United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-167
September 1978

Research and Development

EPA

Wastewater Demineralization by Tubular Reverse Osmosis Process

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EPA-600/2-78-167
September 1978

WASTEWATER DEMINERALIZATION BY TUBULAR REVERSE OSMOSIS PROCESS

by

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Contract No. 14-12-150

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MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
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DISCLAIMER

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the hazardous water pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

One of the goals of wastewater treatment is renovation of wastewater so that it can be reused. It is expected that partial demineralization of conventionally treated wastewater will be required if the wastewater is reused for any purpose which requires high quality water. Among the techniques for demineralization that which is newest but shows the most potential is reverse osmosis. In this process water is forced through a membrane which can reject salts. The permeability of these membranes is low so high pressure is required to achieve an economical production rate. Special configuration of the membrane and its support system are required to withstand the high pressure and maintain a high ratio of membrane surface to system volume. In the studies reported in here a reverse osmosis system using tubular support configuration was tested for its efficacy in demineralization of secondary effluent. This type of configuration is best when water containing suspended solids is being treated as the large passages resist clogging.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

ABSTRACT

A 16 lpm (4.2 gpm) tubular reverse osmosis pilot plant, manufactured by the Universal Water Corporation, Del Mar, California, was operated at Pomona Advanced Wastewater Treatment Research Facility for a total of 10,940 hours. The purpose of the study was to investigate the applicability of the tubular reverse osmosis process to wastewater demineralization.

The study was basically divided into three different phases. The first phase, which covered a period of 1,700 hours of operation, was considered a start-up period. The optimum pilot plant operating conditions and the necessary plant modifications were developed and accomplished during the initial operation period. In the second phase, the pilot plant operational goal was the study of the membrane life. The feed was carbon-treated secondary effluent. This study lasted 7,165 hours until the operating membrane modules reduced from the original 32 modules to 12 modules as a result of membrane module failure. It was subsequently decided to make use of the remaining 12 modules in the system for exploring the behavior of the membrane process in treating primary effluent. The system treated primary effluent during the third phase for a period of 2,074 hours.

The experimental results of the first study period have already been reported in the EPA WATER POLLUTION CONTROL RESEARCH SERIES(1). Therefore, this report only summarizes the experimental data obtained in the last two phases of studies. The results clearly indicate that the Universal Water Corporation's tubular reverse osmosis system is not practical for wastewater demineralization.

This report was submitted by County Sanitation Districts of Los Angeles County in fulfillment of Contract No. 14-12-150 under the partial sponsorship of the Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. Work was completed in January, 1971.

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ACKNOWLEDGEMENTS

This study was jointly sponsored by the U. S. Environmental Protection Agency and the County Sanitation Districts of Los Angeles County.

Mr. James Gratteau and Mr. Harold H. Takenaka, former project engineers at Pomona Advanced Wastewater Treatment Research Facility, were instrumental in initiating the pilot plant study.

The efforts of the laboratory and the pilot plant operating personnel of the Pomona Advanced Wastewater Treatment Research Facility are also gratefully acknowledged.

SECTION 1

INTRODUCTION

The operation of the 16 lpm (4.2 gpm) tubular reverse osmosis pilot plant, manufactured by the Universal Water Corporation, Del Mar, California, was initially started on December 23, 1968. During the initial 1,000 hours of experimental run, the pilot plant system was operated at a low water recovery, approximately 40 percent, to test the operating conditions of the physical components of the system - pumps, pH controller, modules, flow metering system, and sampling system - along with monitoring the performance of the membranes while operating on carbon-treated secondary effluent. The water recovery was set at a low value so that the problems of feed water concentration and insufficient brine velocities could be minimized.

After the first 1,000 hours of operation, the piping of the system was modified to accommodate operations at a higher water recovery of 75 percent. The arrangement of the eight rows of modules (4 modules per row, connected in series) was also revised from the original 5-3 array to a 3-2-2-1 array to maintain sufficient brine velocities throughout the system. However, during the initial period of this intended long-term process study, some serious mechanical and operational problems were encountered, and some membrane modules were found seriously damaged. Consequently, the study had to be temporarily suspended after the first 700 hours of operations. The mechanical design of the entire system was thoroughly reviewed by the Universal Water Corporation and the Los Angeles County Sanitation Districts' engineers, and some necessary modifications were made on the system to prevent the recurrence of the mechanical problems. All the damaged membrane modules were replaced with new membrane modules, and the module arrangement in the system was further revised to the final 3-2-1-1-1 array, as shown in Figure 1.

On November 5, 1969, the pilot plant operation of the 16 lpm (4.2 gpm) Universal Water Corporation tubular reverse osmosis system was put on stream again. The objective of this study was to establish membrane life. Information obtained from previous experimental runs was used to establish operating condition (1). A daily tap water flush and a weekly enzyme-detergent cleaning cycle were used to maintain product water flux rate. During the first part of this experimental run treating carbon-treated secondary effluent, modules which became damaged were replaced with the end modules in the system as time progressed. Operation in this manner was continued to determine whether the frequency of module failure could be intensified or not.

Because of an increasing frequency of module failure, the decision was made to suspend permanently the pilot plant operation after treating carbon-treated secondary effluent for a total of 7,165 hours. On October 15, 1970, an experimental run with the remaining 12 operating modules in the tubular reverse osmosis system was commenced to treat the primary effluent. This was done with a sole purpose of determining the behavior of the tubular membranes in treating the primary effluent, which lasted a period of 2,074 hours of on-stream operation.

This report summarizes the 7,165 hours of operations of the tubular reverse osmosis pilot plant on the carbon-treated secondary effluent and the last phase of operation on the primary effluent.

SECTION 2

CONCLUSIONS

Based on the experimental results of this pilot plant study, the following conclusions are made:

A. The tubular membrane modules manufactured by the Universal Water Corporation were very susceptible to membrane collapse, and they had to be handled carefully. The system should be designed and operated in a manner which would avoid a siphon situation, which could result in membrane collapse.

B. For treating the carbon-treated secondary effluent, the weekly enzyme-detergent cleaning cycle and the daily tap water flushing seemed to be successful in controlling the product water flux rate decline. However, it was necessary to increase the enzyme-detergent cleaning frequency from once a week to three times a week when treating the primary effluent.

C. The pilot plant system was able to achieve a 95 percent salt rejection initially for treating either a carbon-treated secondary effluent or a primary effluent.

D. There was less flux decline between membrane cleanings when operating at a brine velocity of 1.4 mps (4.5 fps) rather than at 0.64 mps (2.1 fps).

E. The product water flux rate was reduced about 30 percent after almost one year of on-stream operation with carbon-treated secondary effluent.

F. Because of the serious problems associated with the frequent membrane module failure, it is impractical to apply the Universal Water Corporation's tubular reverse osmosis system to wastewater demineralization. The physical configuration of the module and the entire system design have to be completely revised to avoid any mechanical failure in the membrane modules.

SECTION 3

RECOMMENDATIONS

Since the frequency of the membrane module failure in the Universal Water Corporation's tubular reverse osmosis system is so high, the application of this system to the demineralization of the wastewater, particularly the carbon-treated secondary effluent, is certainly not practical. However, some encouraging results regarding the demineralization of the primary effluent by this system have been revealed by this rather short-term study.

It is recommended that additional efforts be pursued to treat the primary effluent directly with the tubular reverse osmosis system. However, the new pilot plant system should incorporate the following features to assure satisfactory performance.

A. Adjust the pH of the cleaning solution to the neutral range between 7.0 and 7.5, and the pH of the feedwater to 6.0. This pH adjustment would not only prevent hydrolysis of membranes but prevent extensive deterioration of the nylon cloth membrane backing material.

B. Employ a daily cleaning cycle to maintain a constant higher product water flux level.

C. Recycle brine to obtain higher water recovery.

D. Design the entire system properly to prevent the mechanical failure which may in turn cause membrane collapse.

The main objectives of the new study should be two-fold:

A. To determine the feasibility of the demineralization of the primary effluent with a tubular reverse osmosis process; and

B. To obtain a reliable and realistic process cost estimate on a long-term operation basis.

SECTION 4

PILOT PLANT DESCRIPTION

The tubular reverse osmosis pilot plant consisted of thirty-two tubular modules, 122 cm (48 in) long by 10.2 cm (4 in) in diameter. Eighteen 1.3 cm (0.5 in) diameter plastic perforated tubes were connected in series and placed within a 10.2 cm (4 in) diameter PVC pipe to form a single module that contained approximately 0.65 sq m (7 sq ft) of preformed membrane for a total of 20.8 sq m (224 sq ft) of membrane area available in the entire system.

Figure 1 shows a schematic flow diagram of the tubular reverse osmosis pilot plant. The carbon-treated secondary effluent was chlorinated to provide 1 to 2 mg/l of total residual chlorine and acidified to a pH close to 5 using H_2SO_4 before it was fed into the system. The system was arranged in a 3-2-1-1-1 array to maintain sufficient brine velocities in the downstream modules. The necessary provisions for a daily tap water flush, a weekly enzyme-detergent cleaning cycle, and a chlorinated tap water flush during the downtimes were made. The modifications and changes made to the piping and valving of the original pilot plant system are shown in Figure 2. Two check valves were installed to prevent a siphon from developing, which could result in reduced pressure within the module and cause possible membrane collapse. One check valve was installed at the inlet of the unit to prevent backflow during any unscheduled shutdown. The other check valve was installed in a tee connection off the final brine line. When normal flow conditions existed, this valve remained closed. Should pressure in the brine line decrease as a result of backflow through the system (pipe failure, open valve, etc.), this check valve would open and allow air to enter the system to avoid a positive external pressure. This check valve would be weight loaded to open to the atmosphere, should the pressure within the system drop below 0.69 Kg/sq cm (10 psi). The other valves shown in Figure 2 were used during tap water flushings and enzyme-detergent cleaning cycles. A spring-loaded back pressure regulator was installed in the bypass line to correct the problem of pressure variations during the operation.

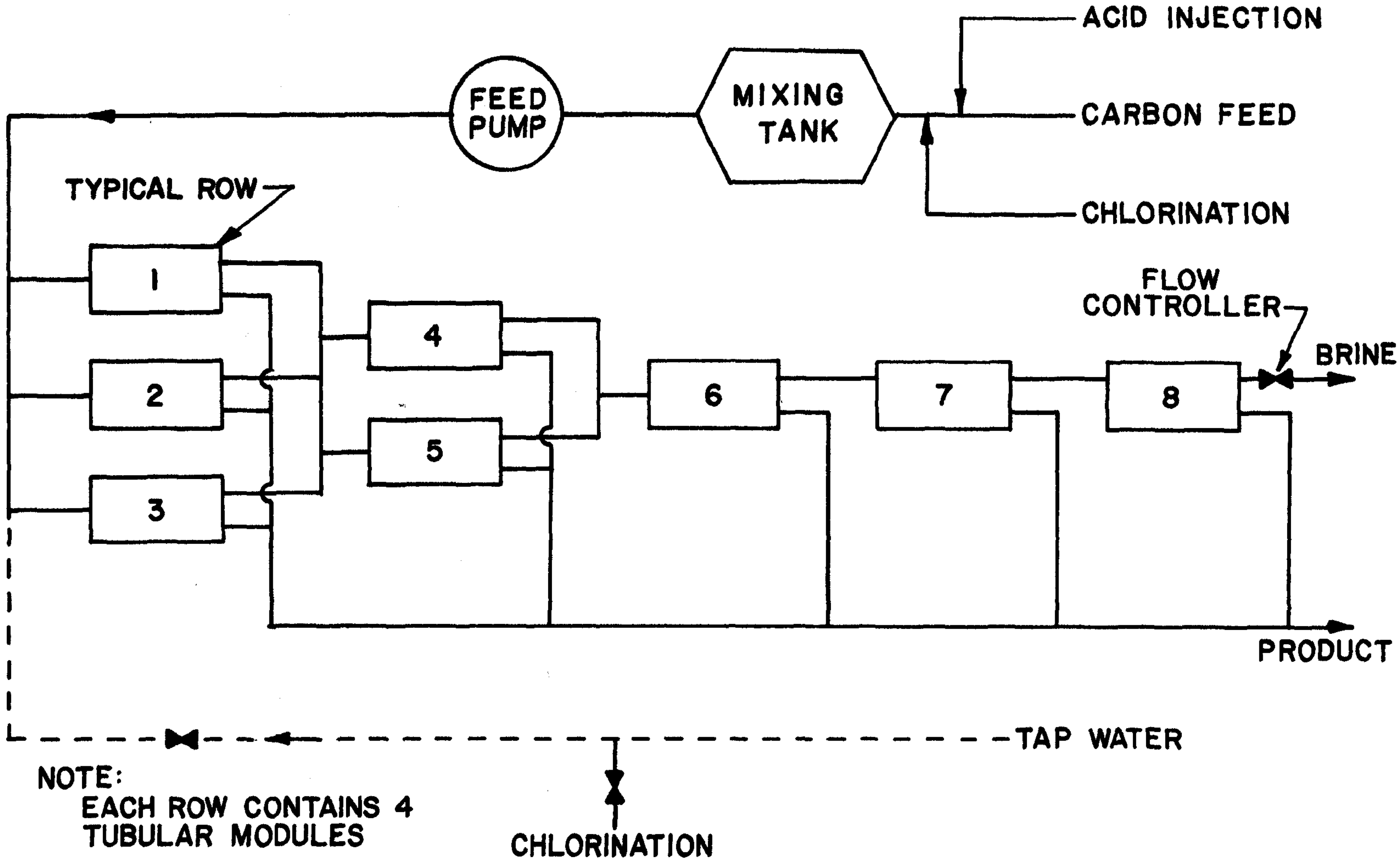


Figure 1. Schematic flow diagram of the reverse osmosis pilot plant.

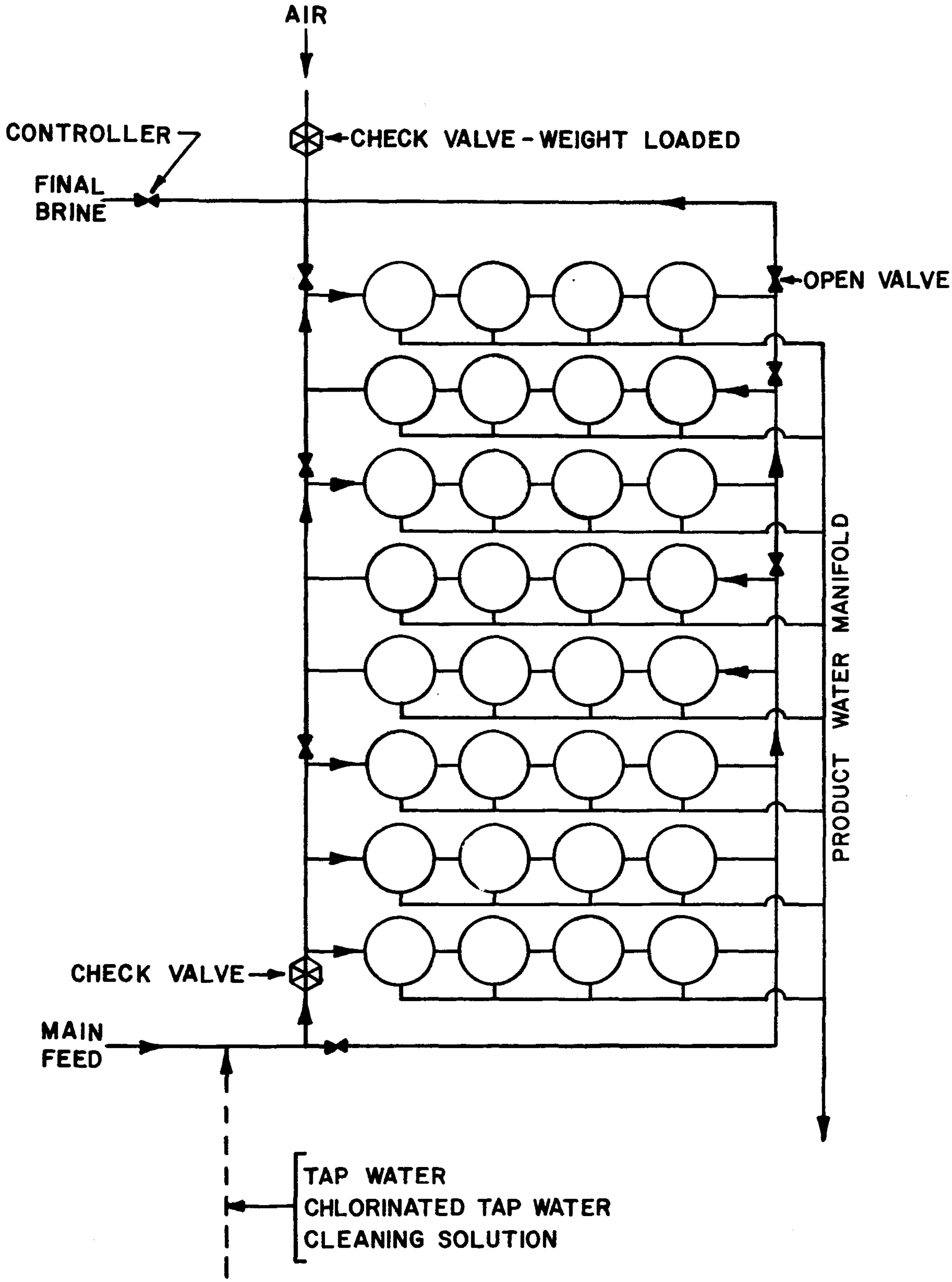


Figure 2. Layout of Universal Water Corporation reverse osmosis pilot plant.

SECTION 5

PILOT PLANT OPERATIONS

DEMINERALIZATION OF CARBON-TREATED SECONDARY EFFLUENT

The pilot plant initially was operated with a carbon-treated secondary effluent as the feed water. The operating conditions and membrane cleaning procedures employed for this study are described in the following sections.

Operating Conditions

A summary of the initial operation conditions is shown below:

A.	Feed Pressure	:41.4 Kg/sq cm (600 psi)
B.	Feed pH	:Maintained at 5 using sulfuric acid
C.	Total Residual Chlorine in Feed Water	:Maintained at 1 to 2 mg/l
D.	Feed Flow	:16 lpm (4.2 gpm)
E.	Product Flow	:12 lpm (3.2 gpm)
F.	Brine Flow	:4 lpm (1.0 gpm)
G.	Membrane Product Flux Rate (at 25° C)	:834 l/sq m/day (20.5 g/sq ft/day)
H.	Water Recovery	:76 Percent

Among the above operating conditions, the feed pressure and the brine flow rate were the major controlling parameters for the pilot plant operation.

Membrane Cleaning Procedures

A daily tap water flushing and a weekly enzyme-detergent cleaning cycle were conducted to maintain the product water flux rate. The procedures for the various cleaning steps are described as follows:

A. Daily Tap Water Flushing

The pilot plant membrane module system was flushed as a whole with tap water for 15 minutes once a day. This tap water flushing was the sole cleaning process for the membrane module system on the non-chemical cleaning days, while on chemical cleaning days it served as a rinsing process after the chemical cleaning cycle.

B. Weekly Enzyme-Detergent Cleaning

The enzyme-detergent cleaning solution was made up by adding 1.42 kilograms (50 ounces) of a commercial enzyme-detergent, Biz, into 189 liters (50 gallons) of tap water.

The main feed pump was used to fill the module system with the cleaning solution. The modules which were not being flushed remained soaking in the cleaning solution while others were being flushed in the following sequence:

1. Row 1 to 3, as indicated in Figure 1, were flushed for 15 minutes at a feed pressure of 3.5 kg/sq cm (50 psi).
2. Rows 4 and 5 were flushed for 15 minutes at a feed pressure of 3.5 kg/sq cm (50 psi).
3. Rows 6 to 8 were flushed for 15 minutes at a feed pressure of 3.5 kg/sq cm (50 psi).

During the enzyme-detergent cleaning cycle, the cleaning solution was recycled for the specified time in the first three rows and then the same cleaning solution was applied to the next rows until the sequence was completed. After each enzyme-detergent flushing, a 15-minute tap water flushing was also conducted.

C. Occasional Acid Flushing

Whenever a malfunction in the pH control occurred during an unattended period, the module system was flushed with an acidified feed to remove the chemical precipitates to recover the product water flux rate. The acid flushing process consisted of depressurizing the pilot plant system and flushing with an acidified feed, pH between 2 and 3, for 30 minutes. If necessary, the enzyme-detergent and tap water flushing could be employed to provide additional cleaning of the membrane surface.

DEMINERALIZATION OF PRIMARY EFFLUENT

The pilot plant operation for the demineralization of carbon-treated secondary effluent was switched to the demineralization of primary effluent after a total period of 7,165 hours of on-stream operation. The total number of membrane modules had been reduced from the initial 32 modules to 12 modules at the outset of the primary effluent demineralization study. The arrangement of the membrane modules was changed from the 3-2-2-1 array to 3 in parallel array to accommodate the remaining 12 modules (4 modules per row) for the study of membrane behavior on the primary effluent. The operating conditions and the membrane cleaning procedures were also properly modified as follows:

Operating Conditions

A summary of the initial operating conditions is shown below:

A.	Feed Pressure	: 41.4 Kg/sq cm (600 psi)
B.	Feed pH	: Maintained at 5 using sulfuric acid
C.	Total Residual Chlorine in Feed Water	: Maintained at 1 to 2 mg/l.
D.	Feed Flow	: 11.0 lpm (2.9 gpm).
E.	Product Flow	: 3.1 lpm (0.8 gpm)
F.	Brine Flow	: 7.9 lpm (2.1 gpm)
G.	Membrane Product Flux Rate (at 25^{o} C)	: 570 l/sq m/day (14 g/sq ft/day)
H.	Water Recovery	: 28 percent

No pretreatment other than acidification and chlorination was performed on the primary effluent before being fed into the reverse osmosis pilot plant system.

Membrane Cleaning Procedures

A daily tap water flush and a three-times-a-week enzyme-detergent cleaning cycle were conducted to maintain the product water flux rate. The enzyme-detergent cleaning cycle was performed on Monday, Wednesday, and Friday. The procedures for the various cleaning steps are described as follows:

A. Daily Tap Water Flushing

The pilot plant membrane module system was flushed as a whole with tap water for 15 minutes once a day. This tap water flushing was the sole cleaning process for the membrane module system on the non-chemical cleaning days, while on chemical cleaning days it served as a rinsing process after the chemical cleaning cycle.

B. Three-Times-A-Week Enzyme-Detergent Cleaning

The enzyme-detergent cleaning solution was prepared in the same manner as the one for the demineralization of carbon-treated secondary effluent.

The main feed pump was used to fill the module system with the cleaning solution while others were being flushed in the following sequence:

1. Row 1 was flushed for 15 minutes at a feed pressure of 3.5 Kg/sq cm (50 psi).

2. Row 2 was flushed for 15 minutes at a feed pressure of 3.5 Kg/sq cm (50 psi).

3. Row 3 was flushed for 15 minutes at a feed pressure of 3.5 Kg/sq cm (50 psi).

During the enzyme-detergent cleaning cycle, the cleaning solution was recycled for the specified time in the first row and then the same cleaning solution was applied to the next rows until the sequence was completed. After each enzyme-detergent flushing, a 15-minute tap water flushing was also conducted.

C. Occasional Acid Flushing

Whenever a malfunction in the pH control occurred during an unattended period, the module system was flushed with an acidified feed to remove the chemical precipitates to recover the product water flux rate. The acid flushing process consisted of depressurizing the pilot plant system and flushing with an acidified feed, pH between 2 and 3, for 30 minutes. If necessary, the enzyme-detergent and tap water flushing could be employed to provide additional cleaning of the membrane surface.

SECTION 6

RESULTS AND DISCUSSIONS

SYSTEM PERFORMANCE

Operation with Carbon-Treated Secondary Effluent

The system performance for the first 800 hours of operation with the carbon-treated secondary effluent is summarized in Figure 3. As indicated in Figure 3, the product water flux rate during this period between 180 and 640 hours of on-stream operation first recovered and then dropped off after each enzyme-detergent flush. This time period also coincided with the upset of the secondary treatment plant. A large dose of hexavalent chromium entered the plant and caused considerable damage to the microbial population of the plant. As a result, the quality of the secondary effluent deteriorated and this caused a corresponding deterioration of the carbon effluent, which was in turn fed to the reverse osmosis pilot plant. Apparently, the daily tap water flush and the weekly enzyme-detergent cleaning cycles were not able to cope with the fouling conditions on the schedule employed.

At about 635 hours of operation, the system was temporarily shut down and flushed with chlorinated tap water for 24 hours while the pump packing was replaced. When the system resumed operation, the product water flux rate was found to increase from 537 l/sq m/day (13.2 g/sq ft/day) to 692 l/sq m/day (17.0 g/sq ft/day). This increase in flux was clearly attributed to the 24-hour chlorinated tap water flush. Subsequently, the flux stayed relatively constant. During this latter period, the activated sludge plant functioned satisfactorily.

It was concluded that, except for the period of treatment plant upset, the daily tap water flush and the weekly enzyme-detergent cleaning cycle were successful in maintaining the product water flux rate. In order to maintain product water flux rate during periods of treatment plant upset, the frequency of the enzyme-detergent flush should be increased.

Figure 4 summarizes the entire series of operation with the carbon-treated secondary effluent. Initially the product water flux rate decreased from 851 l/sq m/day (20.9 g/sq ft/day) to 651 l/sq m/day (16 g/sq ft/day) at 300 hours of operation. Between 300 hours and 5,800 hours, the product water flux rate remained essentially constant at 651 l/sq m/day (16 g/sq ft/day). At 5,800 hours, the product water flux rate increased to 733 l/sq m/day (18 g/sq ft/day). This increase was attributed to some small leaks which

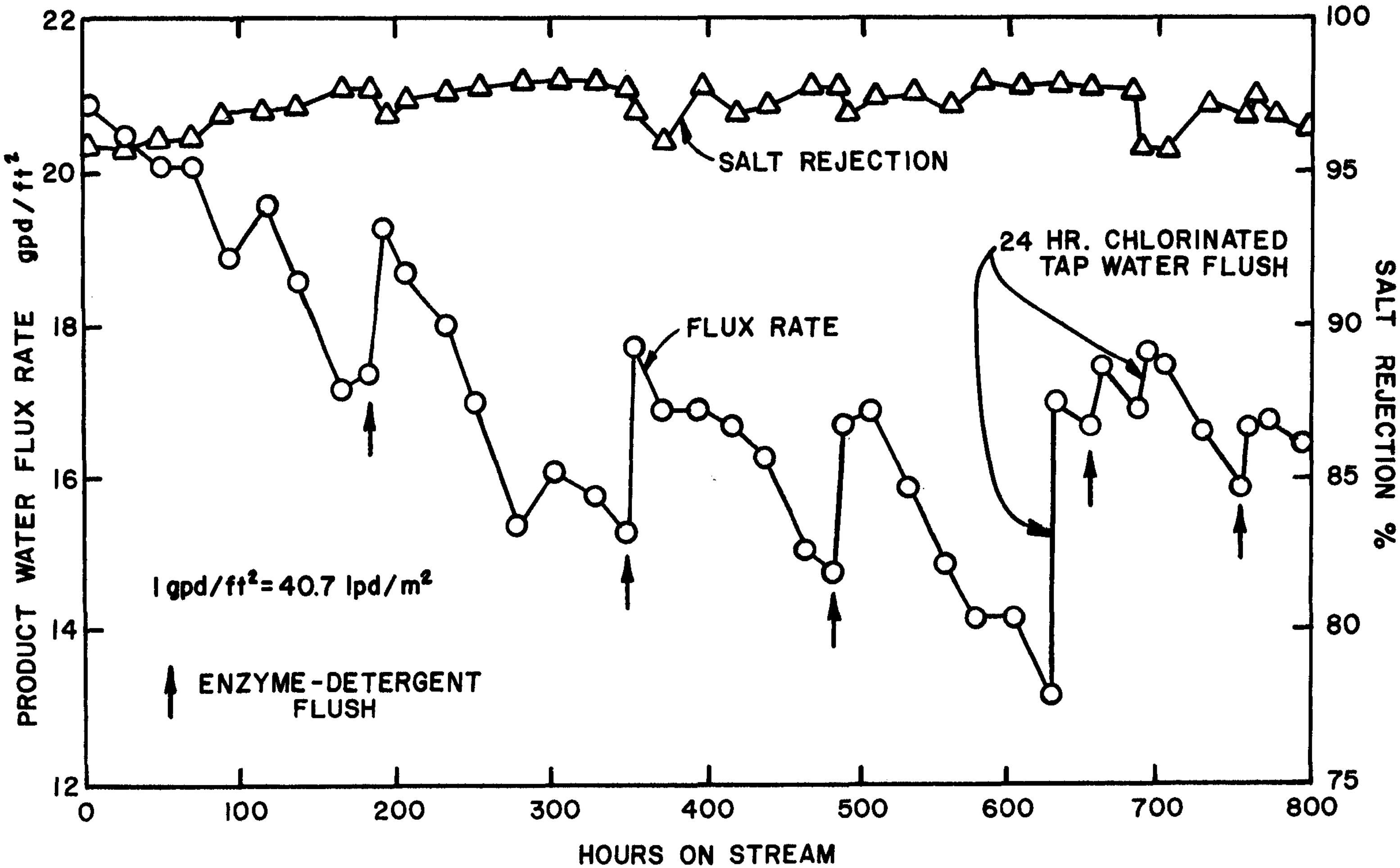


Figure 3. Flux rate and salt rejection variations with operation time.

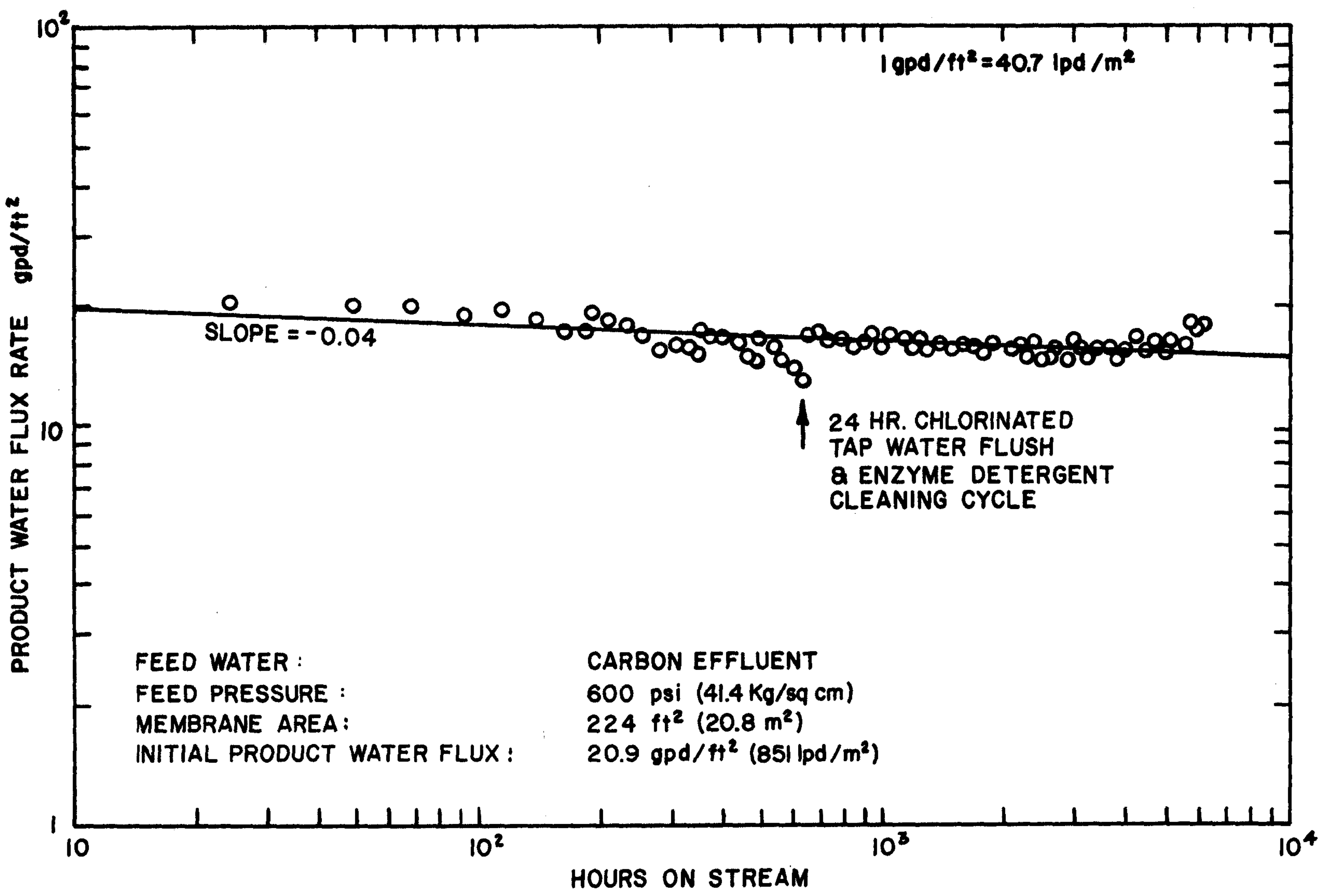


Figure 4. Product water flux rate variation with operation time.

developed in the membrane and eventually resulted in several module failures. The flux decline slope was calculated several times during the experimental run. It changed from -0.06 at 1,250 hours of operation to -0.04 at the end of 7,165 hours of operation. The corresponding values for a spiral-wound membrane system under similar operating conditions were -0.09 and -0.07 (2). These decline slope values seem to indicate that the flux decline in a spiral-wound membrane system was more rapid than a tubular membrane system.

During the entire series of operation with the carbon-treated secondary effluent, the water recovery remained at about 70 to 75 percent. The salt rejection averaged 97 percent until some leaks started to develop at about 5,760 hours of on-stream operation in some of the modules. This caused the salt rejection to decrease to about 90 percent at the end of 7,165 hours of operation.

A summary of all routine chemical analyses run on the feed water, product water, and brine water throughout the study is shown in Table 1. The overall rejection of the inorganic ions, as measured by the reduction in TDS, was about 95 percent. The least rejected ion was nitrate, which was only 53.8 percent.

Operation with Primary Effluent

Figure 5 shows the variations of the salt rejection and the product water flux rate with the time of on-stream operation. Both product water flux rates before and after membrane cleaning are shown in the figure. As indicated in the figure, the brine velocity in the last module was maintained at 0.64 mps (2.1 fps) for the first 800 hours of operation, while for the latter part of the operation, the brine velocity was increased to 1.4 mps (4.5 fps). The brine velocity was increased in an effort to reduce the amount of flux decline due to membrane fouling between cleanings. The experimental data as shown in Table 2 confirm this. There was less product water flux decline between membrane cleanings at a brine velocity of 1.4 mps (4.5 fps) than at 0.64 mps (2.1 fps). As indicated in Figure 5, the membrane cleaning was able to achieve recovery of virtually all of the decline between cleanings. When the flux rates just prior to membrane cleaning and just after cleaning were plotted and the points in each class were connected, a value for flux decline due to other factors than short-term fouling was obtained. As shown in Figure 5, the slope of the flux rate decline was about -0.0125. This decline rate apparently was not affected by the brine velocity.

During the entire period of operation, the salt rejection seemed to remain at approximately 95 percent level. Table 3 shows the averages of the water quality analyses conducted on the feed, product, and brine samples. The percent rejections of the various constituents are also shown in the table.

TABLE 1. SUMMARY OF CHEMICAL ANALYSES FOR PILOT PLANT OPERATIONS WITH CARBON-TREATED SECONDARY EFFLUENT

Parameter	Feed (mg/l)	Product (mg/l)	Brine (mg/l)	Rejection %
Na	123	7.8	373	93.7
K	12.8	1.1	38.4	91.4
Ca	46.3	1.2	138	97.4
Mg	25.8	0.4	101	98.4
Cl	105	11.5	344	89.0
SO_4	306	3.2	1016	99.0
PO_4-P	10.5	0.15	36.6	98.7
NH_3-N	14.9	1.1	46.0	92.6
NO_3-N	2.6	1.2	6.5	53.8
Turbidity, JTU	5.9	0.09	11.0	98.5
Total COD	17.1	1.6	53.7	90.6
TDS	687	34.7	2240	94.9

NOTES: 1. All analyses were run on grab samples taken at 8:00 a.m.

2. Feed samples taken after acidification with H_2SO_4; hence, values of SO_4 shown in table include sulfate contributed by acid addition.

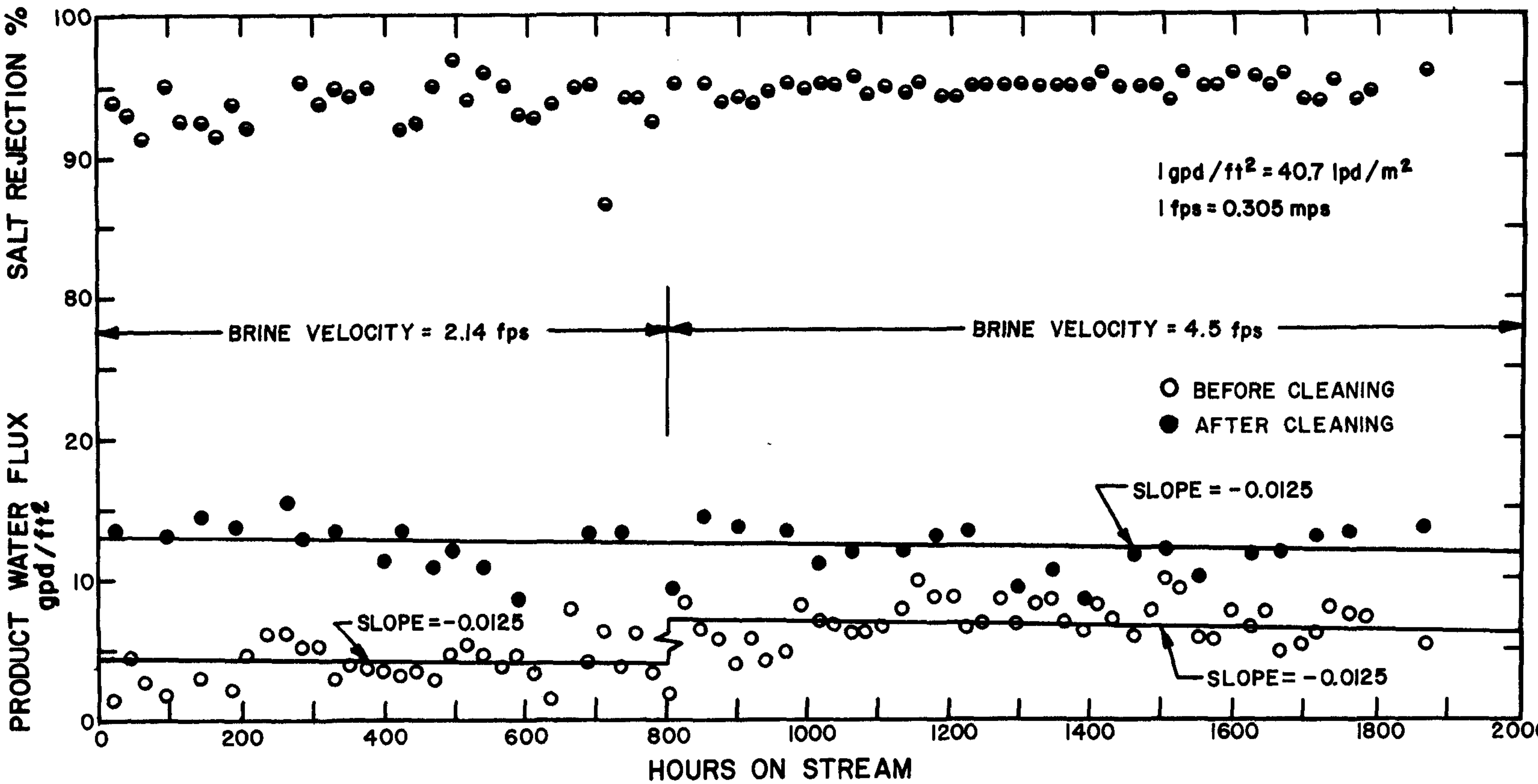


Figure 5. Performance of tubular reverse osmosis process treating primary effluent.

TABLE 2. EFFECTS OF THE BRINE VELOCITY UPON THE OPERATIONS WITH PRIMARY EFFLUENT

Brine velocity, fps	2.14	4.5
Product water flux, gpd/ft^2		
Before Biz cleaning	3.7	6.1
After Biz cleaning	13.1	13.5
Water recovery, %		
Before Biz cleaning	9.1	6.1
After Biz cleaning	26.7	13.
Salt rejection, %	94	95
Biz frequency per week	3	3
No. of operating modules (32 original modules)	6	5

NOTES: 1. 1 fps = 0.305 mps

2. 1 gpd/ft^2 = 40.7 lpd/m^2

3. Biz = enzyme detergent

TABLE 3. SUMMARY OF CHEMICAL ANALYSES FOR PILOT PLANT OPERATIONS WITH PRIMARY EFFLUENT

Parameter	Feed (mg/l)	Product (mg/l)	Brine (mg/l)	Rejection %
Na	126	11.6	146	90.8
K	9.8	0.7	12.2	92.8
Ca	55.9	0.4	67.7	99.3
Mg	13.3	0.5	15.7	96.3
Cl	184	13.6	205	92.6
SO_4	245	1.3	266	99.5
PO_4-P	6.2	0.9	7.2	85.5
NH_3-N	22.6	1.6	24.9	93.0
NO_3-N	1.7	0.6	1.7	64.7
Total COD	110	12.6	124	88.5
TOC	34.3	5.0	37.6	85.5
TDS	760	36.0	883	95.3
Turbidity, JTU	42.9	0.1	47.9	99.7

NOTES: 1. Analyses were run on once-a-week grab samples taken at 8:00 a.m.

2. Feed samples taken after H_2SO_4 addition; therefore SO_4 contribution by acid is also included in the result.

MEMBRANE MODULE STABILITY

A total of 17 membrane modules failed during the entire operation with the carbon-treated secondary effluent between November, 1969 and August, 1970, which covered a total of 7,165 hours of on-stream operation. A summary of the position and the date of each module replacement is shown in Figure 6. The results of an on-site visual examination to determine the cause of the module failure for six of these modules are included in Table 4. Three of the six modules showed no visible signs of membrane damage. These modules were sent back to the Universal Water Corporation for additional studies to determine the cause of failure. Table 5 shows the analytical results of two failed modules, as reported by the Universal Water Corporation. These results indicate that the failure of the modules was due to the failure of the tube, not the membrane, and that this failure was not related to operational procedure.

During August, 1970, some failed modules were replaced with modules from row 8 (the downstream end row of the pilot plant system), instead of obtaining replacement modules from the Universal Water Corporation, and the operation of the system continued with a reduced loading of modules. This was done because the frequency of module failure seemed to be increasing. The operation in this manner was continued to determine if the frequency of module failure would be intensified or not.

There are several possible causes for the increased number of module failures during the month of August, 1970:

A. Hydrolysis of the membrane caused by the enzyme-detergent flushing at a pH of about 10 could have possibly weakened the membrane.

B. Physical attrition of the membrane at a point where the membrane had been heat-treated and flared to form a water-tight seal. This area was considered weak, and it was susceptible to this type of failure.

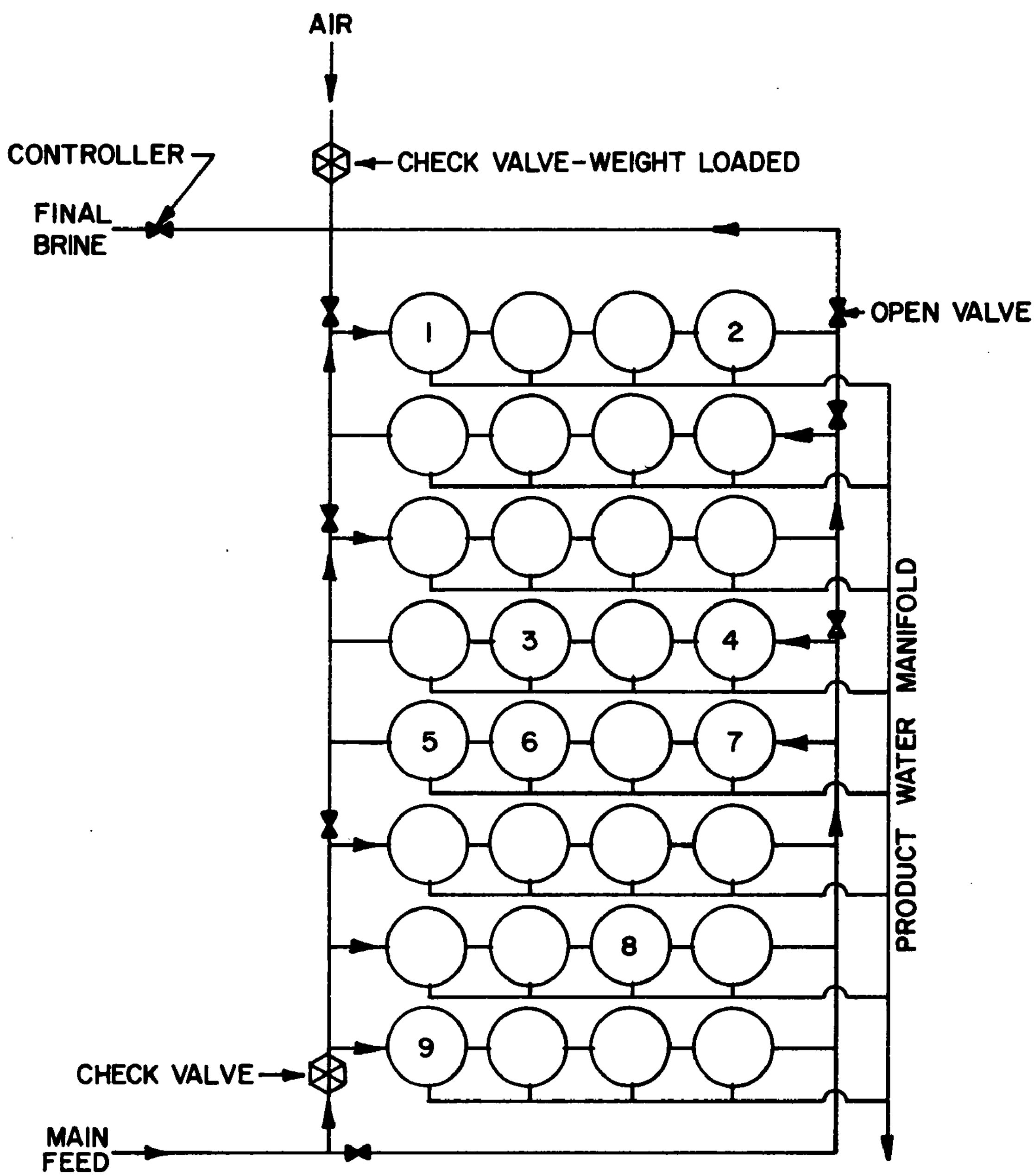
C. Exposure to high levels of chlorine at approximately 10 mg/l occurred on several occasions due to a malfunctioning chlorinator. This problem was corrected as soon as it was discovered, within 24 hours, but it could have already caused some membrane degradation.

D. Physical jarring of the modules while replacing failed modules with new replacement modules or with modules from row 8, could have caused membrane collapse.

E. Fatigue failure of the membrane caused by the daily depressurization and repressurization for the tap water flush.

One or several of the above could be responsible for the module failure.

The experimental run treating primary effluent was concluded after 2,074 hours of operation on January 20, 1971 with four modules remaining. One of these four modules was sent to the Universal Water Corporation for



MODULE REPLACED	DATE OF REPLACEMENT (1970)
(1)	3/10
(2)	1/13, 3/10, 3/16, 7/22, 8/11
(3)	8/17, 8/25, 8/27, 8/31
(4)	2/5
(5)	3/16
(6)	7/31
(7)	7/22
(8)	8/25, 8/31
(9)	6/22

Figure 6. Module replacement in Universal Water Corporation reverse osmosis pilot plant.

TABLE 4. VISUAL EXAMINATION OF FAILED MODULES

Date Replaced	Position in System	Reason for Failure
1/13/70	Exit, Row 8	Tear at O-ring seal.
2/5/70	Inlet, Row 5	Eccentric U bend. Physical attrition of membrane not apparent.
3/10/70	Inlet, Row 8	Physical attrition of membrane not apparent.
3/10/70	Exit, Row 8	Tear at O-ring seal.
3/16/70	Exit, Row 4	Not apparent.
3/16/70	Exit, Row 8	Not apparent.

TABLE 5. LABORATORY ANALYSIS OF MODULE FAILURE (3)

Module	Analytical Results
Exit Module of Row 8	It showed signs of membrane failure in a pressure tube, which would not be related to pilot plant operating procedures.
Exit Module of Row 4	It showed signs of erosion adjacent to the element "O" ring seal. It is possible that some membrane collapse also occurred. The membrane showed negligible signs of chemical hydrolysis, and tensile tests indicated that the yield and break point were within 10% of the standard, and were considered nominal.

module failure analysis. The results reported by the Universal Water Corporation are shown in Table 6. It is believed that the membrane and nylon backing had been exposed to extreme pH conditions and chemical attack. The nylon cloth which served both as a lateral transfer and a support bridge across the perforation of the plastic tube, failed due to chemical decomposition. This, in turn, caused rupture of the weakened membrane at perforation site. The perforation was made to collect the product water through the membrane supporting plastic tube. In addition, possibly due to cyclic exposure to very low and very high pH conditions, the membranes were hydrolyzed, resulting in poor performance and loss of mechanical strength.

Another cause of module failure that had been observed was the collapse of the membrane tube due to negative pressure or siphon. This type of failure was not always immediately apparent. In collapsing and then returning to its original form, the tubular membranes developed a longitudinal ridge that served as a stress point. These areas could puncture any time after pressurization. It could be immediately or it could take days or weeks. Generally, a repeat of siphon conditions in the same tube caused immediate failure. To avoid or minimize this type of failure, some necessary provisions for siphon prevention should be incorporated in the plant design.

TABLE 6. COMPLETE ANALYSIS OF THE MEMBRANE MODULE AFTER A TOTAL OF 10,940 HOURS OF ON-STREAM OPERATION (4)

Module Part	Analytical Results
Module support structure including tubing, headers, and sleeves	No damage, reuseable.
"O" ring seals	Partial deterioration - needs replacement. Damage due to: (a) Cold flow; (b) Chemical attack.
Membrane	Partial hydrolysis and compaction- no mechanical failure. Original performance in 9/23/69: (a) Product water flux rate = 22.5 gpd/ft^2 (916 lpd/m^2) @ 25°C. (b) Salt rejection = 97.5% Performance on 1/23/71: (a) Product water flux rate = 13.0 gpd/ft^2 (529 lpd/m^2) @ 25°C. (b) Salt rejection = 95.0%
Nylon backing	Deteriorated. No tensile strength. Will shred easily. Needs replacement

Notes: 1. The module was fabricated and assembled on 9/23/69, and installed at Pomona on 11/3/69. It was returned to UWC for evaluation on 1/22/71.

2. The 10,940 hours of operations include the 2,074 hours treating the primary effluent.

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-78-167	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Wastewater Demineralization by Tubular Reverse Osmosis Process		5. REPORT DATE September 1978 (Issuing Date)
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ching-lin Chen and Robert P. Miele		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS County Sanitation Districts of Los Angeles County Whittier, California 90607		10. PROGRAM ELEMENT NO. 1BC611
		11. CONTRACT/GRANT NO. 14-12-150
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final Report 1/70 - 6/71
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

A 16 lpm (4.2 gpm) tubular reverse osmosis pilot plant was operated at Pomona Advanced Wastewater Treatment Research Facility for over one year. The purpose of the study was to investigate the applicability of the tubular reverse osmosis process to wastewater demineralization. The pilot plant operational goal was the study of the membrane life. The feed was carbon-treated secondary effluent. This study lasted 7,165 hours until the operating membrane modules reduced from the original 32 modules to 12 modules as a result of membrane module failure. It was subsequently decided to make use of the remaining 12 modules in the system for exploring the behavior of the membrane process in treating primary effluent. The system treated primary effluent during the third phase for a period of 2,074 hours. Repeated membrane failure resulting from poor mechanical design of the system obviated drawing significant conclusions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Demineralizing Desalting Water Reclamation	Membrane Fouling	13B

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 35
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77)

☆U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/1429