Reclamation of secondary sewage effluent by reverse osmosis: a pilot plant study*

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Abstract

Locally developed tubular reverse-osmosis (RO) membrane technology, incorporated into a novel and inexpensive support module, is being used in a 40 m^3/d pilot plant to purify a filtered secondary sewage effluent from an activated sludge treatment works in Port Elizabeth, South Africa. The pilot plant has been in operation for 18 months and membrane performance and product quality are being closely monitored. Initial results indicate that relatively simple, tubular, cellulose acetate RO systems, which have the potential to produce potable water from chlorinated, filtered, secondary sewage effluent, can maintain satisfactory flux levels without any additional pre-treatment.

Introduction

Current assessments of future water supplies for the Port Elizabeth Metropolitan Area include water reclaimed from treated sewage (McCallum, 1978; 1979). This is not due to a lack of exploitable surface water resources but rather to the belief that non-conventional sources can, with advantage, be developed as conjunctive supplies to augment the surface water facilities (McCallum and Vail, 1980), particularly in meeting peak demands or when existing sources are far from the point of use, as is the case in Port Elizabeth.

Also in the case of Port Elizabeth, the reclamation process must include demineralisation. This is because the only secondary effluent available for reclamation on a large scale, although derived mainly from domestic sewage, contains 600-1 000 mg/ℓ of dissolved solids, with an average value of 750 mg/ℓ. Its conductivity is almost double the new SABS recommended limit for domestic water supplies (SABS, 1984). The question then arises whether reverse osmosis (RO) could be used to remove organic pollution as well as dissolved salts. If so, the currently available physico-chemical reclamation processes, which are operationally complex, could be much simplified.

Research on the application of RO to the purification of treated sewage effluents has been in progress for several years overseas, notably in the USA (Argo and Moutes, 1979; Wojcik *et al.*, 1980; Argo and Ridgway, 1982; Stenstrom *et al.*, 1982; Stenstrom, 1983) and also in Holland (Hrubec *et al.*, 1983). An early and valuable start was made in South Africa by the National Institute for Water Research under contract to the Water Research Commission (Botha and de Villiers, 1978; Botha *et al.*, 1980). Nevertheless, the use of RO in the reclamation of sewage is still at an early stage of development in this country, particularly under operational conditions. A number of factors such as the extent of pre-treatment, the type of membrane and the membrane system need to be thoroughly investigated by pilot plant studies. The initial results from one such pilot plant study are presented here.

Choice of RO system

Early local experience with spiral wound and hollow-fibre systems was not promising, mainly due to membrane fouling resulting from inadequate, or inadequate control of, pre-treatment (Leger, 1984) and attention turned to tubular membranes.

At the end of 1979 the first South African cellulose acetate tubular membrane modules were produced by Bakke Industries, under contract to the Water Research Commission, and subsequently patented by the former. A significant saving in module construction costs was achieved through the use of modern engineering plastics. Pilot studies in South Africa on a variety of high-fouling waters indicated the accommodating nature of the system, which included flow reversal and sponge-ball cleaning. Flux decline slopes projected a theoretical membrane life of between 2 and 5 years and the elimination of complex pre-treatment made it possible to operate the system in remote areas with relatively low operator skills. For these reasons, and because there are advantages in having local manufacturing backup, the Bakke system was chosen for the Port Elizabeth experiments.

Description of pilot plant

Module design

A module contains 19 membrane tubes, each 2 300 mm long with a 13 mm diameter, connected in series inside a 100 mm diameter aluminium shell. Total tube length and membrane area are 44 m and 1,75 m^2, respectively, per module. The tubes are supported in a pressure housing of polymer discs and cast end-pieces, allowing the product (permeate) to be collected within the outer aluminium shell.

Hydraulic design

Hydraulic flow characteristics are of particular significance to the problem of membrane fouling. Low feed water velocities may allow severe fouling but high velocities demand a high energy input. The number of modules that can be coupled in series depends on the velocity drop through the series and hence on the required product water recovery. For example, with a feed velocity of 2,0 m/s and a recovery of 75%, the exit velocity after 16 modules in series will only be 0,5 m/s, which is critically low and would normally lead to severe fouling. However, by reversing flow the former exit module is exposed to the high feed velocity. The rapid change in flow direction and acceleration can be expected to assist in the prevention of fouling, as will the insertion of sponge-balls.

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Equipment

The RO equipment (Figure 1) consists of a single-pass, tubular, cellulose acetate membrane system, as described above, arranged in two parallel rows, of 16 modules each, to give a design recovery of 75% at 20 °C and a feed rate of 40 m^3/d. Flow reversal is automatically controlled by an electronic timer actuating a pneumatic piston coupled to a four-way valve. Sponge-ball traps at both ends of both module trains enable the sponge-balls to travel once through the entire series of membrane tubes at each flow reversal. The reversal cycle can be varied from 30 to 600 min. Feed water is filtered through a 50 micron cartridge filter and is automatically dosed with sulphuric acid to maintain a pH of 6,0. Feed water pH, temperature, conductivity, pressure and flow are continuously monitored and visually displayed, as are product conductivity and flow and concentrate (brine) flow and pressure. Alarm lights and automatic trips for all key functions enable the plant to be run unattended.

Experimental procedures

Feed

Throughout this study the feed to the RO unit was an activated sludge secondary effluent, derived from mainly domestic sewage, which was passed through an upflow rapid sand filter, chlorinated (*not* normally to break-point) and stored in a roofed reservoir for about 2 days. No other pre-treatment was applied prior to the RO unit and no attempt was made to protect the RO feed from the usual upsets that occur in sewage treatment.

Operating limits

The feed flow was constant at 30 ℓ/min and feed pressure was maintained in the range 3 900 to 4 500 kPa. Concentrate exit velocity did not fall below 0,46 m/s.

Monitoring and sampling

Appropriate machine readings were taken twice a day, on weekdays, to enable daily average values to be calculated for volume recovery, salt rejection, actual and standard flux.

Standard flux ($\ell/m^2/d$) at 20 °C and 4 000 kPA

$$= \frac{40F}{P} [1 + 0,025\ (20\text{-}T)]$$

Where F = actual flux ($\ell/m^2/d$)
T = feed temperature °C
P = average of inlet and outlet pressures (MPa).

Standard sodium chloride rejections for the RO unit and salt (conductivity) rejections for each module were determined at regular intervals. Spot samples, taken four times a day, on weekdays, were combined to give composite samples for chemical analysis. Spot samples were taken for bacteriological analysis.

Membrane cleaning

For comparison purposes, one of the two rows of modules was operated without sponge-balls after the first 1 000 h. The flow reversal cycle was 60 min throughout the trial. In addition, whenever the feed pressure rose to 4 500 kPa the membranes were flushed for 2 h with a wash solution. A variety of wash solutions were tested: citric acid (2%, adjusted to pH 4,0 with ammonia), 0,8% Biotex (at pH 5,0 and 8,8), 0,5% Ultracil 50 (pH 6,9) and 0,8% and 0,4% Auto Punch (pH 10,3 and 9,5). Washing was found to be necessary once a week.

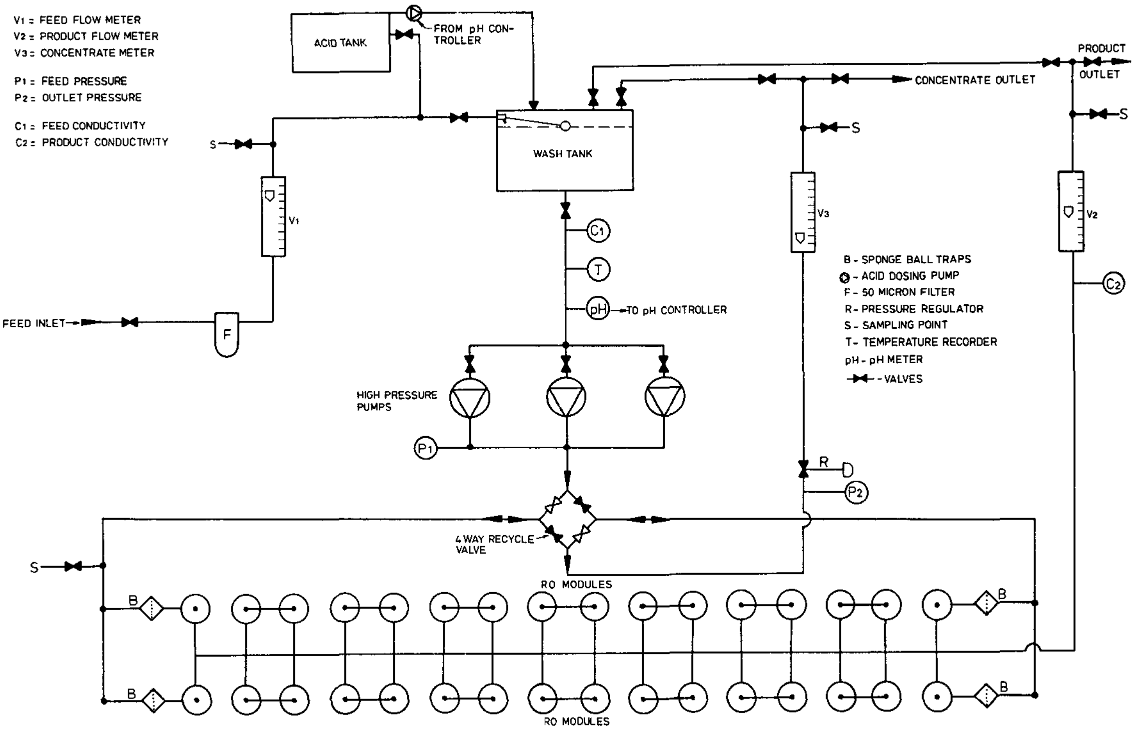

Figure 1
Diagrammatic layout of RO pilot plant.

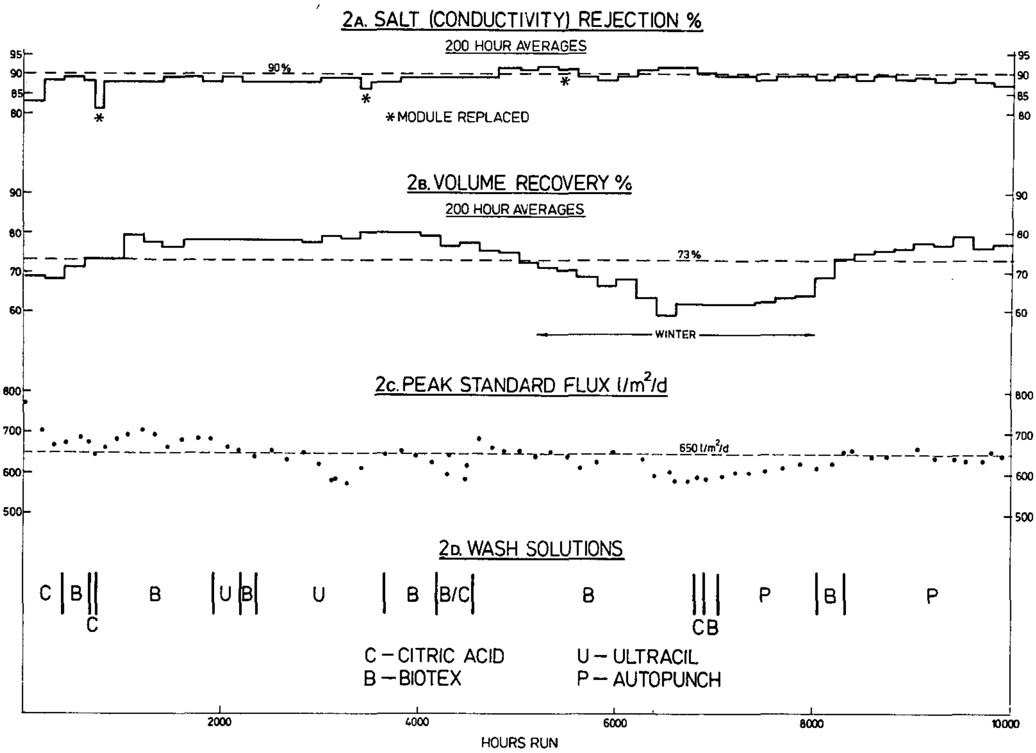

Figure 2
RO unit performance.

Results and discussion

Membrane fouling

One of the main objectives of this study is to determine the rate of flux decline due to membrane fouling. At the start it was expected that fouling and blocking would assume serious proportions unless some additional form of pre-treatment was applied to the feed. In fact, the results (see Figure 2) show that this is not the case. Figure 2B demonstrates that good recoveries were maintained throughout the period reported. Despite the expected sag during winter (effect of temperature), a timeweighted average recovery of 72% was achieved. The average peak standard flux (measured immediately after each wash) was 646 $\ell/m^2/d$, during the 9 000 – 10 000 h period, compared with 679 $\ell/m^2/d$ during the 300 – 2 000 h period, a drop of only 4,9% which is good by any standard. The initial steep drop in the first 300 h is mainly due to membrane compaction and is allowed for in the plant design.

The overall flux decline so far experienced is encouraging and demonstrates that membrane fouling can be effectively controlled, despite the fact that rapid sand filtration is the only pre-treatment. This result appears to confirm the opinion that activated sludge plant effluents have less fouling tendency than the trickling filter effluents on which much of the early American work was done (Stenstrom, 1983). As long ago as 1974 (Bailey *et al.*, 1974), it was suggested that with good quality, sand-filtered, activated sludge effluents, pre-treatment of the RO feed with chemicals or activated carbon did not significantly improve flux and that, even without pre-treatment, there was little drop in flux over 13 months (tubular cellulose acetate membranes with regular enzyme detergent washing).

Membrane degradation

Another important objective of this study was to determine the extent of membrane degradation due to chemical or bacterial (enzyme) hydrolysis. One of the best measures of this is salt rejection, and Figure 2A shows that a consistent level of salt (conductivity) rejection was maintained for more than 9 000 h. This was confirmed by salt rejection surveys on individual modules at regular intervals (range of salt rejection on front modules 94% – 97%). The two modules which were replaced at 800 h and 3 500 h, due to low salt rejection, probably suffered from a manufacturing fault and not hydrolysis, which would have progressively affected all modules. The module failure at 5 500 h was definitely due to a fault in manufacture (see 'Mechanical performance' below).

The gradual decline in salt rejection, apparent after about 9 000 h, levelled off at 10 500 h and 85% rejection, coincidental with a change from alkaline to acid (pH 6,0) Auto Punch wash solution. The loss of salt rejection may have been due to membrane hydrolysis, caused by prolonged use of an alkaline wash, but there could be some other explanation as there was no concurrent increase in membrane flux.

Washing procedures

Various wash solutions have been tested, chosen on an empirical basis (Figure 2D). The lack of any reliable fouling index text, and the fact that some of the fluctuations in flux decline occur independently of the washing agent, make it difficult to draw firm conclusions at this stage. The indications are that both enzyme and detergent components are necessary, while it is unlikely that a chelating agent or citric acid are required for this particular feed water, but investigations to determine the most effective combination will continue. It is important to note that, so far, no significant difference in performance has been observed with and without sponge-balls.

Mechanical performance

After initial problems with pressure surges at flow reversal, due to

TABLE 1
CHEMICAL RESULTS
COMPOSITE DAILY SAMPLES

Results in mg/ℓ unless otherwise stated	Feed			Product					% Rejection		
						95% CL					
	n	M	SD	n	M	H	L	SD	n	M	SD
Conductivity, mS/m	259	129	21	259	14,5	22	7,1	3,8	259	89	2,0
Sodium (as Na)	35	266	58	35	30,5	48	12	9,1	35	89	1,9
Potassium (as K)	35	30	2,6	35	3,2	5,1	1,3	0,98	35	89	3,2
Calcium (as $CaCO_3$)	60	86	14	60	4,7	11	Nil	3,25	60	95	3,4
Magnesium (as $CaCO_3$)	58	74	20	58	5,4	16	Nil	5,4	58	93	6,3
Total alkalinity (as $CaCO_3$)	60	120	33	60	7,8	12	3,2	2,35	60	93	3,2
Chloride (as $C\ell$)	34	318	82	34	39	67	11	14	34	88	2,1
Sulphate (as SO_4)	35	93**	24	34	3,8	6,9	0,7	1,6	34	96°	1,8°
Total phosphorus (as P)	35	3,4	1,85	35	0,09	0,19	Nil	0,05	35	97	1,8
Silica (as SiO_2)	35	11	1,2	35	2,0	2,9	1,1	0,45	35	82	4,1
Ammonia (as N)	58	10	4,5	58	1,7	3,2	0,2	0,78	58	82	6,3
Nitrite (as N)	56	0,13	0,14	56	0,01	(0,19)	(<0,01)	NA	ND	ND	ND
Nitrate (as N)	54	4,8	4,5	54	2,1	5,8	Nil	1,9	54	53	13
Colour (Hazen units)	60	30	12	60	<5	(<5)	(<5)	NA	ND	ND	ND
Turbidity (NTU)	60	2,4	1,3	60	0,40	0,67	0,13	0,14	60	82	7,3
Absorbance (275 nm)	75	0,27	0,05	57	0,013	0,031	Nil	0,009	57	95	2,9
Abs. (254-545 nm)	54	0,35	0,05	54	0,020	0,04	Nil	0,01	54	95	3,2
COD	37	55	8,1	37	6,3	13,5	Nil	3,7	37	89	6,7
Suspended solids	39	3,5	2,3	Nil	ND	ND	ND	ND	Nil	ND	ND
pH (laboratory)	Nil	ND	ND	58	5,4	(6,1)	(4,4)	NA	NA	ND	ND
pH (machine)*	220	6,0	NA	Nil	ND	ND	ND	ND	NA	ND	ND
Free residual chlorine ($C\ell_2$)	214	0,1	NA	Nil	ND	ND	ND	ND	Nil	ND	ND
Total residual chlorine ($C\ell_2$)	42	0,7	NA	Nil	ND	ND	ND	ND	Nil	ND	ND

n = number of samples M = mean or median SD = standard deviation 95% CL = 95% confidence limits; H = higher limit, L = lower limit
( )( ) – maximum and minimum results
* – after addition of sulphuric acid
** – before addition of sulphuric acid
° – uncorrected for sulphuric acid addition
ND – not determined
NA – not applicable
< – less than

a faulty back pressure valve, the unit has run extremely well mechanically. Several tube breaks at the end-cap occurred in one particular batch of modules, due to a manufacturing fault which has been eliminated in the new module design.

Chemical and bacteriological results (Tables 1, 2 and 3)

It was not one of the objectives of this experiment to make an exhaustive study of product water quality. However, the results reported in Tables 1 and 2 show that, for those constituents which were determined, the product is chemically of potable quality, except perhaps for ammonia and trihalomethanes (THM's). Ammonia could be reduced by improving nitrification or by post-RO lime stripping. Post-RO lime stabilisation will in any case be necessary. Reduction of THM's is linked to the optimum procedure for disinfection which will be investigated later. For example, the elimination of feed chlorination except for occasional shock doses or the use of other disinfectants, such as ozone or chlorine dioxide, must be considered.

THM's apart, it is worth noting (Table 3(ii)) that with 0,2 mg/ℓ or more of free residual chlorine in the feed the product is of high bacteriological quality. The minor, sporadic occurrence of coliforms is probably due to post-membrane infection of the product collector tubes. Final disinfection will be simple and effective due to the clarity of the product.

In addition to the bacterial types in Table 3, tests were made for acid-fast bacteria and E. Coliphages, as these have been proposed as crucial indicators of disinfection efficiency (Grabow *et al.*, 1980). However, neither of these organisms was found in sufficient numbers in the feed to justify their use as indicators.

Conclusions

After over 10 000 h running in a works environment, the results obtained from this pilot plant study indicate that, with flow reversal and sufficient attention to membrane cleaning, cellulose acetate, tubular RO systems have the potential to produce potable water efficiently from secondary domestic sewage effluent, with only rapid sand filtration as pre-treatment. Further work is necessary on product stabilisation, membrane washing and disinfection procedures.

TABLE 2
MICRO-POLLUTANTS
COMPOSITE DAILY SAMPLES

	Feed			Product					% Rejection		
					95% CL						
Results in μg/ℓ	n	M	SD	n	M	H	L	SD	n	M	SD
Aluminium	32	14	5,9	Nil	ND	ND	ND	ND	Nil	ND	ND
Arsenic	32	<0,2	NA	Nil	ND	ND	ND	ND	Nil	ND	ND
Cadmium	35	<0,3	NA	35	<0,2	(<0,2)	(<0,2)	NA	NA	NA	NA
Chromium (total)	35	7,0	NA	35	<2,5	(10)	(<2,5)	NA	35	>69	NA
Copper	30	5,0	1,6	30	0,8	(2,0)	(<0,8)	NA	30	82	NA
Iron	35	129	151	35	10,0	27	Nil	8,7	35	89	9,7
Lead	35	<5	NA	35	<2,5	(<2,5)	(<2,5)	NA	NA	NA	NA
Manganese	35	44	17	31	2,1	3,7	0,55	0,79	31	95	4,2
Mercury	35	<0,5	NA	Nil	ND	ND	ND	ND	Nil	ND	ND
Molybdenum	35	<24	NA	35	<12	(<12)	(<12)	NA	NA	NA	NA
Nickel	35	21	9,0	35	<0,8	(4,0)	(<0,8)	NA	35	>95	NA
Selenium	35	<0,4	NA	Nil	ND	ND	ND	ND	Nil	ND	ND
Zinc	35	72	19	35	7,8	15	0,94	3,5	35	89	5,4
Boron (B)	35	234	33	Nil	ND	ND	ND	ND	Nil	ND	ND
Cyanide (CN)	34	17	15	17	4,9	11	Nil	3,1	17	50	28
Detergents (as MBAS)	34	196	74	31	11	28	Nil	8,7	31	95	3,2
Fluoride (F)	35	100	141	Nil	ND	ND	ND	ND	Nil	ND	ND
Chloroform	42	21	15	42	20	49	Nil	15	ND	ND	ND
Bromodichloromethane	42	20,5	14	42	21	48	Nil	13,6	ND	ND	ND
Dibromochloromethane	42	16	17,5	42	16	48	Nil	16,6	ND	ND	ND
Bromoform	40	8,5	22	39	8,0	42	Nil	17,6	ND	ND	ND

n = number of samples M = mean or median SD = standard deviation 95% CL = 95% confidence limits; H = higher limit, L = lower limit
( )( ) – maximum and minimum results ND – not determined NA – not applicable < – less than > – greater than

TABLE 3
BACTERIOLOGICAL RESULTS – SNAP SAMPLES

(i) Free residual chlorine in feed: Less than 0,2 mg/ℓ

	Total Plate Count/mℓ				Total Coliforms/100 mℓ				E. Coli I/100 mℓ				Aerobic bacterial spores/100 mℓ			
	n	Max.	Min.	Med.	n	Max.	Min.	Med.	n	Max.	Min.	Med.	n	Max.	Min.	Med.
Feed	54	2 000 000	10	9 400	45	>200 000	0	60	44	>200 000	0	0	58	8 500	40	335
Product	58	8 600	0	200	61	5 800	0	1	47	1 060	0	0	61	90	0	6

(ii) Free residual chlorine in feed: 0,2 mg/ℓ – 0,9 mg/ℓ (median 0,3 mg/ℓ)

	Total Plate Count/mℓ				Total Coliforms/100 mℓ				E. Coli I/100 mℓ				Aerobic bacterial spores/100 mℓ			
	n	Max.	Min.	Med.	n	Max.	Min.	Med.	n	Max.	Min.	Med.	n	Max.	Min.	Med.
Feed	39	7 200	0	160	42	2 100	0	0	38	37	0	0	44	4 700	0	190
Product	39	30	0	5	42	8	0	0	35	0	0	0	41	290	0	4

> = greater than n = number of samples max. = maximum min. = minimum med. = median value

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