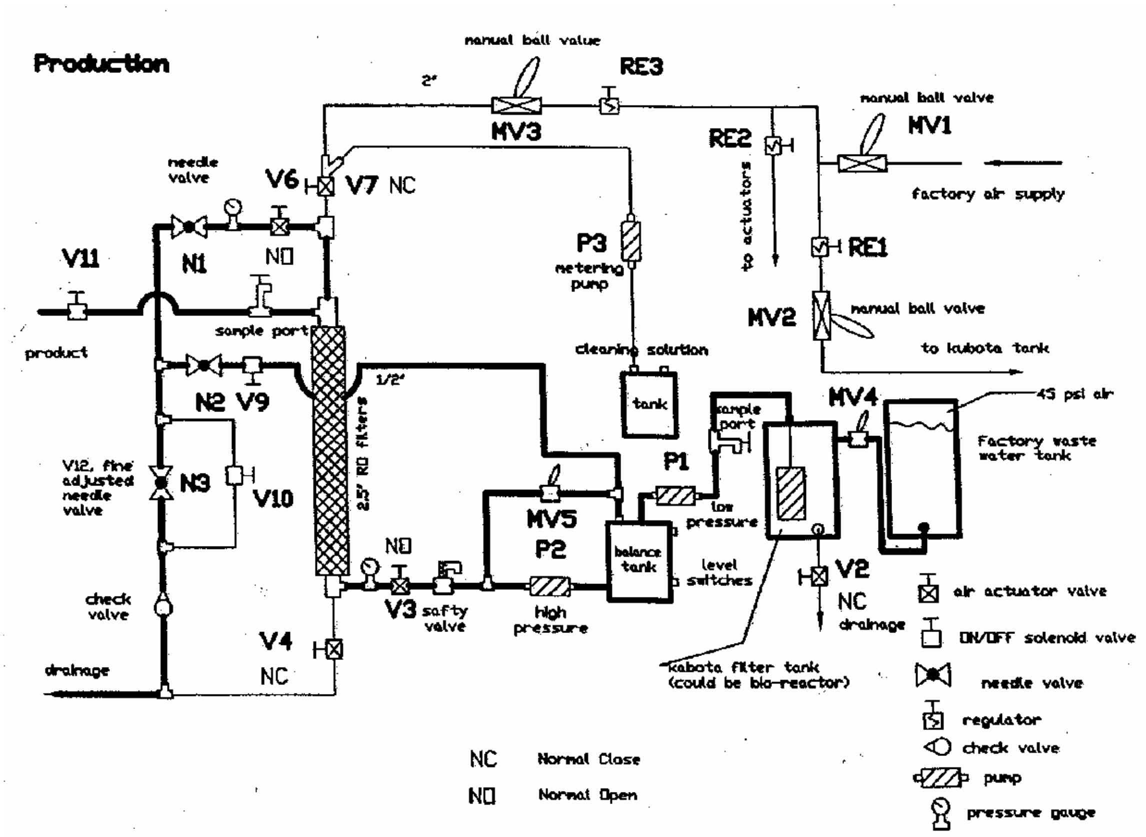


Figure 5.—Schematic of a 2.5-inch test skid for a 1000 gpd system.

4. Work Performed/Research Findings

4.1 Work performed

Task 1: Membrane and application characterization

Due to a change in the situation at the Orange County Water District (OCWD) and the Yuma Desalination Facility, we could not obtain membranes for the study as set forth in the original proposal. This issue was reported in interim reports and was discussed with Mr. Frank Leitz, Contracting Officer's Technical Representative responsible for the present study at the Bureau of Reclamation. At Mr. Leitz's suggestion, we discussed options with Mr. Michael Norris, General Engineer at the Yuma Area Office. He confirmed that he does not have membranes that can be used for the project.

Novaflux pursued other options to secure RO elements for the study and discussed those options again with Mr. Leitz. The option that was acceptable involved using RO elements from U.S. Filter; the latter agreed to provide us with some discarded elements that could not be cleaned with their conventional membrane cleaning process. We used the US Filter elements for cycle development as per Task 2 in the original proposal. However, these elements lacked consistency with respect to fouling type, history and other issues. In spite of these difficulties, the work has been valuable in defining the operating parameters for cleaning single 8-inch RO elements with the two-phase flow cleaning process.

Task 2: Validation of the two-phase process by cleaning 8-inch membranes

Novaflux fabricated appropriate end caps and adapters for cleaning the 8-inch membranes and constructed the 8-inch cleaning and testing apparatus for the off-line COP work as described in Section 3.1. Cleaning chemistry was evaluated and a cleaning cycle was developed consisting of several steps with an overall cleaning time of less than 30 minutes. As described above, the membranes acquired from US Filter were used for testing and cycle development during this task.

Flux measurements were performed before and after cleaning using the flux measurement test rig available at the site, as described above. Trans-membrane pressure, temperature, pH and conductivity of the feed and permeate streams were measured and recorded for each membrane. On the average, each membrane required a total of 2 hours to handle, install, clean and measure flux using the experimental apparatus. In addition, comparisons of cleaning efficiencies for membranes oriented in the vertical and horizontal positions were made.

Significant improvement in flux was achieved using the relatively short Novaflux cycle. Research findings from Novaflux laboratory tests for off-line cleaning indicated that the flux could be improved by 30% in 8 inch membranes using a 10-minute off-line two-phase cleaning cycle. Air capacity and cycle times were evaluated and are discussed in Section 4.2.

We tested about 10 Hydranautics CPA2 elements and achieved good results considering the initial low flux values of these membranes (0.75 - 1.2 gpm). All the elements received were discarded by US Filter because they had failed either the salt rejection rate test or they had failed the pressure drop test. US Filter rejects all elements with rejection rates lower than 95% and all elements end-to-end differential pressure drop higher than 7 psi. US Filter does not measure flux at their facility so we had to measure pre- and post-cleaning flux in our study. Detailed results and cleaning protocol are discussed in the research findings below.

Task 2's investigation was also intended to determine the ability of the technology to clean more than one module at a time. We were able to perform this work using a 2.5 inch RO pressure housing that was part of a 1000 gpd pilot wastewater skid as will be discussed below.

The water treatment system configuration and the CIP apparatus used to study the cleaning of RO elements in series are described in Section 3.2. A single Osmonics RO pressure vessel with two FilmTec TW30-2540 elements in series was modified with a special Novaflux adapter to allow cleaning-in-place, without contaminating the permeate output. This single vessel RO system was part of an integrated pilot plant used to treat a high TSS, high TDS, salt, protein and fat laden dairy waste stream from a dairy plant wash down. The waste water was pretreated using a submerged Kubota FC-25 microfilter (MF) to reduce total suspended solids from >10,000 ppm to <100 ppm. This RO was a single stage with 28% recovery and recirculation to the RO feed tank – see Figure 4. Accordingly, there was rapid increase in the RO feed TDS to over 10,000 ppm on the average. The resulting fouling and scaling caused significant reduction of flux in a matter of hours. This rapid fouling allowed us to study the cleaning of multiple elements in series under controlled fouling conditions.

Task 3: Economic assessment analysis

The data obtained have been used to determine the economic feasibility of the two-phase cleaning, both for in-place or off-line applications. Significant factors included in the analysis were: downtime, flux improvement, capital costs and operating costs. Operating costs include energy costs (including demand charge costs for compressors) and cleaning chemicals – see Section 6.

4.2 Research findings

4.2.1 Research findings on 8-inch RO membrane COP cleaning

Flux data of 8-inch RO membranes prior to and post Novaflux two-phase cleaning are listed in Table 1. The highest final flux is slightly over 3.5 gpm and the lowest is about 2 gpm. This improvement amounts to an average of about 2.0 gpm or 200% increase in product flow from the initial condition. The final protocol for cleaning is as follows:

(i) The first step is an acidic soak at a temperature of 50-55 °C for 10-15 minutes. This process helps to loosen any of the iron and calcium scale present on the membrane. The membrane is then flushed with water to purge the debris that was loosened during the soak and to flush out the acidic solution.

(ii) The second step is a similar soak with an alkaline solution for another 10-15 minutes. After this soak, the membrane is not purged with water; instead it is pulsed with the soaking solution present in the membrane by flowing the solution at pre-set time intervals, purged with water, and

(iii) The third step consists of subjecting the element to 5-10 minutes of high velocity two-phase flow with a low-foaming alkaline solution.

Steps (i) and (ii) are similar to conventional liquid circulation and were used in the protocol to partially remove inorganic scale (i) and decrease the adhesion between the foulant and membrane surface (ii). Step (iii) is the Novaflux two-phase flow cleaning. The application of the above protocol provides optimal cleaning condition where the foulant becomes amenable to effective cleaning with the two-phase flow fluid dynamics.

This process of acidic and alkaline soak, flush with water followed by alkaline two-phase flow is repeated until there is visual evidence that the exhaust liquid is free of debris and discoloration or turbidity due to suspended matter. This cycle of soaking, purging and two-phase cleaning has proved to be the most effective protocol for cleaning the 8-inch spiral elements. The soaking step primes the membrane by wetting it and increasing the temperature of the membrane itself. As a result of this soaking step, the foulants become susceptible to effective cleaning with the two-phase flow process. The latter provides effective shear and impact stresses to detach foulants from the surface of the membrane and at the same time facilitates the mass transfer needed for removing detached foulants from the feeding channels. The test results for the cleaning of 8-inch RO membrane are included in Table 1.

We have dissected 8-inch spiral elements before and after cleaning with the two-phase flow method to examine the nature of fouling and effectiveness of the method. In our examination, we used a disclosing solution that stains biofilm upon exposure – RED-COTE® Dental Disclosing Solution manufactured by John O. Butler Company, Chicago, IL. Our findings were as follows:

(i) Effective two-phase cleaning removes solid matter from membrane surface compared to conventional cleaning methods.

(ii) Biofilm was found to be mostly associated with solid deposits on the membrane, and removing such solids effects the removal of biofilm as well.

In relation to cleaning with two phase flow, we also found the pressure drop between the two ends of the membrane is reduced from $\cong$ 15 psi to less than 7 psi in a 10-minute two-phase flow cleaning cycle. This result was consistent for the membranes listed in Table 1.

Table 1.—Flux improvement on 8-inch RO membrane using Novaflux two-phase cleaning process. The flux design value of the membranes used is 6.9 gpm

RO Filter Serial #	Initial Flux (gpm)	Final Flux (gpm)
197761	0.75	3.2
197686	1.2	1.3
197753	1.2	2.8
197702	~1.0	3.0
196500	~1.0	2.5
197763	~1.0	3.5
197763	~1.0	2.8

* Salt rejection was measured by using potable water having a TDS of about 300. The permeate produced after cleaning had TDS in the range of 7 to 15. We concluded that the two-phase cleaning process does not damage the membrane layer, even with the application of multiple cleaning cycles.

4.2.2 Research findings of RO elements in series – CIP fouling and cleaning study

When microfiltration pre-treated RO influent is used to run the RO stage, as described in Section 3.1, we were able to assess the cleaning of multiple RO elements in series using the two-phase flow process. In this case the foulant remains fresh, i.e., no risk of dehydration or drying. For this purpose, cleaning cycles were developed that resulted in an average of 30-40% increase in flux in under 10 minutes, restoring it to over 80% of the design flux. A typical cleaning cycle includes a two-phase flow cleaning where air (set at 50 psi) is mixed with either acidic or alkaline solution is delivered to RO feeding channels for ten minutes. Detailed RO flux, TDS, pH and temperature data were documented at Kubota permeate, RO feed and RO product daily for about 5 weeks of continuous operation. Results listed in Table 2 present the RO flux data before and after cleaning for four RO fouling conditions. In order to obtain accurate RO performance results, temperature of the RO feed water and the net driving pressure across the RO membrane (indicated by TDS) were taken into account to correct the RO flux values. Typical cleaning results after temperature and pressure correction are given in Table 2. Cleaning for cases 1 to 3 was performed once with two-phase flow using alkaline cleaning solution only; this cleaning was sufficient to bring the RO flux back to above 86% of the manufacturer specifications. However, as inorganic scale builds up on the membrane surface, alkaline cleaning only was not sufficient to remove the foulants. This scenario is clearly indicated in Case 4 where the alkaline cleaning only brought the RO performance back to 66% of new performance flux level, and additional acidic cleaning step following the alkaline cleaning brought the RO back to 88% of new performance flux level. It should be noted that all cleaning for this study was done with the two-phase flow process.

Table 2.—Cleaning results of a 2.5-inch CIP system fouled by a dairy plant washdown

Cleaning Case	RO Flux (lpm) Before	RO Flux (lpm) After	Cleaning Solution	Mfr specs (lpm)	Performance Recovery
1	2.54	3.19	Alkaline	3.47	92%
2	2.95	2.97	Alkaline	3.47	86%
3	3.38	3.50	Alkaline	3.47	100%
4	1.39	2.18 3.07	Alkaline Acid	3.47 3.47	63% 88%

4.2.3 Research findings on system design and dynamics requirements

1. Dynamics requirement for 8-inch RO element COP cleaning: Air requirements expressed in SCFM (standard cubic feet per minute) at various set pressures to clean 8-inch RO elements are given in Table 3. These results have been used to estimate the dynamics requirements for cleaning smaller RO spiral elements.

Table 3.—Air requirements for cleaning an 8-inch RO system

Case	Set Pressure* (psi)	Run Pressure** (psi)	SCFM	Air Velocity (ft/s)		Liquid Rate (gpm)	Air/Liquid	
				In	Out		In	Out
1	20	7	394	32.0	47.0	0.052	37900	55690
2	25	10	448	32.0	53.4	0.052	37950	63300
3	30	12	496	32.2	59.0	0.052	38900	70100
4	40	20	510	26.3	60.0	0.3	5358	12450
5	55	26	627	27.3	74.6	0.3	3950	14460

*Set Pressure is the pressure set at the regulator located at the outlet of gas storage receiver.
**Run Pressure is the actual pressure measured at the inlet of the RO housing during cleaning. The "Out" condition is at 0 psig. The free cross sectional area for flow for the elements tested was approximately 45%.

During the course of 8" RO element cleaning, air was supplied by six 240-gallon air receivers that are fed by a 50 HP compressor at a pressure up to 120 psi. Experiments were designed to estimate the consumption of air for various cleaning conditions. With the regulator set at pressures ranging from 20 psi to 55 psi, total air used during different experimental conditions were estimated by calculating the pressure drop inside the receivers and converting to SCFM. The above numbers may be used as rough guidelines for cleaning RO elements with typical fouling levels.

For performing two-phase flow cleaning, two conditions based on the gas to liquid ratio were identified as follows:

i) High gas to liquid ratio two-phase condition: In the first three measurements (Table 3), the air pressures before entering the RO housing were set at 20, 25 and 30 psi, respectively and the liquid mixed with the air was set at 0.2 LPM (0.052 GPM). The measurements indicate that when the gas/liquid ratios are high, about 3700 or higher, the SCFM is in the range of 400's. The inlet velocities for these three cases remained at about 32.0 ft/sec while the outlet velocities varied from 47.0 ft/sec to 59.0 ft/sec.

ii) Low gas to liquid ratio two-phase condition: In the last two experiments (Table 3), the air pressures before entering the RO element were set at 40 and 55 psi and the cleaning solution was set at 0.3 GPM. The measured air consumption rates were 510 and 627 SCFM, respectively. With the higher liquid rate applied, the air and liquid ratio is about 4000 for the inlet condition and 14000 for the outlet condition.

It can also be noticed from Table 3 that the inlet velocities for the low gas to liquid ratio (cases 4 and 5) were less than the first three cases (cases 1, 2 and 3) which are categorized as high gas to liquid ratio. An explanation of this is that higher liquid rate will usually slow down the air velocity in the initial part of the channels. However, when the air expands along the passage of the RO element, the velocity gradually increases to 60.0 ft/sec and 74.6 ft/sec for cases 4 and 5, respectively. The pressure drop measured from the inlet to the outlet of the RO element is about 25 psi (indicated by the run pressure in Table 3) in these two cases. These values are well within the range recommended by RO manufacturers. The optimal cleaning condition is when the two-phase flow at the inlet section of the membrane is at least 30 ft/sec or above and when the gas to liquid ratio is between 1000:1 to 3000:1.

2. Dynamics requirements for 2.5-inch and 4-inch RO element CIP cleaning: When dealing with smaller RO elements (less than 8-inch), we found that set air pressure of about 50 psi is generally sufficient to clean the RO elements fouled with the high TDS, high protein, high organic level influent. Since there were no actual measurements performed for the smaller sizes of RO elements in terms of air consumption, air/liquid ratio and pressure setting, the above 8" RO element results were used to estimate the dynamics requirements for cleaning smaller RO elements. It is assumed that the small RO elements have 40% of the efficient cross section area for water or two-phase flow to pass through as assumed in the 8" RO element. Table 4 summarizes the air requirements for 2.5" and 4" RO elements at set pressures 40 and 55 psi.

Table 4.—Air requirements for cleaning a 4-inch or 2.5-inch RO system

RO Element	Set Pressure (psi)	SCFM	Liquid Rate (gpm)	Air/Liquid In*	Air/Liquid Out
2.5"	40	49.8	0.031	4000	12000
	55	61.2	0.038	4000	12000
4.0"	40	127.5	0.065	5600	14400
	55	156.8	0.080	5600	14400

* depending on run pressure

It is evident that the air required for cleaning RO elements up to 4” with the two-phase flow process may not exceed 200 SCFM. A conventional compressor with 50 HP can generate about 220 SCFM with a maximum pressure set at 80 psi. Our in-house 50 HP compressor does not have any restriction to clean the RO elements up to 4”. A 76 HP compressor can generate about 250 SCFM and can be considered when cleaning multi RO elements in series. Table 5 can be used as a reference for compressor selection to perform the two-phase flow cleaning:

Table 5.—References for compressor selection

HP	SCFM	Maximum Pressure (psi)	Make/Model
6	11.9	90	Craftsman/919.167310
50	220	80	Hydrovane/218K08-108
76	250	100	Cummins/B3.9-C
110	375	100	Cummins/B3.9-C
174	600	100	Cummins/B5.9-C

5. Conclusions and Recommendations

5.1 Conclusions

Research findings from Novaflux laboratory tests for off-line cleaning indicated flux could be improved by 30% in 8” membranes using a 10-minute off-line two-phase cleaning cycle. Significant flux and ΔP improvement was achieved using the relatively short Novaflux cleaning cycle during the study supported by the Bureau of Reclamation. Additional research results from a small test-scale 1000 gpd RO wastewater skid operating at the dairy packaging plant indicated that fouled RO membranes reduced to 50% of normal/clean flux could be restored and maintained at 80% of design specification for an operating period of three months with only 4 liters of dilute cleaning solution consumed in a 5-10 minute cleaning cycle. During the latter study, a special cleaning adapter was developed to separate permeate stream from the rest of the system during the cleaning step. For the CIP case, the cleaning will be performed once or twice per day or even less frequently depending on flux decline rates. In the case of COP, the frequency of cleaning will be determined by the fouling conditions of the elements.

Based on the results and analysis of the off-line cleaning study, only larger facilities with large captive use (> 1000 elements) would find the on-site off-line cleaning economically viable due to the capital cost of the COP system. However, an off-site, off line unit serving multiple sites would be very viable.

The cleaning technology was successfully demonstrated in cleaning 4-inch (or smaller) CIP system. The latter process can be designed to clean multiple pressure vessels with RO elements in series.

5.2 Recommendations

Additional study is recommended to evaluate the relative economics of various cleaning configurations and cleaning frequencies to determine if lower capital costs and operating costs are possible. The work on the viability of CIP indicates that retrofitting existing RO systems with multiple elements in series is not yet indicated. Based on our experiments, we have been successful in effectively cleaning two spiral elements arranged in series; however, further research is required to determine if there are limitations in using the two-phase flow process for a larger number of elements arranged in series.

Integrating the two-phase membrane cleaning to suitable water treatment technology is now at a pilot plant stage with a need for further process development with the goal of finalizing a practical system design with defined operating parameters. Modification and scale-up of a membrane treatment plant to at least 4000 gpd pilot scale and demonstration of effective and efficient restoration of RO membrane performance, in a short time with minimal consumption of chemicals and water, using the two-phase flow process are under evaluation at Novaflux. The scale-up pilot plant will include an RO pretreatment component based on MF/MBR or UF/MBR as a requirement for an integrated water treatment system. This configuration has been already tested for a short time during our studies to treat high TDS and high organic load water source at a dairy packaging facility in New Jersey. This will enable us to significantly improve the operating performance and affordability of water purification/desalting technologies translating to increase the US water supply in diverse areas of application including both industrial and brackish water sources.

6. Analysis of Results and Commercial Viability of Project

6.1 Potential for broad-based economic benefits of the Novaflux two-phase flow technology – Overall analysis of the technology

Fouling is a problem that occurs in every membrane filtration application. The vast economic impact resulting from fouling is easy to understand. It is not some minor effect operating on the margin, but has a significant impact on plant performance, often at the 30% level. In particular, it requires that plants must be designed much bigger than they would be otherwise in order to achieve the required output. Larger plants require more resources in every capital category. In addition, operating costs are much higher than they otherwise would be because of increased size. Typical operating costs include:
i) Energy requirement to provide the volume of air needed for two-phase flow cleaning.
ii) Cleaning chemicals
iii) Replacement parts - membrane replacement costs are higher not only because the original plant was bigger, but because both high energy operation and frequent cleaning with aggressive chemicals shortens membrane life
iv) Labor.

These economic penalties not only increase the life cycle costs of membrane-based separation technologies, but impede the diffusion of the technology into application areas that now rely on more traditional processes such as evaporation, centrifugation or dead-end filtration.

This program concerns the commercialization of a technique for cleaning spiral wound and hollow fiber membrane elements, since these constitute the largest share of installed capacity and of current sales. More specifically, spiral wound membranes represent the bulk of current sales in the critical membrane application of water treatment, an area where biofouling is a major issue. These applications are primarily in reverse osmosis and nanofiltration.

Fouling is also a major issue in ultrafiltration and microfiltration applications. These processes are sometimes used to pretreat process streams prior to injection into reverse osmosis and nanofiltration. When so employed, their major role is to reduce fouling in the downstream membranes. Naturally, this membrane pretreatment is very expensive, comparable to the cost of the process it protects, but the overall economics may be better with pretreatment. Ultrafiltration and microfiltration have large and diverse applications outside the prefiltration field. There are huge applications in the dairy, food, automotive, pharmaceutical, textile, and laundry industry to cite a few. All of these applications are affected by fouling, and frequently by biofouling.

Fouling affects every membrane in use in a filtration system, but how big a problem is it on a national scale?
One estimate of the overall world filtration market made in 1995 was about $75 billion in annual sales, and that membranes and related equipment accounted for about $2 billion in sales [1]. Others, using more recent data, suggest that market sales for membrane filtration systems are about $5 billion. Sources estimate substantial annual growth rates for membrane filters, ranging from about 8% to as high as 15% [4,15].

The worldwide distribution of membrane filtration systems by application is shown in Table 6 based on data collected in the mid-1990s. Kidney dialysis is the dominant application, so medical devices is the dominant industry group, followed by water and wastewater treatment, which accounted for about 30% of the total [4,15]. North American sales of membrane products was a little less than half of the worldwide demand [6].

Table 6.—Major applications and markets for membrane processes

	Water and Wastewater*	Food Industry*	Medical Devices*	Chemical and Pharmaceutical*	Total*
Microfiltration	310	95	20	35	460
Ultrafiltration	60	44	130	15	249
Reverse Osmosis	120	15	-	10	145
Electrodialysis	60	15	-	20	95
Dialysis	-	-	900	-	900
Gas Separation	-	-	-	45	45
Pervaporation	-	-	-	5	5
Total:	550	169	1050	130	1899

* Sales are in million US$ per annum

Once a system has been installed, the operator faces operating costs. These include electricity, replacement membranes, membrane cleaning chemicals, and labor. There is a wide variation in the relation between annual operating costs, with estimates or reports ranging from 10% to 50%, with the variation depending on the specifics of the application [3,13,16]. Replacement membrane costs and electricity are almost always identified as the most significant operating costs.

The annual cost of membrane replacement is believed to be typically about 40% of the installation cost [4,5,11], which suggests worldwide membrane sales of about $800 million in 1995, with about $400 million of that in North America. This further suggests a market for replacement filters in the mid-1990s of about $160 million for North America. At an annual growth rate of about 10%, the current sales of membranes would be around $250 million.

This is a low estimate, compared with some observers, who estimate more than $1 billion in membrane sales in the US currently [4]. Part of the explanation for these differences is that observers frequently do not distinguish membranes from membrane filtration systems [14].

A New Market: Membrane Cleaning Equipment and Services

The Novaflux process will allow membrane lifetime to be doubled since the cumulative exposure to chemicals, such as chlorine bleach, will be drastically reduced. This estimate is accurate if the chlorine-minute argument used in the dairy industry is used to estimate membrane lifetime. Since membrane cost accounts for 36% of the entire process cost, we estimate that there will be savings to filtration system operators reaching more than $100 million per year, even into the low multiple hundreds of millions, when the membrane filtration market has been well penetrated. Those savings are due only to cost reductions that flow from the reduction in membrane replacements.

Possibly even more important is the saving that results from the ability of operators to clean filters rapidly, so that production down-time is minimized. The Novaflux process, with proper optimization, could achieve flux levels of 80 to 90%, compared to the industry norm of 30 to 50%. This scenario is possible for large-scale operations such as potable water production, wastewater treatment and whey processing. To illustrate this point for an application in biotechnology, cost analysis was performed according to models developed by Davis *et al.* [7,17] at the University of Colorado. They estimate, based on these models and on industry knowledge, that the annualized cost of using the current microfiltration membrane process is $488 per square meter per year. This cost is comprised of the following components: 41% capital, 36% membranes, 8% labor, 5% cleaning chemicals, 6% power and 4% maintenance. According to this analysis, if the Novaflux process is successfully applied to this application, the annualized process cost will be reduced to 17% of the baseline value. Table 7 summarizes this cost analysis. It is clear that the potential for the process is excellent, especially with respect to reduction of capital and membrane cost.

Reduction in production time due to shutdown periods for membrane cleaning operations can be tangible indeed. In corn wet milling membrane operations, 4 hours per day is spent on membrane cleaning which translates to 16.6% loss in productivity [12]. If the Novaflux process can decrease this cleaning time by only 1 hour, production can increase by over 12%, and in such large-scale operations this is a considerable improvement.

In addition to the benefits cited above, the Novaflux process offers two major environmental and economic benefits: significant reduction in the volume of cleaning chemical waste streams and the tonnage of fouled membranes. Disposal cost services charge about $10/gallon and the fouled membranes have to be incinerated at a significant cost. According to the cost analysis performed by Davis *et al.* [7,17], the Novaflux process should reduce the generated waste stream in membrane cleaning by 95%, thus translating to major economic benefits.

The process can also reduce or possibly eliminate the quantity of chlorine bleach, as is used in dairy and water treatment membrane cleaning, that can enter the environment resulting in the production of carcinogenic halogenated organics. The value of this advantage cannot be simply estimated without getting into environmental risk assessment and impact of this on the general economy.

Table 7.—Annualized costs of membrane microfiltration of a bacterial suspension with different cleaning strategies

Item	Basis ($/m^2-yr)	Conventional Cleaning*	Novaflux Cleaning**
Capital	200	$35,000	$ 6,000
Membranes	175	$30,600	$ 5,200
Chemicals	25	$ 4,400	$ 800
Power	28	$ 4,900	$ 800
Labor	40	$ 7,000	$ 1,200
Maintenance	20	$ 3,500	$ 600
Total	488	$85,400	$14,600

* The conventional cleaning system used for the basis of the referenced cost analysis was a pumped liquid flushing system for cleaning-in-place using standard membrane cleaning chemicals; ** The Novaflux cleaning system was based on using air flow to replace 90-95% of water, 80% of chemicals, a 1 hour (25%) reduction of downtime and 6 fold increase in membrane life.

In summary, these examples illustrate that there are many opportunities, each of which is in the $100 million range, to save monies now expended to operate various types of process plants and benefit the environment. These benefits are only the first level of savings given the potential for price reductions in foods, chemical products, and items such as industrial feed stocks.

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