The Feasibility of Reverse Osmosis for Water Reclamation on a large Scale

J A Slim. D G Devey and J W Vail

WRC Report No. 192/1/91

PORT ELIZABETH CITY COUNCIL

CITY ENGINEER'S DEPARTMENT

Report to the

WATER RESEARCH COMMISSION

on

THE FEASIBILITY OF REVERSE OSMOSIS FOR WATER RECLAMATION ON A LARGE SCALE

by

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REPORT ON THE FEASIBILITY OF REVERSE OSMOSIS FOR WATER RECLAMATION ON A LARGE SCALE

EXECUTIVE SUMMARY

The City of Port Elizabeth designed its main sewage treatment works with water reclamation in mind in order to supply a second class non potable water to local industry. Experience has proved that the demand for this water is very limited because of the high dissolved solids content. The future of water reclamation will depend on the ability to produce a water of fully potable standard which could then be used to supplement existing potable water supplies in the city. Previous work on a small pilot plant had shown that the reverse osmosis process could be used to satisfactorily produce such a potable water from a sewage works tertiary effluent. This supplied the motivation for funds to be provided by the Water Research Commission for the installation of a full scale tubular reverse osmosis (RO) plant having a nominal output capacity of 400 m^3 per day. The plant was supplied and installed by Bintech (Pty) Limited at a total cost of R516 000, (of which R 482 000 was the cost of the potable water production plant). The investigational work carried out on this plant is described in this report.

The plant ran during the period 16 March 1987 to 31 August 1990 for a total of 11 621 hours, or a total of 37,4% of the total available time. This low percentage was a result of frequent mechanical and instrument failures which indicated the need for the installation of higher quality and more reliable equipment. Feed flow to the plant averaged 25 475 ℓ/h with a product recovery rate of 67,5%. A 13% reduction in peak standard flux occurred over the period of the project, indicating that membrane fouling could be controlled within acceptable limits even though the feed received no pretreatment other than rapid sand filtration. Average salt rejection was maintained at 88,3% which indicated no abnormal degradation of the membrane by hydrolysis, although this could have been masked by the high number of module replacements which were necessary due to mechanical failure.

Regular samples of the feed and product were taken for analysis throughout the duration of the project. An intensive ten week quality surveillance programme was carried out by Port Elizabeth Municipality and the CSIR, Division of Water Technology to assess the quality of the product water with regard to micropollutants, toxicity, mutagenicity, indicator micro-organisms and pathogens.

The results of this surveillance programme indicated that chemically the RO product was of good potable quality with the possible exception of the levels of ammoniacal nitrogen, phenols and organic pollution indicators. With regard to bacteriological quality the RO product was not satisfactory but this could easily be rectified by the provision of adequate post disinfection. According to the Division of Water Technology, the *Daphnia pulex* toxicity tests indicated that the RO product was on occasion undesirable for human consumption.

Plant operational expenditure was constantly monitored and the total cost of the RO product was R 1,86/kℓ, including capital costs. Maintenance and replacement of

equipment was responsible for 50% of this figure.

This work has highlighted the great potential of the RO process in the production of potable water from a tertiary sewage effluent in that it requires no pretreatment. However, it cannot be considered as a stand alone process, and requires a further stage of treatment, e.g. activated carbon, to remove possible organic micropollutants, which may render the water toxic.

If this process is to be considered for producing potable water, further investigations will be necessary to determine the most reliable and economic means of removing the organic micro-pollutants from the RO product.

ACKNOWLEDGEMENTS

The work described in this report was carried out in accordance with the Memorandum of Agreement between the Water Research Commission, the Council of the Municipality of Port Elizabeth, Bintech (Pty) Limited and the Council for Scientific and Industrial Research. The project was guided by a Steering Committee constituted as follows :-

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A special word of appreciation is offered to Messrs. Dyssell and Sinclair for their enthusiastic and conscientious operation of the RO plant, and also to the operational and maintenance staff of the Fishwater Flats Water Reclamation Works. Thanks are due to the laboratory staff of the Scientific Services Division of the City Engineer's Department for their willing and able assistance in the analytical work of the project.

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1. INTRODUCTION

There are a number of reasons which can be used to justify research into the reclamation of sewage effluent by means of reverse osmosis (RO). The process offers advantages such as comparative simplicity of operation, a positive barrier to pollutants and micro-organisms and a high level of removal of dissolved salts. There may of course be disadvantages such as membrane fouling and membrane degradation, but the Water Research Commission has, for many years, recognised the possible potential of reverse osmosis in effluent reclamation and has supported a number of projects to develop and test the process in South Africa.

In the City of Port Elizabeth, the use of reclaimed water to meet peak demands has long been considered as a possible method of supplementing conventional potable water supplies. A further consideration which favoured this possibility is that the geographic location of the City's main sewage treatment plant may give reclaimed water an economic advantage over water derived from extensions to existing sources and treatment plants situated at long distances from the point of use. For this reason the Fishwater Flats Water Reclamation Works, which treats some 90% of the city's sewage, was designed with water reclamation in mind. The sewerage network collects separately from the predominantly domestic and the industrial areas of the city and this separation is maintained throughout the liquid purification process. Tertiary treatment in the form of sand filtration and additional chlorination can therefore be applied to an effluent which is mainly domestic in origin. At the present time about 5 Mℓ per day of secondary effluent is being treated to produce a second class water for use by local industry and on the sewage works itself. Despite the low tariff charged for this grade of water, the demand has proved to be disappointing. Industrialists find that the dissolved salts concentration in the water, which renders it corrosive, is too high for many purposes and the fact that this non-potable water requires a completely separate reticulation system has also proved to be a negative factor.

It has become obvious that a large scale and economic outlet for reclaimed water from the Fishwater Flats works will only be found if treatment to full potable standard is viable. Any reclamation process used to achieve this standard must include demineralization because the secondary effluent at Fishwater Flats contains 600 to 1 000 mg/ℓ of dissolved solids. The electrical conductivity, which is a relative measure of the dissolved salts concentration, is, at an average of 140 mS/m, double the South African Bureau of Standards recommended limit for potable water supplies.

In order to investigate the viability of producing reclaimed water of potable quality, a tubular, cellulose acetate, RO pilot plant, having a capacity of 30 m^3 per day was purchased in 1983 from Bakke Industries (Pty) Ltd, [Bintech (Pty) Ltd]. Having chosen RO for the demineralization stage of the process, the question then arose whether it could also remove organic pollution without extensive pretreatment. If this was found to be possible then the currently available physico-chemical reclamation processes, which are operationally complex, could be greatly simplified. Also having decided on RO as the core of the process, the choice of the locally manufactured Bakke system was not difficult because its unique cleaning system, based on flow reversal in a tubular membrane format, seemed to offer the best defence against membrane fouling.

The pilot plant was operated for a period of three years during which it achieved an on-line running time of 20 300 hours before being closed down to make room for this new project. The results obtained (Vail and Barnard 1986) were very encouraging and suggested that, with sufficient attention to membrane cleaning, the Bakke system had the potential to consistently produce potable water from secondary treated sewage effluent, with only rapid sand filtration and chlorination as pretreatment stages. These promising results indicated a need to proceed to a full scale operational plant. This conclusion was also reinforced by the results of earlier work carried out by the Polymer Research Institute at Stellenbosch University, the CSIR at Bellville and Bakke Industries, most of which was supported by the Water Research Commission.

Despite the successful results obtained from the pilot plant, there remained a number of factors which required investigation before this method of reclamation could be considered in practice. These factors included the problems which arise in full scale operational plants which cannot be adequately assessed on a pilot scale or in a research environment, and a realistic assessment of costs.

In 1986 an agreement was entered into by the Water Research Commission, the Port Elizabeth Municipality, Bintech (Pty) Ltd, and the CSIR (NIWR), resulting in the installation of a 400 m^3 per day tubular reverse osmosis unit at Fishwater Flats to be operated with the intention of investigating, over a three year period, the following:-

(i) Full scale operational procedures. There was no experience available in South Africa of operating large RO plants for sewage reclamation.

(ii) The quality of the product water, as assessed by an independent body, and including micro-pollutants, toxicity, mutagenicity and pathogens.

(iii) The consistent full scale production of a water of potable quality under normal treatment plant operating conditions.

(iv) Operating costs at full scale production.

This report contains the results of the investigation carried out during the period from 16 March 1987 to 31 August 1990.

2. DESCRIPTION OF PLANT

2.1 Module design

Reverse osmosis separates a solute from a solution by means of a semi-permeable membrane. Pressure is used to drive the solvent, namely water, from a stream containing dissolved salts through a membrane, resulting in a stream of purified water (the product), and a stream which increases in dissolved salts concentration as it flows through the system (the concentrate).

There are many configurations for RO membrane systems on the market. The locally manufactured tubular RO process was chosen because its tubular format,

incorporating a flow reversal facility, with sponge balls, was expected to counteract the high fouling potential of a sewage effluent feed. The descriptions given below refer to the RO system installed, i.e. the Bakke (now Membratek) system.

The membrane is a film of specially prepared cellulose acetate, approximately 0,5 microns thick, supported by a more porous film of about 100 microns thick. This membrane is supported on a fabric which is tubular in form having a diameter of 13 mm and a length of 2 300 mm. 19 of these membrane tubes are supported by means of a pack of perforated plastic plates so arranged as to allow the water permeating through the membrane to pass between them. The pack of membrane tubes is enclosed in a 100 mm diameter aluminium shell pressure housing from which the product can be collected, a module. The total membrane tube length is 44 metres and the membrane area is 1,75 m^2 per module.

2.2 Hydraulic Design

The hydraulic flow characteristics within the module are very critical in their effect on membrane fouling. As with any RO system, permeability through the membrane is affected by polarisation and bacterial growth. It is therefore vitally important to keep the membrane surface as clean as possible. Low feed water velocities result in severe fouling but high velocities require increased energy.

The membranes can be kept reasonably free from excessive fouling by ensuring that the average velocity through the system does not fall below approximately 1 metre per second. The number of modules which can be connected in series depends on the velocity drop through the system and therefore on the required percentage recovery of the product water. Thus for a 75% flow recovery, with an input feed velocity of 2,0 m/s, and 16 modules connected in series, the average velocity will be 1,0 m/s with an exit velocity of 0,5 m/s, which could result in fouling at the outlet end of the module row. This problem is overcome by reversing the flow, so causing the modules which have been exposed to low flow conditions to receive the high feed velocity. Thus by means of frequent flow reversal the average velocity through the system can be optimised to give a time average value of 1,0 m/s. The rapid changes in flow acceleration lead to a reduction in membrane fouling. The tubular membrane system has the further advantage of permitting the use of sponge balls to aid cleaning. These sponge balls are inserted at one end of a row of 16 membranes and move in the direction of flow so effecting a scouring action on the membrane surface. At each flow reversal the balls move from one end to the other of the module row.

The water is forced through the membrane at an inlet operating pressure of between 3 000 and 5 000 kPa.

2.3 Equipment

The RO plant installed at the Fishwater Flats Water Reclamation Works (shown diagrammatically in Figure 1), consists of a once through, tubular, cellulose

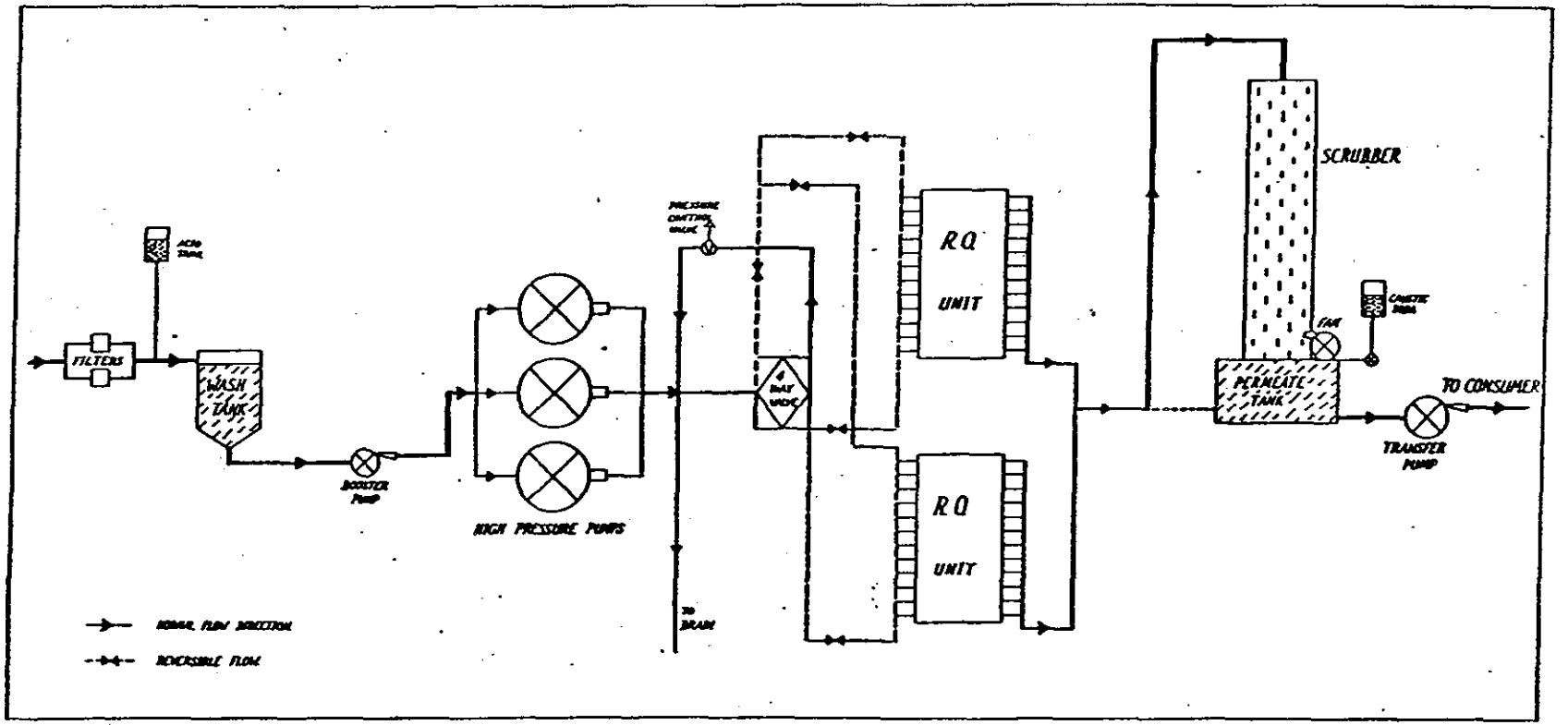

FIGURE I DIAGRAMMATIC LAYOUT OF TRO PLANT - FISHWATER FLATS WORKS

acetate membrane system arranged in two banks of modules. Each bank contains 14 parallel rows of 16 modules per row in series. The number of modules in the two banks is 448 giving a total tube length of 19,6 km. The plant was designed to give a 70% recovery at 20°C and a feed rate of 610 m^3 per day.

Feed water from the works' reclaimed water reservoir is supplied to the plant at a pressure of approximately 600 kPa via a 150 mm diameter polyethylene pipe. On entering the plant, the water is filtered through one of two 150 micron nitrile filter bags contained in a basket strainer before passing into the 2 m^3 capacity stainless steel feed buffer tank. The feed line into the tank is fixed at a tangent to provide mixing of the contents.

98% sulphuric acid is pumped from a 375 ℓ capacity stainless steel tank by means of a small dosing pump into the feed buffer tank in order to maintain the feed water at a pH of 6,0. Dosing is controlled by means of a pH meter equipped with set points. In the event of the pH of the feed water exceeding a limit of 7 for a period in excess of 15 seconds, the main feed pumps will shut down. pH control is necessary as the cellulose acetate membranes are susceptible to hydrolysis at pH levels above 6,0.

The water is transferred from the buffer tank by means of a booster pump to the inlet of the high pressure pumps. This booster is a stainless steel centrifugal pump which nominally delivers 22,5 kℓ per hour at a pressure of 250 kPa. This ensures that the main high pressure pumps are always fed with a positive head.

Three high pressure pumps are installed, two duty pumps and one standby unit. The pumps are Crown Triplex, model 707, positive displacement pumps of the piston plunger type and each is designed to deliver 194ℓ per minute at 5 000 kPa pressure. The three pumps are connected in parallel and each fitted with isolating valves. The pump pressure is limited by means of a shear pin relief valve set to shear at 6 000 kPa.

The high pressure pumps supply the feed water to the module banks.

The modules are designed to operate at a maximum inlet pressure of 4 600 kPa. Pressure throughout the system is controlled by means of a manually operated, angle seat valve situated on the concentrate line. The valve is set to the fully opened position for plant start up and is then slowly closed until the desired product flow is obtained.

High pressure safety features, in addition to the relief valve mentioned above, include a pressure safety valve set at 5 300 kPa and a pressure transducer which is set to give an alarm signal at 4 800 kPa and to trip the plant at 5 000 kPa.

Flow reversal in the module banks is automatically controlled by means of an electronic timer actuating a pneumatic piston operating a four way valve system. The valves are designed for high pressure and are manufactured from stainless steel. The reversal cycle can be varied from intervals of 1 to 600 minutes. The

function of the flow reversal facility is to alter the direction of flow through the modules and so alternate the pressure gradient in the system. At each reversal the sponge balls move from the inlet to the outlet end of the row of modules. Sponge ball traps are situated at each end of the 16 series module trains with ball insertion points at one end only. Each train of 16 modules is equipped with a product sampling point.

The following parameters were continually monitored and visually displayed:-

Feed and product flow
Feed and concentrate pressures
Feed and product conductivity
Feed temperature and pH.

Alarm systems and automatic plant trips on all key functions enable the plant to run unattended. Any plant trip is signalled back to the works' main control room so that an immediate investigation can be made into the reason for the shut down and corrective action quickly taken.

2.4 Post Treatment

It was the intention during the operation of this full scale plant to make the product water available either to the nearby Municipal power station or to a neighbouring manufacturer of carbon black. In both cases the water would be used as a boiler feed make up, after further pretreatment by ion exchange. In the case of the neighbouring firm, no guarantee of continuous supply could be made so this supply possibility was rejected. The power station also ceased continuous generation and went onto a standby mode, thus drastically reducing the demand for boiler feed water. However water has been supplied to the station during the period from April 1989.

In order to meet the requirements of these possible end users, it was necessary to install certain post treatment stages which consisted of carbon dioxide scrubbing and pH adjustment.

The decarbonising scrubber is situated on the product line and consists of a tower down which the water cascades in counter current to an air stream supplied by a centrifugal fan. The air passing through the cascading product water reduces the carbon dioxide level from approximately 100 mg/ℓ to less than 10 mg/ℓ.

A stainless steel product tank situated at the base of the scrubber acts as a buffer tank for the pumps delivering water to the end user. A small dosing pump controlled by a pH meter adds a 20% solution of sodium hydroxide to the water in the buffer tank in order to maintain the pH of the product water at 8,0. The pH of the final product water is continually monitored and displayed.

A small chlorinator was later installed to give the added facility of being able to chlorinate the product before pumping to the user.

The post treatment installation was not intended to play a major role in the investigation as any such treatment would entirely depend on the intended use of the product water. In fact, if the product water is intended for potable use, the scrubber and sodium hydroxide dosing would not be required. All that would be necessary is the addition of lime to give a well buffered, non- corrosive water and, of course, chlorination.

During the times when the water was not required by the power station it was pumped back into the works reclaimed water reservoir.

The concentrate from the plant was discharged to the head of the sewage treatment works.

Sample points were provided at required positions on the plant.

3. OPERATING PROCEDURES

3.1 Feed

The feed to the RO plant was the Fishwater Flats reclaimed effluent which is an activated sludge secondary effluent derived from a sewage of mainly domestic origin, and which receives tertiary treatment consisting of upward flow rapid sand filtration. The reclaimed effluent is chlorinated and stored in a covered reservoir having a capacity of 9 Mℓ. No further treatment was carried out prior to the RO plant and no attempt was made to protect the plant from the upsets and resultant inferior quality works' effluent, which are sometimes experienced at a treatment works.

3.2 Operating limits

Either of two methods could be adopted for setting the flow criteria through the plant; (1) operating at a fixed feed pressure and allowing the product flow to reduce as the membranes become fouled, or (2), operating at a fixed product flow and allowing the feed pressure to rise. The second option was adopted, as on any full scale plant the most important aspect is the volume of water produced which should be kept as constant as possible. Automatic plant control is also more easily achieved by fixing the flow and monitoring the pressure.

The feed to the plant was maintained at 25 500ℓ per hour resulting in an initial feed pressure of approximately 4 200 kPa. The high pressure alarm was triggered at 4 800 kPa and the plant would automatically shut down if the feed pressure reached 5 000 kPa. At these feed volumes the concentrate exit velocity was maintained at greater than 0,48 m/sec.

3.3 Performance monitoring

The following readings were taken once per day, on weekdays, to enable plant performance to be monitored:-

Feed water: Pressure, flow, pH, temperature, conductivity, free and total residual chlorine.

Product water before post treatment : Flow and conductivity.

Final water after post treatment: pH, free and total residual chlorine

Plant running hours, pump motor current, electrical unit consumption and chemical consumption were also monitored.

A data sheet (Figure 2) was supplied to the operating staff for the logging of the above daily readings.

The following calculations were used in monitoring the plant performance:-

% Salt rejection =

$$\frac{\text{Feed conductivity mS/m - Product conductivity mS/m x 100}}{\text{Feed conductivity mS/m}}$$

$$\text{Actual flux} = \frac{\text{Product flow } (\ell/h) \times 24}{\text{Area of membrane}} \quad \ell/m^2/day$$

where area of membrane = 784 m^2 for 448 modules

$$\text{Standard flux} = \frac{4000F\,[1+0{,}025\,(20-T)]}{P} \quad \ell/m^2/day \text{ @ } 4000kPa \text{ \& } 20°C$$

where F = actual flux ($\ell/m^2/day$)

T = temperature °C

P = average of inlet and outlet pressures (kPa)

$$\text{Volume recovery \%} = \frac{\text{Product flow x 100}}{\text{Feed flow}}$$

The above calculations were carried out on a daily basis by the staff operating the plant and were logged as a performance record (Figure 3).

FIGURE 2. RO PLANT DATA SHEET

FISHWATER FLATS REVERSE OSMOSIS PLANT DATA SHEET

Name of Supervisor : .....

Date					
Flow (ℓ/h)	Feed				
	Product				
Pressure (bar)	Feed				
	Product				
E.C. (mS/m)	Feed				
	Product				
% Rejection					
Temperature °C					
Feed - pH					
Final - pH					
Feed chlorine - DPD 1					
Feed chlorine - DPD 4					
Final chlorine - DPD 1					
Final chlorine - DPD 4					
Duty pumps 201/202/203					
Pump amps	1				
	2				
Pump hours	1				
	2				
Plant running hours					
Duty filter					
Feed flow integrator					
Product flow integrator					
Electricity	Meter 1				
	Meter 2				
	Meter 3				

FIGURE 3. RO PERFORMANCE RECORD

FISHWATER FLATS REVERSE OSMOSIS PLANT - PERFORMANCE RECORD.

Date					
Feed flow - ℓ/h					
Product flow - ℓ/h					
Volume recovery - %					
Actual flux - $\ell/m^2/d$					
Feed pressure - bar					
Back pressure - bar					
Average pressure - bar					
Feed temperature - °C					
Standard flux - $\ell/m^2/d$					
Feed E.C. - mS/m					
Product E.C. - mS/m					
Salt rejection - %					
Feed free chlorine - mg/ℓ					
Feed total chlorine - mg/ℓ					
Final free chlorine - mg/ℓ					
Final total chlorine - mg/ℓ					
Plant hours run					
Filter number					
Feed pH					
Total feed volume - m^3					
Total product volume - m^3					
Electricity units	M1				
	M2				
	M3				
	Total				

3.4 Membrane cleaning

Sponge balls were used in the modules throughout the running period. Following experienced gained in the previously operated pilot plant (Vail and Barnard 1986), it was decided to fix the flow reversal interval at 60 minutes as this was found to be an adequate period between reversals.

In addition, washing, using low foam enzymatic detergents, was carried out when the feed pressure rose above 4 300 kPa. Three detergents were used during the operational period of the plant, these were Jet, Biotex and Auto-Punch. A 0,35% detergent solution at a pH of 8,5 was used for the washing process.

On two occasions when "post mortem" examinations of modules indicated that there could be some metal oxide fouling of the membranes, a citric acid wash was carried out using a 2% solution of the acid adjusted to pH 4,0 with ammonium hydroxide.

All washes were carried out for a period of two hours during which time flow reversal was effected at 30 minute intervals.

3.5 Staff levels

During the initial commissioning of the plant, the two Works' Superintendents were trained in its operation and for the period of the trial operated the plant as part of their normal routine duties. Shift Supervisors were also trained to identify alarm situations and to take action to alleviate the alarm and restart the plant or, if this was found to be impossible, to ensure the plant was safely and correctly closed down.

The plant was easy to operate and, providing it was running well, was not labour intensive, normally occupying one man for 30 minutes per day.

Detergent washes were more labour intensive and occupied two men for approximately 5 hours per wash. Module changes and sampling required additional staff time.

4. OPERATING HISTORY

The operation of the plant commenced on 12 February 1987. As was expected, initial teething problems were experienced during commissioning. However, a number of more serious problems occurred during the period of operation of the plant which resulted in frequent and extended shutdowns. Details of these problems, together with the steps taken to alleviate them, follow.

4.1 Vibration

By far the most serious initial problem was the severe vibration which occurred in the pipework and which in turn was transmitted to the module banks.

The stainless steel pipework both to and from the high pressure pumps was rigidly fixed, and the delivery pipework from the pumps to the modules was carried on overhead stanchions some 2 metres above floor level. The vibration originating in the high pressure pumps was therefore transmitted through the whole pipework system, causing frequent and rapid failure of welded joints. Vibration in the module banks also caused concern regarding possible damage to the internal structure of the modules.

In March 1987, modifications to the pipework were commenced. These basically consisted of moving the feed pipes from an overhead position to ground level in order to provide a more robust fixing; the installation of flexible high pressure rubber hoses as connections to the inlet and outlet sides of the high pressure pumps; and the installation of gas filled high pressure surge pots or accumulators to dampen any remaining vibration.

The solving of this vibration problem was very much a matter of trial and error, and an ongoing process, but by the end of 1987 it had been overcome. Although occasional cracks in the pipework have since occurred, usually at welded points, for example where sample cocks are fitted, together with infrequent failure of rubber hoses, these problems are no longer considered to be abnormal or serious and can easily be remedied on site.

4.2 High pressure pumps

For this specific application the three high pressure pumps proved to be very unsatisfactory units in that they required an extraordinary high level of expensive maintenance. The pistons, valves and seats required to be stripped, cleaned and inspected at intervals of between 600 and 700 hours and any parts showing excessive wear had to be replaced. In fact, experience showed that after only approximately 400 running hours, the pistons were badly scored and required replacement. Valve breakages also occurred. Oil changes were necessary after 1 000 running hours. This level of maintenance was unacceptable, both with regard to the cost of parts and labour. For example, the replacement of a set of plungers and valves cost in the order of R 2 500 per pump for parts alone. Long delays in obtaining the necessary spares were also experienced. As a result of this, the staff of the Plant Maintenance Division of the City Engineer's Department, developed and carried out modifications to the fluid end of the pumps. These basically consisted of machining the pistons to a reduced diameter and re-hardchroming them. The conventional packing in the stuffing box was replaced with a Vesconite sleeve in which the piston moved. Hydraulic seals were installed at the extremities of the sleeve. The valves were also redesigned and manufactured from stainless steel with a moulded synthetic insert at the contact with the valve seat. Since these modifications have been carried out the pumps have operated in excess of 5 000 hours without any sign of excessive wear. This is compared to the 400 hours working life of the original units. These modifications cost in the order of R 3 410 per pump, (consisting of R 1 360 for materials and R 2 050 for labour), and resulted in a reliable pumping unit with realistic maintenance requirements.

4.3 Acid dosing

Concentrated sulphuric acid was dosed as required to the feed water by means of an eductor operating on a venturi system. A number of problems were experienced with this unit culminating in the occasion when water was drawn back into the concentrated acid storage tank. Following this, it was decided to replace the eductor with a system based on a small variable speed dosing pump of the diaphragm type. After an initial failure, the 98% acid completely dissolving the head of the pump, a pump having a stainless steel head and fitted with a diaphragm manufactured from EPDM synthetic rubber faced with PTFE was installed. This unit has proved to be very effective and reliable.

4.4 Feed water control valve

The level of the water in the feed buffer tank is controlled by an automatic valve actuated by a pilot ball float. This unit failed on a number of occasions and eventually had to be replaced having corroded beyond repair.

4.5 Instrumentation

All instruments have given problems, the more serious of these being as follows:-

(a) The trip amplifier had to be returned to the manufacturer for repair, which took two months. During this time the plant had to be continuously manned, as no alarms or trips were operative, and therefore could only be operated during normal working hours.

(b) Two major failures of the pH meter necessitated its return to the manufacturer on both occasions. This resulted in a shut down of the plant for a total period of three months as it cannot be operated without pH control.

(c) The conductivity meter failed on a number of occasions and also had to be returned for repair, which resulted in a two month shut down of the plant.

(d) Other instrument failures, with resultant plant shutdowns, have been caused by faulty temperature probes, pH probes, pressure recorders, flow reversal timer and switch. Even the main panel isolator had to be replaced. Corrosion of terminals and connections in the instrument panel began to give problems in the latter period of the project.

The frequent failure of instrumentation resulted in very erratic and intermittent plant operation. The selection of suitable industrial instrumentation is critical to the successful operation of such a plant. Unfortunately, due to a limited budget, the corrosive atmosphere around the plant and the robustness of items were not given sufficient consideration during the stage of instrumentation specification.

4.6 Flow reversal mechanism

The pneumatic pistons and cylinders became badly worn and corroded and had to be replaced. During the two week period taken to effect repairs, the plant could only be run during the working day as flow reversal had to be carried out manually.

4.7 Modules

200 modules (44,6% of the original modules installed) failed during the 11 621 hours of plant operation, i.e. one module failure every 58 hours of plant operation. This failure rate is much higher than the expected 33% of the total over a three year period, and greatly contributed to the much reduced plant running time. In each case of module failure, the indication was that a mechanical breakdown of the internal structure had taken place so allowing feed water to "break through" into the product water. This high percentage of mechanical failure of the module indicates a serious manufacturing and quality control problem. Autopsies performed on defect modules showed two causes of module failure, viz. (i) Failure of membrane tube welds. (ii) Poor epoxy/turncap interface. The manufacturer claims that these problems have since been resolved by adopting a lower weld speed, resulting in substantially increased weld seam strength, and by redesigning the turncap as well as adaptation of the curing procedure. It is further recommended that the operating pressure be lowered from 4 600 kPa to 4 000 kPa to increase the safety margin. The replacement cost, on an exchange basis, was R 529 per module and the high replacement requirement questions the economic viability of the process. Figure 4 shows the accumulative total of module replacements. These replacements are also reflected in Figures 5 - 10.

The sponge ball insertion blocks situated on each row of 16 modules had been designed to allow the insertion of the balls while the plant was in operation however these were never successful and need to be redesigned. Sponge balls could only be added by shutting down the plant, removing one of the module interconnecting pipes and inserting the ball.

As a result of the dismal saga of failures described above, the plant operated for only 11 621 hours out of a possible total of 31 104 since commissioning, i.e. for 37,4% of the total available time. 5 - 10% downtime can reasonably be expected from an RO plant. No standby instrumentation was installed because of initial economic restraints, and the frequent failure of both mechanical and electrical equipment has highlighted the imperative requirement that high quality equipment with 100% standby for certain vital parts must be installed on any plant which is expected to operate continuously. However, even with such equipment, there still remains the serious question of module reliability which must be addressed by the manufacturer before any large scale plant becomes a viable proposition.

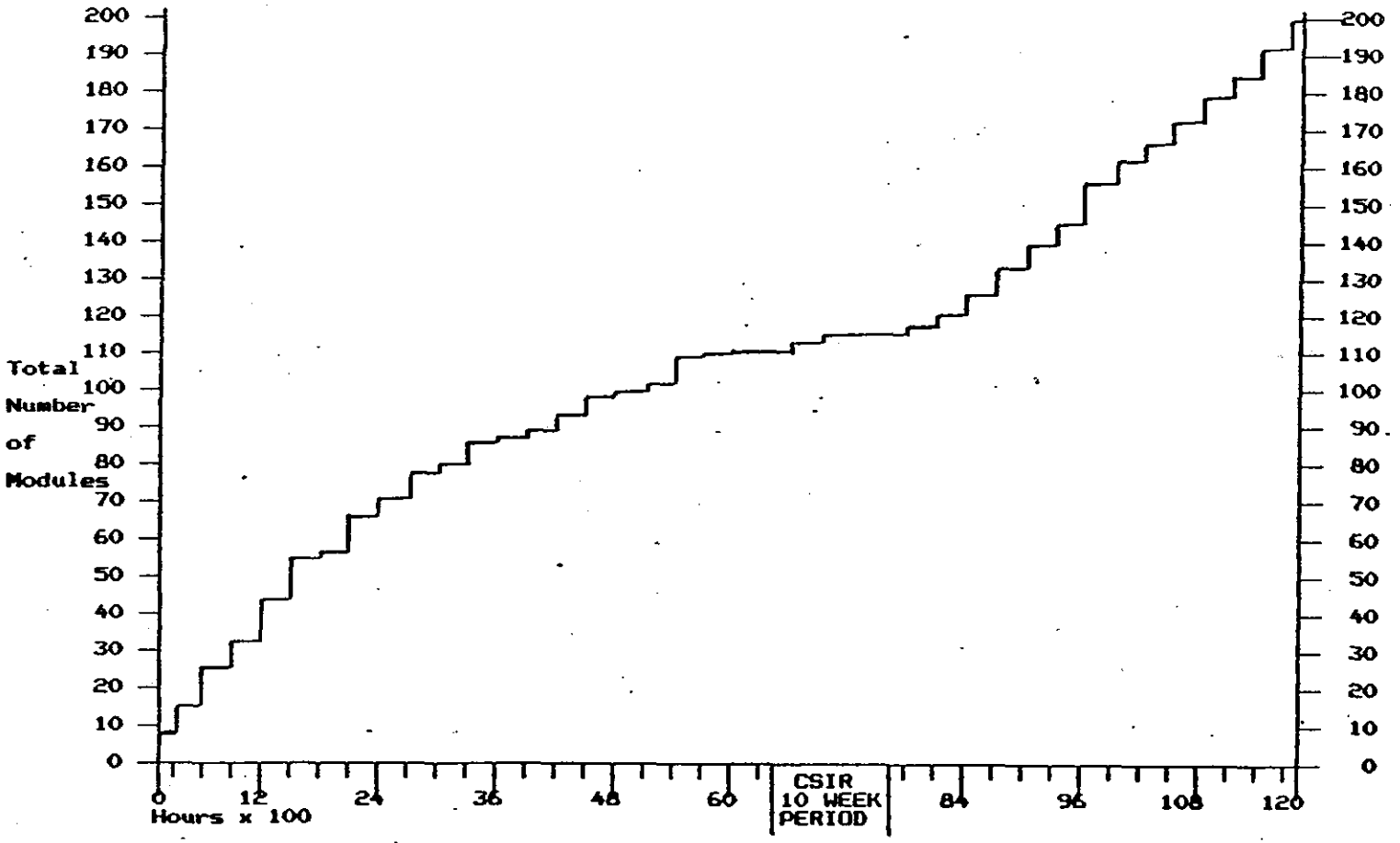

FIGURE 4 ACCUMULATIVE RECORD OF MODULE REPLACEMENTS

5. OPERATIONAL RESULTS AND DISCUSSION

5.1 Production

Figures 5 and 6 show the percentage flow recovery and the 200 hour average flow recovery respectively.

The feed flow to the plant averaged 25 475 ℓ/h, with an average product flow of 17 186 ℓ/h, i.e a 67,5% recovery rate, which is marginally lower than the design figure of 70%.

The fall off in flow recovery which occurred at just over 6 000 hours, as shown in Figure 5, was as a result of the deliberate reduction in feed pressure in an attempt to reduce the number of module failures.

The decline in flow recovery which occurred during the period from 10 870 to 11 350 hours occurred because up to five rows of modules had to be taken out of service. The reason for this was that a number of modules failed but replacements had not been received from the manufacturer.

The temperature of the feed water ranged from 17,5°C to 29°C with an average of 22,9°C.

Figure 7 shows plant performance as measured by the standard flux which averaged 570 $\ell/m^2/d$ during the period of the trial.

Figure 8 gives the peak standard flux, which is measured immediately after each wash. The average peak standard flux during the period from 10 000 to 11 621 hours, i.e. during the last part of the trial period, was 562 $\ell/m^2/d$ compared with the average of 636 $\ell/m^2/d$ obtained during the period from 300 to 2 000 hours. This represents a drop in flux of 13%. The initial steep fall in flux due to compaction of the membranes, which was expected to take place during the first 300 hours of operation, is not reflected in the results. This probably occurred during plant commissioning when mechanical problems precluded normal continuous operation and readings were therefore not taken.

The sudden decline in peak standard flux which occurred at approximately 9 000 hours cannot be explained. However, the plant seemed to recover and flux levels returned to above average.

The overall flux decline was higher than reported in earlier work, (Vail and Barnard 1986), however it continues to demonstrate that membrane fouling can be controlled within reasonable limits without any pretreatment of the feed water other than rapid sand filtration.

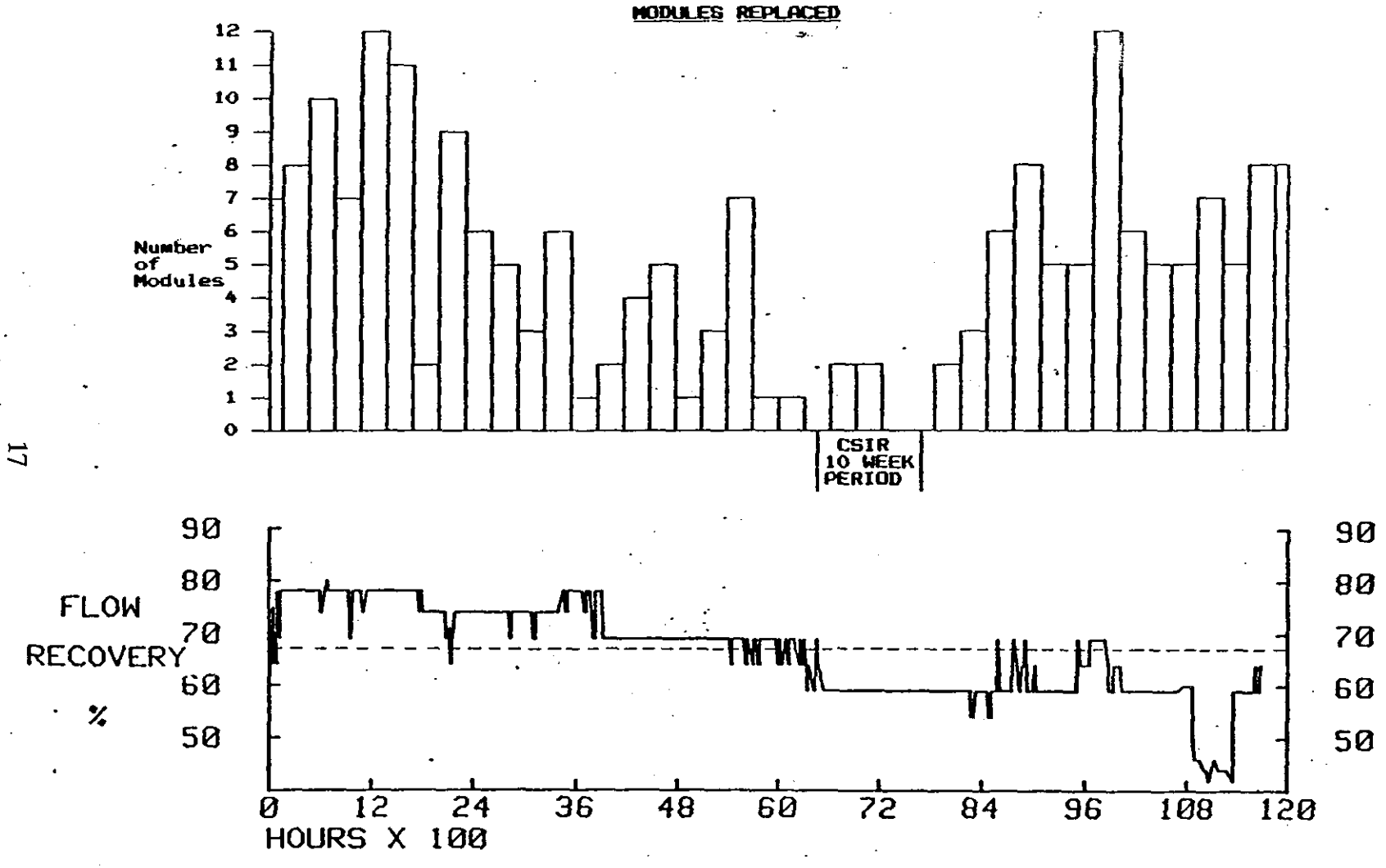

FIGURE 5 PERCENTAGE FLOW RECOVERY AND MODULE REPLACEMENT

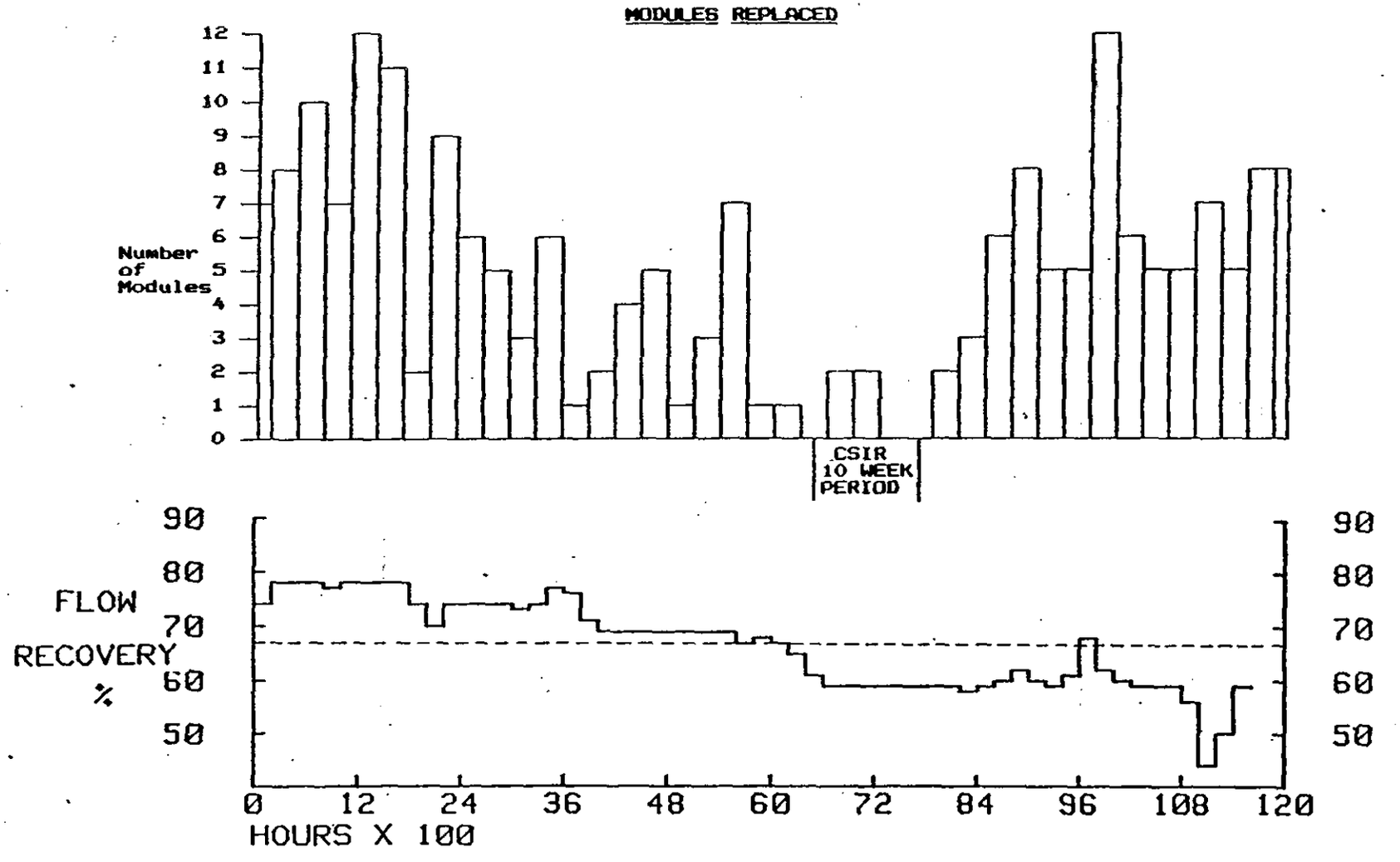

FIGURE 6 PERCENTAGE FLOW RECOVERY - 200 h AVERAGES AND MODULE REPLACEMENTS

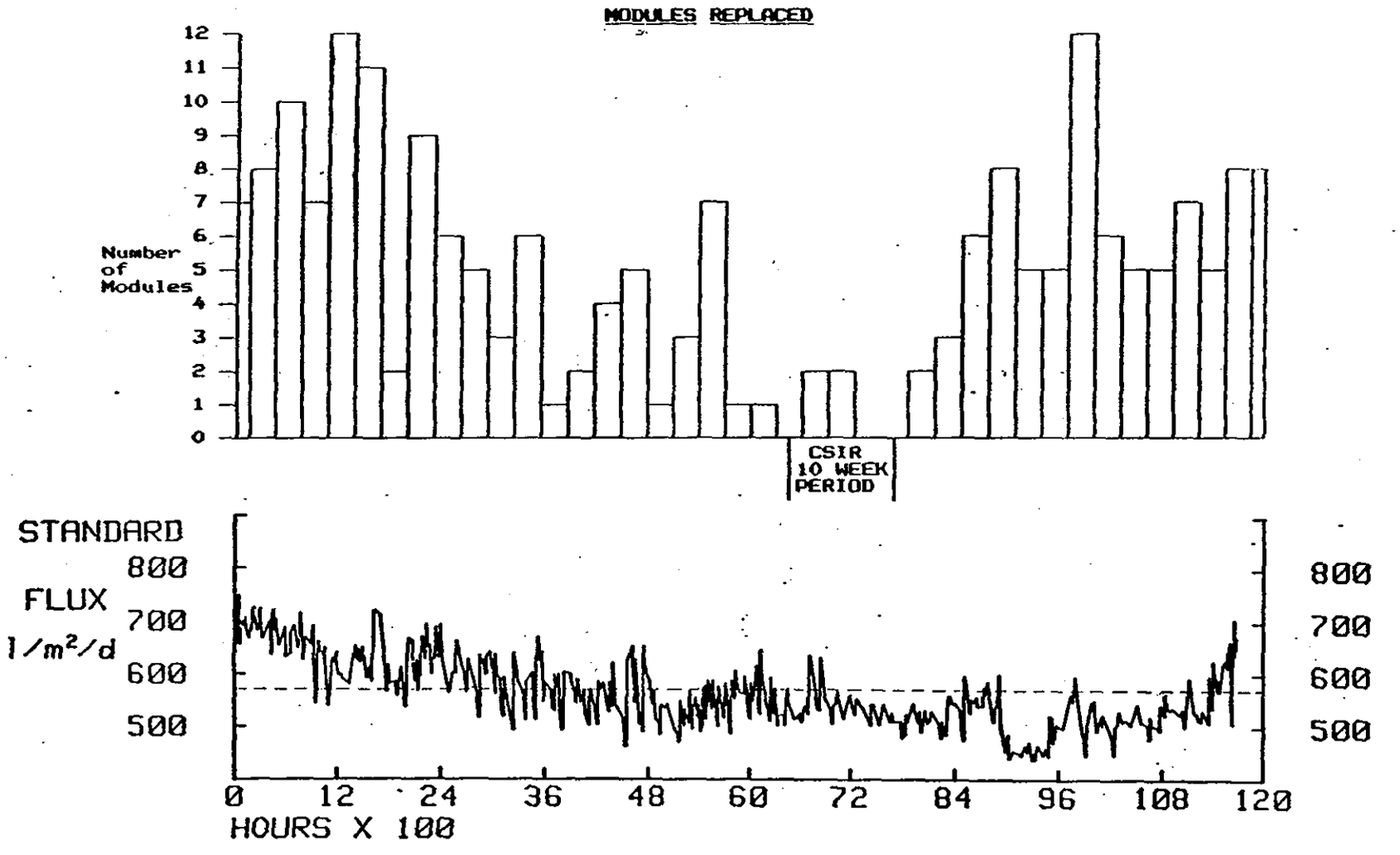

FIGURE 7 STANDARD FLUX AND MODULE REPLACEMENTS

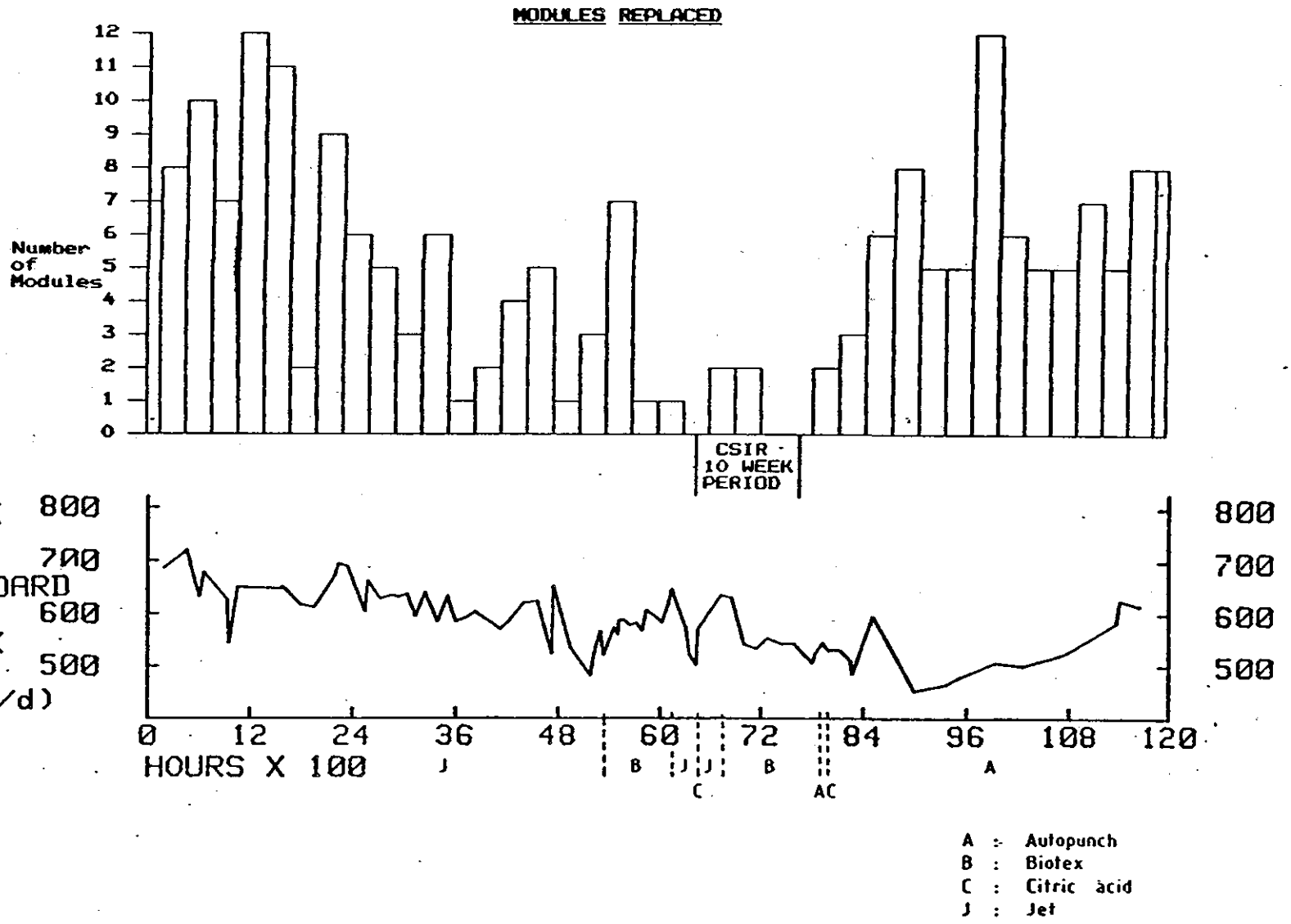

FIGURE 8 PEAK STANDARD FLUX AND MODULE REPLACEMENTS

5.2 Membrane degradation

One of the best available indicators of membrane degradation caused by chemical and/or bacteriological hydrolysis is the measure of salt rejection. Figure 9 shows the salt rejection obtained and Figure 10 gives the 200 hour averages of salt rejection. The average rejection was 88,3%, the maximum level obtained being 97,1% and the lowest 68,8%. The low points on the graph shown in Figure 9 were due to mechanical failures in modules and not degradation by hydrolysis.

The decrease in salt rejection, which occurred from approximately 7 000 to 10 000 hours, was also reflected in a decline in both flow recovery and flux measurements and suggests that it could have resulted from polarisation consequent on fouling. The results do not suggest any serious degradation of the modules.

5.3 Membrane Washing

The enzymatic detergents used in the membrane washing procedures were changed at random intervals. These were as follows:-

Up to 5 450 hours	-	Jet Low Foam at pH 8,5.
From 5 450 to 6 255 hours	-	Biotex at pH 8,5.
From 6 255 to 6 451 hours	-	Jet Low Foam at pH 8,5.
From 6 460 to 7 921 hours	-	Biotex at pH 8,5.

From 7 921 hours until the end of the programme, Autopunch at pH 8,5 was used.

At 6 451 hours, a citric acid wash at pH 4,0 was carried out. This was to remove any form of metal oxide which may have been deposited on the membrane surface.

A further citric acid wash was carried out at 7 992 hours.

The various types of detergent did not show any significant differing effects on plant performance, except for the significant increase in flow recovery and flux which occurred from about 9 000 hours onward during the period in which Autopunch was being used. However, no firm conclusions can be drawn as to the relative performance of the various types of detergents used.

The first citric acid wash was followed by a significant increase in peak standard flux, but this did not reoccur when the second acid wash was carried out.

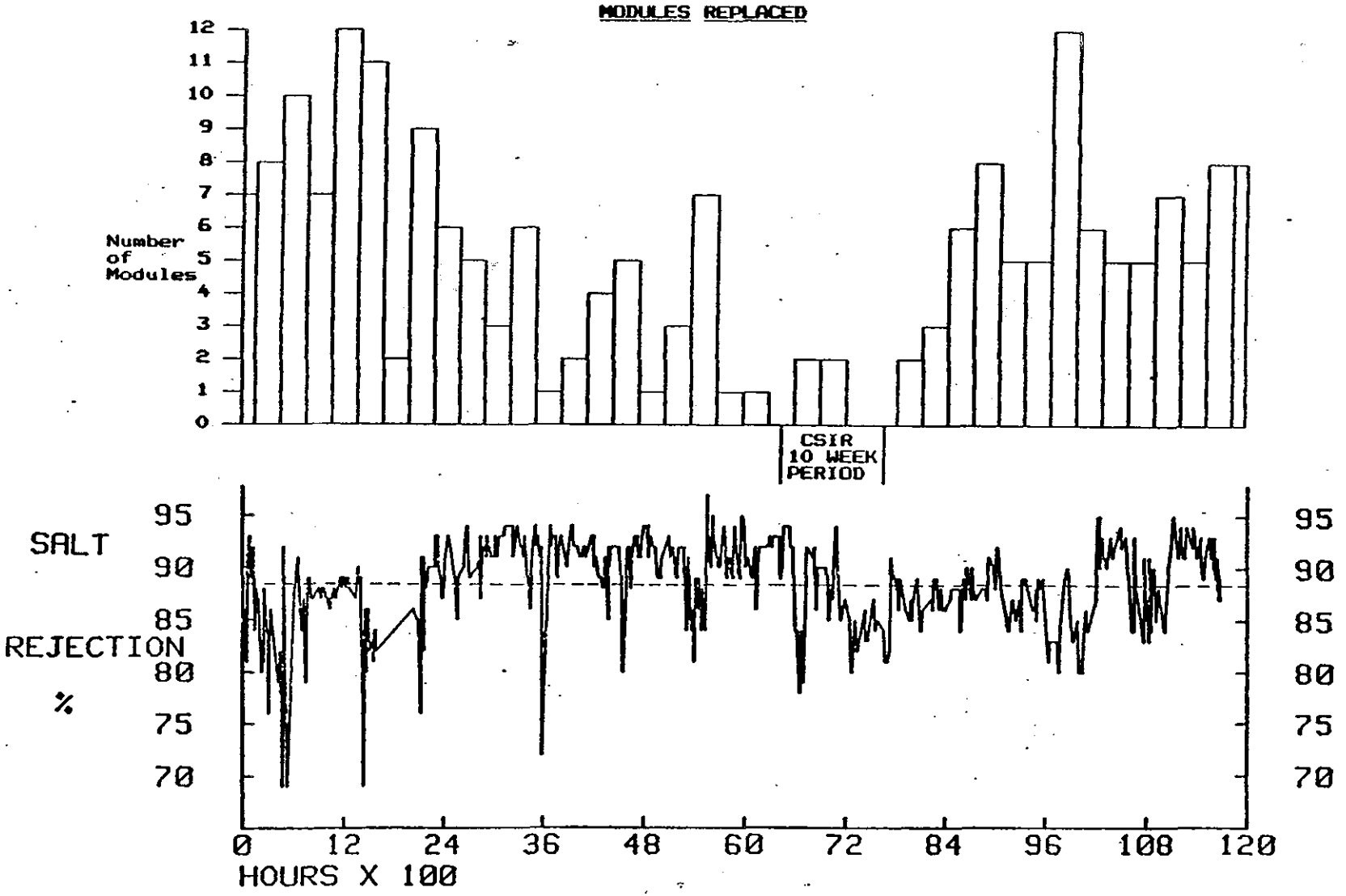

FIGURE 9 PERCENTAGE SALT REJECTION AND MODULE REPLACEMENTS

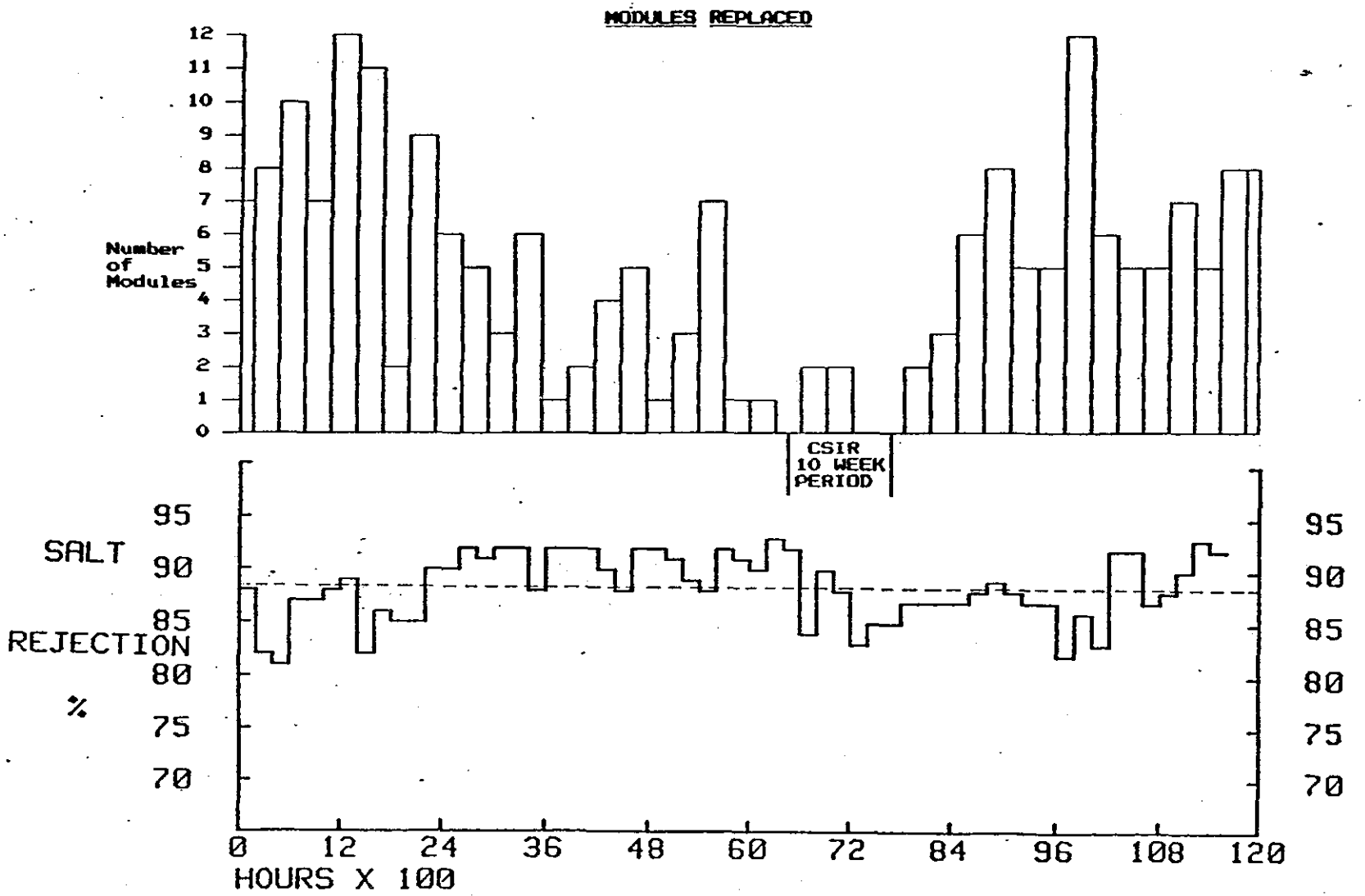

FIGURE 10 PERCENTAGE SALT REJECTION - 200 h AVERAGES - AND MODULE REPLACEMENTS

6. SAMPLING AND ANALYTICAL PROGRAMME

The sampling and analytical programme was drawn up in the light of the results achieved during the operation of the pilot scale RO plant.

It was decided that for routine chemical analysis there would only be three sample points, namely, feed to the RO unit after pH adjustment; product, before post-RO treatment; and final product, after post-RO treatment. The type of water quality variables that were to be tested fell into two different categories, firstly those which were mainly aimed at assessment of plant performance and secondly those which were to be used to assess the suitability of the RO product as a potable water.

There was a basic sampling and analysis programme drawn up for the in-house Port Elizabeth Municipality routine chemical and bacteriological monitoring of the RO plant and this is set out below.

6.1 P.E.M. Routine Chemical and Bacteriological Monitoring Programme for Full Scale RO Plant

6.1.1 Sampling Points

1. Feed to RO, after pH adjustment
2. Product, before post RO treatment.
3. Final product, after post RO treatment.

6.1.2 Types of Samples

Composites: One sample per 8 hour shift (i.e. 3 samples per 24 hours), kept cool, and combined equally to give a one day composite, Sundays to Thursdays inclusive. For each of sample points 1 & 2, 2,5 litre samples were taken on each of the three shifts, and these were then mixed in the laboratory before the commencement of any analyses.

Snaps : Grab samples taken once per day, Mondays to Thursdays inclusive, or as required, and cooled if necessary.

6.1.3 Analyses Required

Point No.1	Composite	pH, E.C., alkalinity, calcium, sodium, chloride, sulphate, ammoniacal nitrogen, suspended solids, turbidity, U.V. abs. 275 nm.
	Snap	Standard bacterial count, total coliforms, faecal coliforms, coliphages
Point No.2	Composite	As for Point No.1, except suspended solids.
	Snap	As for Point No.1.

Point No.3 Composite pH, E.C., alkalinity, calcium and sodium.

Snap As for Point No.1.

This routine monitoring programme was commenced from the start of operation of the full scale RO plant. Sampling was rather hit and miss at times because of the frequent breakdown of various items of plant, and there were long periods of time when samples were not submitted. However, many samples were fully analysed thus building up the quantity of analytical data to support the operational data. In fact the number of water quality variables tested far exceeded those in the above list, and included many, if not all, of the water quality variables set out in the Water Quality Surveillance Programme that is detailed below.

6.2 Water quality surveillance programme

After consideration by the Working Group Sub-Committee, a Proposed Water Quality Surveillance Programme was drawn up, which was basically an expansion of the above routine monitoring programme. The purpose of this programme was to carry out, in conjunction with the CSIR, D.W.T., as the independent body, an in-depth assessment of the water quality achieved by the plant. The work was to be undertaken over a ten week period and the actual surveillance programme was carried out as set out below.

6.2.1 Sampling Points

As set out in P.E.M. routine monitoring programme above.

6.2.2 Types of Samples

As set out in P.E.M. routine monitoring programme above.

6.2.3 Analyses Required

Group A (Composite samples) by Port Elizabeth Municipality
Electrical conductivity, calcium, ammoniacal nitrogen, pH, suspended solids, orthophosphate, alkalinity, UV Abs. 275 nm, organic nitrogen, turbidity, magnesium, organic phosphorus, colour, chloride, phenols, chemical oxygen demand, sulphate, cyanide, sodium, nitrate nitrogen, fluoride, potassium and detergents (as MBAS).

Group B* (Composite samples) by Port Elizabeth Municipality

Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, Sr, Zn.

* No analysis for this group will be necessary on the RO product unless the level of the water quality variable in the RO feed is greater than the recommended limit for that variable.

In actual fact the analyses for Ba, Be and Sr could not be done by P.E.M. and these were carried by CSIR, D.W.T.

Group C (a) (Snap samples) by P.E.M. and CSIR, D.W.T.

Standard bacterial count, faecal coliforms and total coliforms.

Group C (b) (Snap samples) by CSIR, D.W.T.

Acid fast bacilli, faecal streptococci, spore formers, coliphages.

Group D (Snap samples) by CSIR, D.W.T.

Viruses

Group E (Snap samples) by CSIR, D.W.T.

Organic profile, PAH's, THM's, D.O.C., chlorinated pesticides and U.V. absorption (Scan)

Group F (Snap samples) CSIR, D.W.T.

Ames test, Luciferase test, bacterial growth inhibition test and *Daphnia pulex* lethality test.

6.2.4 Summary of Sampling

		Points
P.E.M.		
Group A	2 points x 2 per week = 4 samples/week	1 & 2
Group B	2 points x 2 per week = 4 samples/week	1 & 2
Group C(a)	3 points x 3 per week = 9 samples/week	1,2&3
CSIR, D.W.T.		
Group C(a&b)	3 points x 1 per week = 3 samples/week	1,2&3
Group D	3 points x 1 per week = 3 samples/week	1,2&3
Group E	3 points x 1 per week = 3 samples/week	1,2&3
Group F	1 point x 1 per week = 1 sample/ week	3

6.2.5 Plant Operation

Copies of the operational data sheets for the ten week period are available on request from the Water Research Commission.

6.3 Analysis of Samples

The normal sample preservation techniques were carried out on all samples where the analysis could not be commenced within 24 hours, otherwise samples were stored in the refrigerator. All analytical methods were primarily standard methods

with a few exceptions such as nitrate nitrogen. For low level water quality variables such as the toxic metals analysed by atomic absorption spectrophotometry, samples were concentrated by evaporation. The one water quality variable which did cause some problems was "phenols". Very little success was had with the low level chloroform extraction method that is in Standard Methods, 1985, and consequently the minimum detection level, at approximately 6 micrograms/litre was higher than was wanted. However, this was the only water quality variable which gave any problems in the analytical procedures.

Several water quality variables consistently gave results below the minimum detection level of the methods used. In order to obtain as much statistical information as possible from this project, wherever this occurred the results have been expressed as half the minimum detection level. The water quality variables that were at times or on all occasions below the minimum detection level are set out in Table 1, together with the minimum detection limits. The reason for the differences between the minimum detection levels of the feed and product was because the feed was concentrated 30 times, whereas the product had to be concentrated 60 times to obtain solutions of sufficient strength for representative analysis. In the case of arsenic selenium and mercury, where detection levels are the same for both feed and product, analysis was by vapour generation, and no concentration was necessary. Fluoride levels in both samples were generally below the sensitivity limit of the selective ion electrode, and no preconcentration was carried out.

Table 1. Minimum Detection Levels for Selected Elements

Water Quality Variable	Minimum Detection Level ($\mu g/\ell$)	
	Feed	Product
Arsenic	0,2	0,2
Cadmium	0,33	0,17
Chromium (total)	5	2,5
Cobalt	2,2	1,1
Copper		0,8
Fluoride	100	100
Lead	5	2,5
Mercury	0,5	0,5
Nickel		0,8
Selenium	0,4	0,4

7. ANALYTICAL RESULTS DURING PERIOD 16 MARCH 1987 - 25 MAY 1990

All the analytical data for the period 16 March 1987 to 25 May 1990 has been statistically treated to arrive at the overall result. Because of the frequent breakdown of equipment and machinery the total number of samples analysed was less than was anticipated at the start of the project. However, there were in the order of 180 composite sets of analyses carried out, which makes a satisfactory statistical evaluation possible. Chemical results for feed, product and % rejection are set out in Tables 2 and 3. The water quality variables have been separated into macro and micro constituents to allow for an easier appraisal of the results.

Macro variables are :-
Chloride, sulphate, total Kjeldahl nitrogen, ammoniacal nitrogen, nitrate nitrogen, sodium, potassium, silica, total phosphorus, orthophosphate, UV absorbance 275 nm, electrical conductivity, pH, colour, turbidity, suspended solids, chemical oxygen demand, calcium, magnesium and total alkalinity.

Micro variables are :-
M.B.A.S., cyanide, fluoride, trihalomethanes, phenols, arsenic, aluminium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, selenium and zinc.

Bacteriological results are given in Table 4

8. DISCUSSION OF CHEMICAL AND BACTERIOLOGICAL RESULTS

In order that a satisfactory evaluation of the performance of the RO plant can be carried out it is necessary to compare the results achieved with prescribed standards for potable water quality. To this end Table 5 sets out various limits as prescribed by the following Standards/Guidelines :-

1. S.A.B.S. 241-1984, Water for Domestic Supplies

2. Proposed aesthetic/physical and inorganic drinking water criteria for the Republic of South Africa. Kempster, P.L. and Smith, R.. CSIR Research Report No. 628, 1985

3. Guidelines for Drinking Water Quality, Volume 1, Recommendations, World Health Organisation, Geneva 1984.

8.1. Chemical Results

A review of the chemical composition of the RO product shows that it is of a high quality when compared to drinking water standards. As far as the macro-pollutants are concerned, there is only one area for discussion, and that is the level of ammoniacal nitrogen, which on average is above the maximum permissible level of the guideline value as given by Kempster and Smith, 1985.

TABLE 2. CHEMICAL RESULTS - MACRO CONSTITUENTS - COMPOSITE DAILY SAMPLES

Results in mg/ℓ unless otherwise stated	Feed		Product				% Rejection	
					95% CL			
	M	SD	M	SD	H	L	M	SD
Conductivity @ 25°C, mS/m	151,2	21,1	28,0	14,6	30,5	25,5	82	9
Sodium (as Na)	221	38,6	42,5	19,2	45,3	39,6	81	8
Potassium (as K)	22,3	4,8	3,2	0,9	3,6	2,9	85	4
Calcium (as $CaCO_3$)	85,4	17,7	10,7	8,0	11,9	9,6	87	9
Magnesium (as $CaCO_3$)	70,0	18,9	11,5	6,8	12,8	10,3	84	9
Total alkalinity (as $CaCO_3$)	54,1	28,6	12,6	4,7	13,3	11,9	71	17
Chloride (as Cl)	302	53,7	52,0	28,7	56,2	47,8	83	8
Sulphate (as SO_4)	141	46,4	18,2	14,8	20,4	15,9	87	9
Total phosphorus (as P)	1,9	1,70	0,39	0,33	0,55	0,24	75	24
Orthophosphate (as P)	1,75	1,19	0,24	0,22	0,35	0,14	81	16
Silica (as SiO_2)	9,8	1,76	1,48	0,62	1,71	1,25	83	6
Total Kjeldahl nitrogen (as N)	14,7	7,8	4,96	1,85	5,70	4,22	75	10
Ammoniacal nitrogen (as N)	11,7	7,4	2,19	1,47	2,41	1,97	78	13
Nitrate nitrogen (as N)	3,7	3,2	0,93	0,60	1,20	0,66	60	13
Colour (Hazen units)	30	NA	<5	NA	-	-	NA	-
Turbidity (NTU)	2,3	1,1	0,57	0,40	0,63	0,51	73	14
UV Absorbance (275 nm)	0,286	0,047	0,036	0,024	0,039	0,032	87	9
Chemical oxygen demand	64,7	14,5	ND	-	-	-	NA	
Suspended solids	6,0	4,8	ND	-	-	-	NA	-
pH (Laboratory)	ND	-	5,9	NA	-	-	NA	-
Residual chlorine - free	0,5	-						
Residual chlorine - total	1,5	-						

M = Mean or Median SD = Standard Deviation 95% CL = 95% confidence limits of mean

ND = not determined NA = not applicable

A minimum of 100 feed samples were analysed for each water quality variable.

TABLE 3. CHEMICAL RESULTS - MICRO-CONSTITUENTS - COMPOSITE DAILY SAMPLES

Results in µg/ℓ	Feed		Product				% Rejection	
					95% CL			
	M	SD	M	SD	H	L	M	SD
Aluminium *	31	26	43	6	46	40	-135	102
Arsenic	0,28	0,11	0,11	NA	-	-	>59	-
Cadmium	0,38	0,73	0,27	0,32	0,42	0,12	58	13
Chromium	10,78	6,18	3,19	2,89	4,52	1,85	81	13
Cobalt	1,28	1,17	0,54	NA	-	-	>50	-
Copper	5,00	5,70	0,54	NA	-	-	>82	-
Iron	89,3	27,2	12,30	5,11	14,66	9,94	85	8
Lead	5,64	12,18	1,25	NA	-	-	>53	-
Manganese	55,1	24,07	8,64	3,82	10,40	6,87	88	5
Mercury	0,32	0,27	0,25	NA	-	-	-	-
Nickel	17,3	6,14	3,08	1,94	3,98	2,19	86	7
Selenium	0,37	0,32	0,25	NA	-	-	-	-
Zinc	38,3	10,22	5,64	2,05	6,58	4,69	85	5
Boron (as B)	170	69,3	171	49,9	194,4	149,1	NA	-
Cyanide (as HCN)	15,9	16,1	2,16	1,29	2,77	1,54	89	13
Detergents - MBAS (as LAS)	86,0	124,0	17,0	22,0	28,0	6,0	60	42
Fluoride	268	255	56,1	18,1	62,8	49,4	NA	-
Phenols (as C_6H_5OH)	29,9	30,2	10,6	7,2	14,7	6,5	76	21
Chloroform	12,4	7,6	ND	-	-	-	NA	-
Bromodichloromethane	14,9	11,3	ND	-	-	-	NA	-
Dibromochloromethane	9,1	10,7	ND	-	-	-	NA	-
Bromoform	1,4	1,8	ND	-	-	-	NA	-

* Aluminium increase because of Al casing on modules.

M = Mean or Median SD = Standard Deviation 95% CL = 95% confidence limits of mean

ND = not determined NA = not applicable

TABLE 4. BACTERIOLOGICAL RESULTS - SNAP SAMPLES

Sample Date	Feed before acidification						Product after RO				Final product after treatment					
	Total bacterial count per ml	Total coliforms per 100 ml	Faecal coliforms per 100ml	Coliphage per 100 ml	Total res. chlorine (mg/l)	Free res. chlorine (mg/l)	Total bacterial count per ml	Total coli-forms per 100 ml	Faecal coli-forms per 100 ml	Coliphage per 100 ml	Total bacterial count per ml	Total coli-forms per 100 ml	Faecal coliforms per 100 ml	Coliphage per 100 ml	Total res. chlorine (mg/l)	Free res. chlorine (mg/l)
18-03-87		0	0	76		0,4	1	0	0	0						
23-03-87	38	0	0		3,0	1,0	0	0	0		1	0	0			
24-03-87	40	0	0	78	2,5	0,6	1	0	0	0	1	0	0			
25-03-87	13	0	0	281	3,0	0,5		0	0	0	4	0	0	0		
01-04-87	17	0	0	343	3,0	0,6	48	16	19	122	58	7	5	327		
07-04-87	>2 000	0	0	22	2,5	1,0	>20 000	CG*	420	0	>20 000	CG*	550	3		
08-04-87	18	0	0	17	2,5	1,0	3	0	0	0	7	0	0	0		
27-04-87	>2 000	10	1	*	2,0	0,3	>2 000	3 100	190	12	>2 000	>2 000	400	55		
28-04-87	>20 000	14	2	*	1,0	0,2	20 000	1 800	80	*	18 700	3 600	280	*		
04-05-87	6 900	0	0	87	1,5	0,3					860	0	0	6		
11-05-87	>2 000	10	10	137	0,6	0,3	>2 000	90	23	23	>2 000	80	60	11		
12-05-87	>2 000	<100	0	*	1,0	0,2	>2 000	<100	9	*	>2 000	<100	2	*		
17-01-89	>2 000	<10	0				>200	<10	0		>200	<10	0			
18-01-89	>2 000	<10	0				1 120	<10	0		360	<10	1			
24-01-89	160	0	0				>2 000	>20 000	>20 000		176	>2 000	980			
31-01-89	>2 000	20	0	457			>200	20	1		>200	16	1	0		
07-03-89	>20 000	CG	6	192			>2 000		1		>2 000		4			
08-03-89	10 700	<10	0	170			<10	0	0	0	240	0	0	0		
15-03-89	80	0	0				3	0	0	4	6	0	0	0		
04-04-89	2 000	10	0	672			570	0	0	67	360	0	0	0		
26-04-89	1 230	0	0	140			8	0	0	7	16	0	0	13		
01-08-89	920	0	0	2 080			12	0	0	5	6	0	0	4	2,5	
02-08-89	9 900	1 000	2	1 040			89	4	0	4	79	0	1	2		
03-08-89	21 000	<100	0	1 800			1 320	10	0	224	2 130	3	0	640	1,0	
08-08-89	>20 000	<1 000	<10	3 160			>2 000	<100	0	383	>2 000	<100	0	368		
09-08-89	3 200	100	0	1 566			1 910	20	0	204	>2 000	<10	0	342		
10-08-89	20 000	100	10	766			>2 000	10	0	154	>2 000	10	0	177		
15-08-89	36 000	1 000	<10	481			3 700	<10	0	23	820	<10	0	16	0,4	0,3
16-08-89	198 000	<10 000	10	761			>2 000	1 000	10	9	380	<100	0	22	1,0	0,2
17-08-89	13 700	<100	<10	624			16 700	30	2	42	1 110	<10	0	11	1,0	0,3
22-08-89	207 000	100	<10	540			33 400	10	0	5	11 300	<10	0	10	0,2	0,1
24-08-89	20 000	<100	<10	641			13 200	<10	0	45	2 100	<10	0	26	0,4	0,1
29-08-89		<100	<10	353				<10	0	17		10	0	25	0,4	0,1
30-08-89	>200 000	100	<10	682			9 300	10	0	44	2 100	<10	0	31	0,4	0,1
31-08-89	13 700	<100	<10	838			700	<10	0	6	450	<10	0	13		
05-09-89	<100	<10	<10	73			220	0	0	1	320	0	0	1	0,4	0,1

TABL4. (Continued)

Sample Date	Feed before acidification						Product after RO				Final product after treatment					
	Total bacterial count per ml	Total coliforms per 100 ml	Faecal coliforms per 100ml	Coliphage per 100 ml	Total res. chlorine (mg/l)	Free res. chlorine (mg/l)	Total bacterial count per ml	Total coli-forms per 100 ml	Faecal coli-forms per 100 ml	Coliphage per 100 ml	Total bacterial count per ml	Total coli-forms per 100 ml	Faecal coliforms per 100 ml	Coliphage per 100 ml	Total res. chlorine (mg/l)	Free res. chlorine (mg/l)
06-09-89	1 630	<10	0	354			128	0	0	0	14	0	0	1	1,0	0,1
07-09-89	620	<10	0	281			107	0	0	21	13	0	0	3	1,0	0,1
14-09-89	3 800	70	0	877			114	0	0	26	106	0	0	6	1,5	0,2
19-09-89	970	10	0	757			67	0	0	2	43	0	0	15	1,0	0,2
26-09-89	210	<10	<10	142			60	<10	0	3	30	<10	0	5	0,4	0,3
27-09-89	90	0	0	261			950	0	0	54	16	0	0	3	0,8	0,3
28-09-89		16	12	1 214				0	0	3		0	0	44	0,7	0,2
03-10-89	>200 000	320 000	2 000	111	0,3	0,1	>20 000	19 000	100	2	>20 000	17 000	30	0	0,4	0,1
11-10-89	33 000	<1 000	<100	612	0,3	0,1		<100	<10	86	2 400	<100	<10	94	0,4	0,1
12-10-89	790	0	0	201	2,0	1,0	130	0	0	5	19	0	0	3	0,8	0,2
18-10-89	51 000	<1 000	<100	269	0,4	0,1	7 500	100	<10	249	120	<100	<10	54	0,8	0,1
19-10-89	440	0	0	171	2,0	1,0	310	0	0	134	6	0	0	1	1,0	0,2
24-10-89		0	0	115	2,0	1,0		0	0	18		0	0	37	0,7	0,1
25-10-89	400	0	0	715	1,3	0,4	52	4	0	348	5	1	0	37	1,2	0,3
26-10-89	200	0	0	463	2,0	1,0	10	0	0	4	3	0	0	0	1,4	0,3
31-10-89	80	<2	<2	30	2,0	1,0	18	0	0	9	5	0	0	3	1,3	0,3
01-11-89	870	0	0	304	1,0	0,2	55	0	0	14	15	1	0	5	1,5	0,5
02-11-89	980	<10	0	366	1,4	0,3	45	0	0	13	12	0	0	35	1,2	0,2
07-11-89	30	0	0	51	2,0	1,0	4	0	0	1	255	0	0	0	1,2	0,2
08-11-89	60	0	0	94	2,0	1,0	11	0	0	15	5	0	0	3	1,5	0,6
22-11-89	20	<10	<10	58	0,8	0,2	3	0	0	2	1	0	0	0	1,2	0,4
07-12-89	22	0	0	61	1,5	0,5	15	0	0	15	9	0	0	11	1,0	0,3
12-12-89	28	<10	<10		0,7	0,1	12	0	0		4	0	0		0,8	0,2
19-12-89	25	0	0	128	1,5	0,4	7	0	0	6	8	0	0	8	1,2	0,3
25-01-90	1 300	0	0	62	2,0	1,0	4	0	0	0	4	0	0	0	1,2	0,3
31-01-90	40	0	0	22	2,0	1,0	10	0	0	2	6	0	0	1	1,5	0,8
01-02-90	100	0	0	35	2,0	0,8	14	0	0	4	10	0	0	1	1,5	0,5
06-02-90	40	0	0				8	0	0		5	0	0			
13-02-90	31	0	0	3	2,0	0,6	5	0	0	0	2	0	0	0	1,5	0,4
14-02-90	25	<10	<10	1	2,0	0,8	8	<10	0	1	5	0	0	0	1,5	0,8
28-02-90		0	0	4	1,0	0,3		0	0	1		0	0	0	1,5	0,6
06-03-90	10	0	0	2	1,4	0,7	3	0	0	1	3	0	0	1	1,0	0,5
07-03-90	13	0	0	2	2,0	1,0	5	0	0	0	3	0	0	0	2,0	0,8
14-03-90	60	0	0	192	2,0	0,8	21	0	0	7	12	0	0	7	1,5	0,6
24-04-90	5	0	0		2,0	1,0	1	0	0		1	0	0		1,8	0,6
10-05-90	3	0	0	1	2,5	1,5	1	0	0		0	0	0		2,5	1,0
22-05-90	21	0	0		1,8	0,8	5	0	0		6	0	0		0,7	0,3
Max.	207 000	320 000	2 000	3 160	3,0	1,5	33 400	20 000	20 000	383	20 000	17 000	980	640	2,5	1,0
Min.	3	0	0	0	0,3	0,1	0	0	0	0	0	0	0	0	0,2	0,1
Median	895	2	0	192	2,0	0,6	58	0	0	5	18	0	0	3	1,0	0,3

* : Unable to enumerate coliphage due to confluent lysis CG : Unable to enumerate coliforms due to confluent growth

TABLE 5. RESULTS ACHIEVED FROM RO PLANT COMPARED WITH OTHER PRESCRIBED STANDARDS

Water Quality Variable	RO Plant Product Results				SABS 241-1984 Water for Domestic Supplies		Kempster & Smith Proposed Criteria for RSA Drinking Water		WHO Drinking Water Quality Guidelines
			95% CL						
	M	SD	H	L	RL	MAL	RL	MPL	
MICRO POLLUTANTS - mg/ℓ									
Conductivity @ 25 °C - mS/m	28,0	14,6	30,5	25,5	70	300	70	300	
Sodium (as Na)	42,5	19,2	45,3	39,6	100	400	100	400	200
Potassium (as K)	3,2	0,9	3,6	2,9			200	400	
Calcium (as $CaCO_3$)	10,7	8,0	11,9	9,6	300	650	375	1 000	500
Magnesium (as $CaCO_3$)	11,5	6,8	12,8	10,3	288	412	288	823	
Total alkalinity (as $CaCO_3$)	12,6	4,7	13,3	11,9					
Chloride (as Cl)	52,0	28,7	56,2	47,8	250	600	250	600	250
Sulphate (as SO_4)	18,2	14,8	20,4	15,9	200	600	200	600	400
Total phosphorus (as P)	0,39	0,33	0,55	0,24					
Orthophosphate (as P)	0,24	0,22	0,35	0,14					
Silica (as SiO_2)	1,48	0,62	1,71	1,25					
Total Kjeldal nitrogen (as N)	4,96	1,85	5,70	4,22					
Ammoniacal nitrogen (as N)	2,19	1,47	2,41	1,97			1	2	
Nitrate nitrogen (as N)	0,93	0,60	1,20	0,66	6	10	6	10	10
Colour (as Hazen)	<5	-	-	-	20	NS	20	NS	15
Turbidity (as NTU)	0,57	0,40	0,63	0,51	1	5	1	5	5
UV Absorbance @ 275 nm	0,036	0,024	0,039	0,032					
MICRO POLLUTANTS - µg/ℓ									
Aluminium (as Al)	43	6	46	40			150	500	200
Arsenic (as As)	0,11	0,034	0,129	0,096	100	300	100	300	50
Cadmium (as Cd)	0,27	0,32	0,42	0,12	10	20	10	20	5
Chromium (as Cr)	3,19	2,89	4,52	1,85			100	200	50
Cobalt (as Co)	0,54	0	0,54	0,54			250	500	
Copper (as Cu)	0,5	0,27	0,67	0,42	500	1 000	500	1 000	1 000
Iron (as Fe)	12,3	5,1	14,7	9,9	100	1 000	100	1 000	300
Lead (as Pb)	1,25	0	1,25	1,25	50	100	50	100	50
Manganese (as Mn)	8,6	3,8	10,4	6,9	50	1 000	50	1 000	100

TABLE 5. (Continued)

Water Quality Variable	RO Plant Product Results				SABS 241-1984 Water for Domestic Supplies		Kempster & Smith Proposed Criteria for RSA Drinking Water		WHO Drinking Water Quality Guidelines
			95% CL						
	M	SD	H	L	RL	MAL	RL	MPL	
Mercury (as Hg)	0,25	0	0,25	0,25	5	10	5	10	1
Nickel (as Ni)	3,08	1,94	3,98	2,19			250	500	
Selenium (as Se)	0,37	0,16	0,33	0,17	20	50	20	50	10
Zinc (as Zn)	5,6	2,05	6,58	4,69	1 000	5 000	1 000	5 000	5 000
Boron (as B)	171	49,9	194,4	149,1			500	2 000	
Cyanide (as HCN)	2,2	1,29	2,77	1,54	200	300	200	300	100
Detergents (MBAS) (as LAS)	17,0	22,0	28,0	6,0			500	1 000	
Fluoride (as F)	56,1	18,1	62,8	49,4	1 000	5 000	1 000	1 500	1 500
Phenols (as C_6H_5OH)	10,6	7,2	14,6	6,5	5	10	5	10	**
MICROBIOLOGICAL POLLUTANTS									
Total Bacterial Count/mℓ	58				100	NS			
Total coliforms/100 mℓ	0				Nil	5			Nil
Faecal coliforms/100 mℓ	0				Nil	Nil			Nil
Coliphages/100 mℓ	5								

M = Mean or Median SD = Standard Deviation 95% CL = 95% Confidence Limits of Mean

H = Higher L = Lower RL = Recommended Limit

MAL = Maximum Allowable Limit MPL = Maximum Permissible Limit

** No health related guideline, taste and odour problem.

With regard to the micro-pollutants the RO product is of a very high quality, except for the level of phenols which will be discussed below.

Ammoniacal nitrogen in the feed to the R.O. unit arises from incomplete nitrification in the aerobic sewage treatment process. Because the RO plant follows on the end of the conventional sewage treatment plant it is inevitable that it will be subjected to varying levels of ammoniacal nitrogen and nitrate nitrogen as the two are linked. If the sewage treatment process is producing an effluent that complies with the General Standard including an ammoniacal nitrogen standard of 10 mg/ℓ, then the RO plant must accept this feed. On this basis it is likely that the ammoniacal nitrogen level in the RO product will exceed 1 or even 2 mg/ℓ on a regular basis when the feed level is around 10 mg/ℓ. The question of whether the sewage treatment processes should be modified to suit the RO unit is a matter of economics together with the purpose for which the product is to be used. Similarly, there is a potential problem with nitrate nitrogen, as the level in the RO feed depends on the degree of denitrification taking place in the activated sludge process. If these denitrification processes do not take place the nitrate nitrogen level in the feed could increase, and owing to the fact that the percentage rejection of nitrate does not approach that of other pollutants, the level of nitrate in the RO product could approach the recommended limits of the standards and/or guidelines. However, the nitrate level in the feed would have to be in the order of 25 mg/ℓ coupled with a 60% rejection in the RO to approach the maximum allowable limit of 10 mg/ℓ. It is essential that account is taken of the nitrification and denitrification processes that take place in the activated sludge system of the sewage treatment plant, when considering the operation of a RO plant at the end of the system. However, when taking these points into consideration, it must also be remembered that if RO was to be used in Port Elizabeth, it would only be used to supplement the existing water treatment facilities, and the RO product would be mixed with other treated water. In this case the higher than recommended levels of ammoniacal nitrogen, nitrate nitrogen and phenols would be diluted to below the recommended levels.

Phenol levels in the RO product would appear to be a problem area, but this must be put into perspective. As was stated previously, the level of detection of phenols in both the feed and the product gave cause for concern because of the analytical procedures. In the case of the RO product many of the results were below the minimum detection level of the method, which was in the order of 10 μg/ℓ . In both the S.A.B.S., 1984, and the Kempster and Smith, 1985, standards and/or guidelines the maximum allowable limit for phenols was set at 10 μg/ℓ on organoleptic grounds. The World Health Organisation, 1984, does not set a standard for phenols, but a standard for chlorophenols.

It is of interest to note that the aluminium level of the RO product was always higher than the feed, i.e. the feed mean level was 0,031 mg/ℓ increasing to 0,043 mg/ℓ in the product. The reason for this increase is believed to be due to the aluminium casing of the modules.

Although the determination of the quality of the RO final product was not part

of the investigation, samples were taken and analysed and the results obtained are set out in Table 6.

TABLE 6. FINAL PRODUCT AFTER POST R.O. TREATMENT CHEMICAL RESULTS

Determinant	Median	Standard Deviation
pH	7,2	1,0
Conductivity @ 25°C - mS/m	28,0	14,4
Total alkalinity as $CaCO_3$	18,7	11,1
Calcium as $CaCO_3$	11,1	7,0
Magnesium as $CaCO_3$	13,2	6,3
Sodium as Na	48,6	17,7

8.2 Bacteriological Results

A review of the bacteriological results shows that none of the sample points can comply with the recommended standards for drinking water bacteriological quality, because of inadequacies of the disinfection process. As far as the feed is concerned, the bacteriological quality was satisfactory when the free residual chlorine level was in the order of 1 mg/ℓ, however, that sort of level is detrimental to the RO membrane.

Results for the product show that the RO system could not always adequately remove the bacteria from the feed water. The quality was much improved in the product, but a further adequate disinfection stage is necessary for the water to be of satisfactory bacteriological quality. The median levels for total bacterial count, total coliforms and faecal coliforms were all satisfactory as far as standards are concerned, but results were obtained which exceeded them. The level of coliphages was not satisfactory when compared to prescribed guidelines. Prescribed guidelines for coliphages seems to change from time to time, and in several papers since 1978, Grabow et al have set limits of 0/10 mℓ; 0/100 mℓ and 0/10 litres, which is a very wide range. The results for the final product after post-RO treatment show that the post chlorination was inadequate, or else the bacteria were growing in the CO_2 scrubbing tower. When the free residual chlorine levels were greater than 0,5 mg/ℓ the water quality was satisfactory for all bacteria tested, including coliphages.

All of the bacteriological results indicate that it is essential that the RO product is subjected to an adequate disinfection stage before it can be considered suitable for use as a potable water. If a free residual chlorine level of 1 mg/ℓ or more can be maintained for a reasonable contact time the bacteriological quality of the RO product will be satisfactory.

9. CSIR, DIVISION OF WATER TECHNOLOGY SAMPLING AND ANALYSIS PROGRAMME

Under the terms of the contract with the Water Research Commission the Council for Scientific and Industrial Research through its National Institute for Water Research, now Division of Water Technology, undertook to carry out the working programmes as recommended by the Steering Committee. These included Water Quality Surveillance Programme for the R.O. Plant. This surveillance programme was to include chemical, microbiological and biotoxicological monitoring of the system over a ten week period. The programme was drawn up by the Working Sub Committee and the CSIR, D.W.T.'s part with regard to analysis was as set out below.

Group C (a) (Snap samples)
Standard bacterial count, faecal coliforms and total coliforms.

Group C (b) (Snap samples)
Acid fast bacilli, faecal streptococci, spore formers, coliphages.

Group D (Snap samples)
Viruses

Group E (Snap samples)
Organic profile, PAH's, THM's, D.O.C., chlorinated pesticides and U.V. absorption (Scan)

Group F (Snap samples)
Ames test, Luciferase test, bacterial growth inhibition test and *Daphnia pulex* lethality test.

The samples were taken, (in cooled containers submitted by CSIR, D.W.T.) over a ten week period between 1 August and 2 October 1989, by Port Elizabeth Municipal personnel. These samples were then airfreighted on the same day for analysis in Pretoria. The type and number of samples taken were as set out below.

		Points
Group C(a&b)	3 Points x 1 per week = 3 samples/week	1,2&3
Group D	3 Points x 1 per week = 3 samples/week	1,2&3
Group E	3 Points x 1 per week = 3 samples/week	1,2&3
Group F	1 Point x 1 per week = 1 sample/week	3

9.1 CSIR, D.W.T. Analytical Results and Report

The report submitted by the CSIR Division of Water Technology is available on request from the Water Research Commission.

10. EVALUATION OF TREATMENT COSTS

In order to arrive at a realistic cost for the product water, data obtained during the 11 621 hours of plant operation has been used. During this period 199 718 kℓ of product water was produced. The costs do not include any allowance for the post- treatment of the product to render it suitable for supply to the power station, as the post treatment would be different (and cheaper) for potable water.

Each parameter, where possible, has been expressed in units per kℓ of water produced. Actual costs are based on prices paid in Port Elizabeth in 1990.

10.1 Modules

200 modules were changed during the period of the trial,
i.e. $\frac{200}{199718}$ modules per kℓ

= 1,00 x 10^{-3} modules per kℓ of product water

Cost per module, on exchange basis and inclusive of delivery charges = R 529
Cost of modules = 529 x 10^{-3} x 1,00 x 100 cents per kℓ
= 52,90 cents per kℓ of product water

10.2 Chemicals

10.2.1 Sulphuric acid

Sulphuric acid was used to reduce the pH of the feed water to 6,0.
Total weight of acid used = 20189 kg,
i.e. $\frac{20189}{199718}$ kg/kℓ of product

= 0,101 kg acid per kℓ of product water

Cost of acid = 44,23 cents per kg
= 4,47 cents per kℓ of product water

10.2.2 Detergents

The following detergents were used in the total of 83 membrane washes:-

Jet Low-foam	605 kg at R 4,54 per kg
Biotex	320 kg at R 10,34 per kg
Autopunch	238 kg at R 5,23 per kg

Total weight of detergent used = 1163 kg
i.e. $\frac{1163}{199718}$ kg/ kℓ of product

= $5{,}82 \times 10^{-3}$ kg detergent per kℓ of product water

Total cost of detergent = R 7 300

Cost of detergent = $\frac{7300 \times 100}{199718}$

Cost of detergent = 3,66 cents per kℓ of product water

10.2.3 Citric acid

A citric acid wash was carried out on two occasions and a total of 190 kg of acid was used.

Weight of acid used = $\frac{190}{199718}$ kg/kℓ of product

= 0,95 g citric acid per kℓ of product

Cost of acid = R 8,90 per kg

= 0,85 cents per kℓ of product water

10.2.4 Ammonium hydroxide

A 25% solution of ammonium hydroxide was used in the citric acid washes in order to adjust the pH. A total weight of 90 kg was used.

Weight of ammonium hydroxide = $\frac{90}{199718}$ kg per kℓ of product

= 0,45 g per kℓ of product

Cost of ammonium hydroxide = R 1,20 per kg

= 0,05 cents per kℓ of product

10.2.5 Formalin

Formalin was used to protect the membranes from biological degradation during prolonged plant shutdowns. A total weight of 720 kg of formalin was used which is equivalent to $\frac{720}{199718}$ kg per kℓ of product

= 3,6 g formalin per kℓ of product

Cost of formalin = R 1,35 per kg

= 0,49 cents per kℓ of product

10.3 Electricity

Electricity consumption meters were installed on the plant at 6 700 hours.

During the period from 6 700 hours to 11 616 hours a total of 193 350 units of electricity were consumed.

By extrapolation, total number of units consumed during the 11 621 hours of plant operation = 457 063 units.

Electricity used = $\frac{457063}{199718}$ units per kℓ of product

= 2,29 units per kℓ of product

Cost (inclusive of maximum demand charge) = 8,019 cents per unit.

Electricity cost = 18,36 cents per kℓ of product water

10.4 Mechanical and Electrical Maintenance

Mechanical and electrical plant maintenance costs include all man hours, spares and equipment. It is not possible to define this item in terms of units per kℓ of product and therefore only the costs involved have been given.

Total expenditure on maintenance = R 75 108

Therefore cost per kℓ of product = $\frac{75108 \times 100}{199718}$ cents

Maintenance cost = 37,60 cents per kℓ of product water

This cost for maintenance is very much higher than originally expected and reflects the numerous faults and breakdowns listed earlier in this report.

10.5 Staffing

The treatment works' superintendents were used to operate the plant. Normal plant operation required 0,5 man hours per day for 5 days per week, i.e. 2,5 man hours per 168 hours of operation. Therefore during the 11 621 hours of plant operation, normal staffing = $\frac{11621 \times 2,5}{168}$ man hours

= 173 man hours.

Membrane washing demanded the presence of two men during the wash cycle totalling 5 hours. A total of 83 washes were carried out. Therefore time involved in membrane washing = 83 x 2 x 5 h = 830 man hours.

Module changes required 0,3 man hours each. 200 modules had to be replaced, therefore total time = 60 man hours.

Total man hours = 173 + 830 + 60 = 1 063

Total man hours = $\frac{1063}{199718}$ hours per kℓ of product

Staffing requirements = $5{,}32 \times 10^{-3}$ man hours per kℓ of product

Allowing R 18,50 per man hour (based on basic salary only without any additions or overheads)

Staff costs = 9,84 cents per kℓ of product

10.6 Capital Costs

The total cost of the plant was R 516 000, but this included the sum of R 34 000 for the post treatment facility required in order to facilitate the re-use of the product either by industry or the local power station. This latter figure has not been included in ascertaining the RO treatment costs as it would not be required for a potable water plant.

Cost of plant = R 482 000, amortized at 18% per annum

= R 86 760 per annum or 8760 hours.

Capital cost = $\frac{\text{R 86 760}}{8760}$ per hour.

The plant produced 17,19 kℓ per hour

Therefore capital cost = $\frac{86760 \times 100}{8760 \times 17{,}19}$

= 57,62 cents per kℓ of product

10.7. Summary of Costs

	Units/kℓ product	Cents/ kℓ product
Modules	$1,0 \times 10^{-3}$	52,90
Chemicals:		
Sulphuric acid	0,101 kg	4,47
Detergents	$5,82 \times 10^{-3}$ kg	3,66
Citric acid	0,95 g	0,85
Ammonium hydroxide	0,45 g	0,05
Formalin	3,6 g	0,49
Electricity	2,29 units	18,36
Repairs & maintenance	--	37,60
Staff	$5,32 \times 10^{-3}$ h	9,84
Capital	--	57,62

Total cost of producing the RO product water = R 1,86 per kℓ

11. CONCLUSIONS

The performance of the RO plant will be assessed against the prescribed aims of the project which are set out in the introduction to this report.

11.1 Operational Procedures

This plant was considered to be of the minimum required size to assess the practical application of the process. It proved to be extremely easy to operate and was not labour intensive when running well. Although plant operation was carried out by qualified works superintendents, experience has shown that a lower level of operator could satisfactorily be employed to do the work. Membrane washing tended to be labour intensive, but this requirement could probably be halved by the use of one man only during the procedure.

Repeated equipment failure, casing the plant to be operational for only 37,4% of the available time, has highlighted the need for the provision of high quality equipment with 100% standby for certain plant which is expected to operate continuously. The higher than expected rate of module failure also caused concern as it adversely affected both the cost of the process and its reliability in producing a continuous supply of water of satisfactory quality.

11.2 Quality of RO Product

11.2.1 Chemical Quality

The results have shown that the RO product is of satisfactory quality as far as prescribed standards/guidelines for potable water are concerned, with two exceptions, phenols and ammoniacal nitrogen. As far as phenols are concerned,

the analytical method employed did not allow for accurate evaluation of the lower phenol levels. However, phenols at the levels detected are not considered to give rise to a toxicity problem, but more a potential taste and odour problem following chlorination. The mean ammoniacal nitrogen level in the product exceeded the only prescribed guideline available. However, ammoniacal nitrogen is normally included in potable water analysis as a pollution indicator, but this is irrelevant in this situation. An alternative and higher ammoniacal nitrogen level is acceptable in disinfected water, e.g. in the chloramine process, which deliberately uses high ammonia levels.

Both the results obtained by the Port Elizabeth Municipality and the CSIR show that the rejection of chemical pollutants achieved by the plant was excellent and that it could consistently produce a water of chemically potable standard except for organic pollution indicators (OPI) and phenols, regardless of feed water quality.

11.2.2 Microbiological quality

Initially the RO plant was not equipped with any facility to chlorinate the product. A small chlorinator was later installed to disinfect the product prior to it being supplied for use at the power station, but this unit, without sufficient contact time, proved to be inadequate to achieve complete disinfection to potable water standards. However, the product water was very low in colour, turbidity and dissolved organic carbon and there is no reason, therefore, why good disinfection should not be obtained by correctly applied chlorination. Results achieved when the free residual chlorine level in the product approached 1 mg/ℓ showed that the bacteriological quality of the RO product was excellent, (see Table 4). Both internal and independent analytical results confirm these findings. The results also suggest that post RO contamination could have occurred in the scrubber, which would not be required for the production of potable water.

11.2.3 Toxicity

Toxicity tests carried out by the CSIR showed that the RO product had a severe adverse effect on *Daphnia pulex*. For this reason the report states:- "Although chronic effects (mutagenicity) are unlikely, on occasions the treated water showed acute toxicity, and is, therefore, undesirable for human consumption."

11.2.4 General

Based on results obtained during the ten week quality surveillance programme, it can be concluded that reverse osmosis cannot be considered as a stand alone process to produce potable quality water from a tertiary treated sewage effluent.

It is therefore recommended that future investigations should be aimed at evaluating suitable post RO treatment methods for the continuous removal of any residual organic pollutants or toxicants.

11.3 Production

The feed flow to the plant averaged 25 475 ℓ/h with a product recovery rate of 67,5% which was marginally lower than the design figure of 70%. The overall peak standard flux decline was 13% and although this was higher than expected it continued to show that membrane fouling can be controlled by flow reversal and regular washing even though there was no pretreatment of the feed other than rapid sand filtration.

Salt rejection averaged 88,3% and no abnormal degradation of the membranes was indicated.

No precautions were taken to protect the plant from the variations and abnormalities in the quality of the sewage treatment works effluent. Despite this the RO plant was able consistently to produce a water of high quality.

11.4 Operating Costs

The highest operating cost components in the production of the RO product were capital at R0,562/kℓ, module replacement at R0,529/kℓ and repairs and maintenance at R0,376/kℓ. The latter two components could be significantly reduced by improving the quality of the equipment and materials. Power costs amounted to only R0,1836/kℓ, staff R0,0984/kℓ, and chemical costs made up the balance to give a total production cost of R1,86/kℓ.

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