DEVELOPMENT OF A CROSSFLOW MICROFILTER FOR RURAL WATER SUPPLY

Final Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Background

The provision of potable water to rural and peri-urban areas is a national development priority in South Africa. Package water treatment plants may have various advantages over conventional water treatment works in terms of potable water provision to such areas. These include rapidity of deployment, lower capital costs, simplified operation, suitable capacity and modularity.

There are various package units available internationally. This project concerns the evaluation of woven fibre crossflow microfiltration (WFMF) as a viable process for potable water production. In contrast to the rigid supports used in conventional microfilters, the woven fibre system utilises an inexpensive flexible woven polyester support. This could extend the economic viability to high volume, low product value applications, e.g. the production of potable water and the treatment of waste water. This technology was developed at the University of Natal in the late eighties. It is now licenced to a company called High Tech Water HTW NV, and is marketed internationally as the EXXFLOW process. In terms of a licencing agreement between the Water Research Commission and High Tech Water HTW NV, the Water Research Commission stands to receive royalties from the international commercialisation of the technology.

Objectives

The objectives of the project were as follows :

- To evaluate the applicability of the EXXFLOW process for the supply of potable water to rural and peri-urban areas. Aspects to be considered include :
    - water quality
    - permeate production rates
    - reliability
    - manpower requirements
    - economics
- To compare the performance of the unit with that of a conventional water works
- To assess and improve the design and operation of the unit where possible
- To demonstrate the process to potential users
- To assist in the development of a local technology to a stage where a commercially acceptable product has been produced
- To train operators in the use of cross-flow microfiltration

Approach

A full-scale EXXFLOW unit was constructed in the workshop of the Department of Chemical Engineering, University of Natal, from January 1991 to March 1992. It was then relocated to the Process Evaluation Facility at Umgeni Water's Wiggins Water Treatment Works, Wiggins, Durban in April 1992. The design of the unit was based on plans supplied by HTW High Tech Water NV. The unit was commissioned in September 1992.

From March 1993 to December 1994, the unit was operated under fully automated control and its performance was monitored. Performance indicators included turbidity removal, permeate production rates and bacteriological removal. This was done for three modes of operation - on raw water only, with a filter aid, and with a precoat. The reliability of the unit was also monitored.

Details of EXXFLOW Unit

The unit was designed for 8 WFMF curtains, but was installed with 4 curtains. Each curtain has a length of 8 m and contains 70 tubes of 12 mm diameter. This gives a nominal filtration area of 80 m^2 (installed) and 160 m^2 (capacity). A high pressure spray system is used for cleaning. The unit is fully automated and controlled by a programmable logic controller. The unit operates at an inlet pressure of 4 bar, and a tube velocity of 1,4 m/s.

The unit was constructed from plans supplied by High Tech Water HTW NV.

Unit Reliability

During the period of continuous operation, various periods of unscheduled downtime were experienced. Unscheduled downtime accounted for approximately 50 % of the project time for this period. The main reason was inherent mechanical flaws in the original design of the unit. This included poor manifold and endblock design, resulting in gasket failure, and poor manifold contouring, resulting in tube blockages. Other problems experienced included blockage of the spray nozzles, holes developing in the tubes and failure of some electrical components. In these instances, corrective action and modifications essential for the operation of the unit were implemented. However, these mechanical problems still need to be addressed holistically, to improve the overall reliability and robustness of the unit.

Unit Performance

The performance criteria monitored included turbidity removal, microbiological removal efficiency and permeate production rates. Three modes of operation were investigated - raw water only, raw water with a filter aid, and raw water with a precoat. The performance with a precoat was vastly superior to that obtained on raw water only or with a filter aid. When operating on raw water only, the permeate turbidity is initially > 5 NTU and takes about an hour to drop to 0,1 NTU. With a filter aid, the permeate turbidity takes up to 15 minutes to drop to 0,1 NTU, while with a precoat a turbidity of 0,1 NTU is obtained from the start of the filtration cycle. The permeate production rates with a precoat are up to three times greater than that obtained on raw water only, and up to twice that obtained with a filter aid.

Overall, the unit shows an excellent turbidity rejection. In the precoat mode the permeate turbidity is usually around 0,1 NTU for feed turbidities ranging from 5 NTU to > 800 NTU. The unit consistently produced this high turbidity removal over the project period. The bacteriological rejection capabilities are also very good. In tests conducted by Umgeni Water's laboratories, a > 99,9 % removal of coliforms, E.Coli and Fecal Streptococci was reported. The ability of the unit to remove viruses was not tested during the project.

In the precoat mode the unit produced a weekly average flux of 90 ℓ/m^2h at a water recovery of 97 %. The unit produced this output consistently over a sixteen month period, with no long term decline in productivity. This translates into a production capability of 0,15 Mℓ/day (with 4 curtains installed) and 0,3 Mℓ/day (at full capacity, 8 curtains). Assuming a daily allowance of 200 ℓ of potable water per household, the unit is capable of servicing a town of 1 500 households.

The unit has also demonstrated the ability to cope with upset conditions. It has continued to operate when turbidity spikes in the incoming raw water (> 1000 NTU) have caused other water processing units at the Process Evaluation Facility as well as the conventional water works to shut down. This could be of significance in rural and peri-urban areas, where operator error is likely to increase due to lower skills levels.

Labour Requirements and Economics

The unit is fully automated and requires very little attantion during normal operation. It is estimated that the unit would require a semi-skilled operator (standard eight certificate) for approximately 2 hours per day. This is mainly to monitor the quality of water and the production rates.

Due to factors of scale, it is expected that the potable water produced from the unit will invariably cost more than that produced by a conventional water works. However, the unit is meant to produce water at a point of demand and hence obviate the expensive reticulation costs associated with conventional water works situated some distance from the point of demand. The unit is also modular, and hence increases in demand can be quickly met without the major planning and capital required for conventional water works. Hence, the economically viability of the unit will have to be determined for each particular application, taking into account the above factors.

For the purposes of this project, the capital, operating and maintenance costs per unit volume of water produced are estimated in the following table :

Cost Component	**R / m^3**
Capital (1997 Rands)	833 [/(m^3/day)]
Chemicals	0.13
Power	0.66
Labour	0.04
Maintenance	0.17
Total Operating	1.00

In summary, therefore, the unit consistently produces a very good quality of water that is well within the potable water standards and guidelines in terms of the parameters tested. The permeate production rate has been increased significantly during the course of the project and the unit has maintained this higher level of production over an extended period, with no long term decline. The unit is fully automated, and very little attention is required during normal operation.

However the unit cannot at present be regarded as a reliable one, due to the various mechanical problems that exist. Further improvements to the mechanical reliability are necessary before the unit may be regarded as a viable one for the production of potable water in rural and peri-urban areas.

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1 INTRODUCTION

The supply of potable water to rural and peri-urban areas is a national development priority. Package, or preconstructed, water treatment plants could have a major role to play in the rapid provision of potable water. Package plants may have various advantages over conventional potable water treatment processes, including,

(i) **Rapid deployment** - Most package plants can be transported, installed and operational within days.

(ii) **Lower capital costs** - In general, reticulation of water from conventional water treatment works to rural and peri-urban communities would be extremely expensive. Package plants which produce potable water at the point of demand would save on reticulation infrastructure and could results in a significant saving in capital. Since a major component of the selling price of water is capital redemption, package plants could lead to a significant reduction in the cost of supplying potable water.

(iii) **Simplified operation** and maintenance procedures in comparison with conventional water treatment processes.

(iv) **Suitable capacity** for small and isolated communities.

(v) **Modularity** - Most package units are modular and the capacity of the plant can be easily upgraded to cater for changing demographics.

There are various package water treatment plants being marketed internationally and locally. A comparative study of some of the units available locally is presented in Water Research Commission Report No. 450/1/97, *Package Water Treatment Plant Selection* [WRC (1997)]. This project concerns the evaluation of **woven fibre crossflow microfiltration** (WFMF) as a process for the production of potable water in rural and peri-urban areas.

Cross-flow microfiltration (CFMF) is a technology which is highly efficient in the removal of contaminants down to the sub-micron. Application of CFMF range widely, from the filtration of beer and wine to the recovery of bacterial cultures. CFMF has also shown potential in treating sewage work streams, industrial effluents and water works sludges. One of the largest potential areas of application is in the provision of potable water for rural and peri-urban communities. The proving of the viability of CFMF for the large scale filtration of water for potable use, as well as the filtration of waste water, could be of major significance to the water industry, and CFMF could replace a substantial fraction of conventional water treatment facilities. The use of CFMF for the provision of potable water is of special significance in the South African context. Rapid growth of informal settlements in peri-urban areas has created an almost overnight demand for potable water, a demand that cannot be met in the immediate future by the existing conventional water treatment facilities [Umgeni Water (1990)]. CFMF, being relatively simple in concept, could potentially fulfil a substantial fraction of this demand.

Many of the package units that are available are based on foreign technology and are not necessarily suitable for local conditions. The former State President, F. W. de Klerk, has been quoted in a recent CSIR publication [CSIR (1990)] :

"We should concentrate our efforts on generating our own applicble technology through innovation. Although foreign technology is often effective and relatively cheap, the importance of such technology also restricts our export capability. There is still considerable scope for industrial development in respect of projects and unique products where South Africa enjoys competitive advantage."

The potential benefits and markets for cross-flow microfiltration encompass both the First and the Third Worlds.

Woven fibre crossflow microfiltration (WFMF) uses flexible fabric tubes, and was introduced in the sixties (using firehose jackets !). The technology underwent significant development at the Pollution Research Group, University of Natal, in the late eighties, and is now being commercialised internationally. The international licence to the technology is held by High Tech Water HTW NV. A technology transfer and licencing agreement exists between the Water Research Commission and High Tech Water HTW NV, and the Water Research Commission receives royalties from the commercial exploitation of the technology. Internationally the technology is marketed as the EXXFLOW process. Since the Water Research Commission has a financial interest in the technology, the benefits to the country include both the local application of potentially cost effective processes and licencing income from abroad.

2 PROJECT OBJECTIVES

(i) To evaluate the applicability of the EXXFLOW process for the supply of potable water to rural and peri-urban areas. Aspects to be considered include :

a. water quality

b. permeate production rates

c. reliability

d. manpower requirements

e. economics

(ii) To compare the performance of the unit with that of a conventional water works

(iii) To assess and improve the design and operation of the unit where possible

(iv) To demonstrate the process to potential users

(v) To assist in the development of a local technology to a stage where a commercially acceptable product has been produced

(vi) To train operators in the use of cross-flow microfiltration

3 APPROACH

(i) A full-scale EXXFLOW unit was constructed in the workshop of the Department of Chemical Engineering, University of Natal, from January 1991 to March 1992. It was then relocated to the Process Evaluation Facility at Umgeni Water's Wiggins Water Treatment Works, Wiggins, Durban in April 1992. The design of the unit was based on plans supplied by HTW High Tech Water NV, the international licencees of the technology. The details of the unit are presented in Section 4. The unit was commissioned in September 1992. The construction, relocation and commissioning of the unit was supervised by Mr B Townsend of the Pollution Research Group.

(ii) From March 1993 to December 1994, the unit was operated under fully automated control and its performance was monitored. Performance indicators included turbidity removal, permeate production rates and bacteriological removal. This was done for three modes of operation - on raw water only, with a filter aid, and with a precoat. The unit's performance is reported in Section 6.

(iii) During this period of continuous operation, various periods of unscheduled downtime were experienced. Reasons included interruptions to utilities and various mechanical failures. In these instances, modifications essential for the operation of the unit were implemented. The mechanical problems experienced, and the remedies adopted are reported in Section 5.

(iv) The labour requirements, capital cost and operating costs associated with the unit were then estimated.

4 DESCRIPTION OF EXXFLOW UNIT

4.1. Flexible woven fibre microfiltration

The technique of cross-flow microfiltration (CFMF) potentially enables the continuous filtration of particulate suspensions. The suspension is pumped into a porous tube (Figure 1).

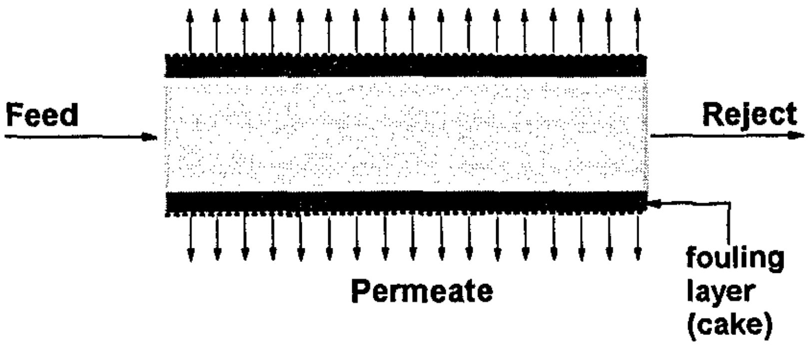


Figure 1 : Schematic of Crossflow Microfiltration

Clear liquid permeates the tube wall, driven by the pressure difference across the wall, and is recovered as the permeate. This flow of fluid normal to the wall convects particles to the wall where they accummulate to form a polarized layer, the cake. The cake constituting an increase in the hydraulic resistance, decreases the permeate flux. However the flow of the bulk suspension tangential to the cake tends to limit its growth, eventually resulting in a cake thickness, and hence permeate flux, that is relatively constant with time - the steady-state condition. Porous supports utilized in CFMF include stainless steel, ceramic, rigid plastic and woven fibre tubes. Woven fibre tubes can be produced relatively inexpensively in large lengths. This potentially extends the economical viability of CFMF to large-scale high-volume applications, e.g. the production of potable water and the treatment of waste water.

In considering the rigid tubes, the tube wall is usually the filtration barrier, and the formation of the cake is usually unbdesirable. In the woven fibre tubes the actual filtration barrier is invariably the cake that forms on the tube walls. The close packing of the cake can enable the retention of particles that are often orders of the magnitude smaller than the pores in the tube wall. This system thus affords the advantage that tubes with relatively large pores may be used, enabling easier cleaning and minimising irreversible fouling of the pores (Kraus (1974)). Effectively, the fouling layer which is undesirable in conventional microfiltration systems acts as a "formed-in-place" membrane in woven fibre microfiltration.

Woven fibre microfiltration technology (WFMF) is marketed internationally as the EXXFLOW process.

4.2. Details of the Original EXXFLOW Unit (as commissioned)

4.2.1. Process and Instrumentation Diagram

The process and instrumentation diagram of the EXXFLOW unit, as constructed, is shown in Figure 2. The main elements of the unit are as follows :

(i) raw water feed tank and permeate storage tank - each 5 m^3 capacity

(ii) permeate collection tray with clean and waste permeate accummulation tanks

(iii) feed pump - maximum capacity 400 m^3/h at 6 bar. In the trials reported here, the impeller had been replaced with a smaller diameter one yielding 200 m^3/h at 6 bar. This was due to the fact that four curtains were installed whereas the unit had been designed for a capacity of 8 curtains

(iv) permeate pumps - waste permeate pump and clean permeate pump, both actuated by level probes in waste and clean permeate accummulation tanks respectively

(v) high pressure cleaning system - consists of high pressure spray pump, spray bars and spray carriage

(vi) associated piping and actuated valves - all piping fabricated from PVC. All valves are electrically actuated.

(vii) programmable logic controller (PLC) - controls all valves, pumps and spray cleaning system

(viii) curtains. The unit utilises 12 mm "duplex" curtain modules, i.e. two curtains are attached to a common endblock. During the course of the project, the unit was fitted with two duplex modules, giving four curtains in total. However, the unit was designed for a capacity of four modules (eight curtains). Each curtain has a length of 8 m, and contains 70 x 12 mm tubes arranged in a vertical array. This yields a nominal filtration area of 80 m^2 (installed) and 160 m^2 (capacity). Valves on the inlet and outlet manifolds enable the tubes of the curtain to either operate in parallel (single pass) or in a four pass mode (see Figure 3). In the single pass mode the path length is 8 m and in the four pass mode the path length is 32 m.
The curtains and endblocks were supplied by High Tech Water HTW NV, England.

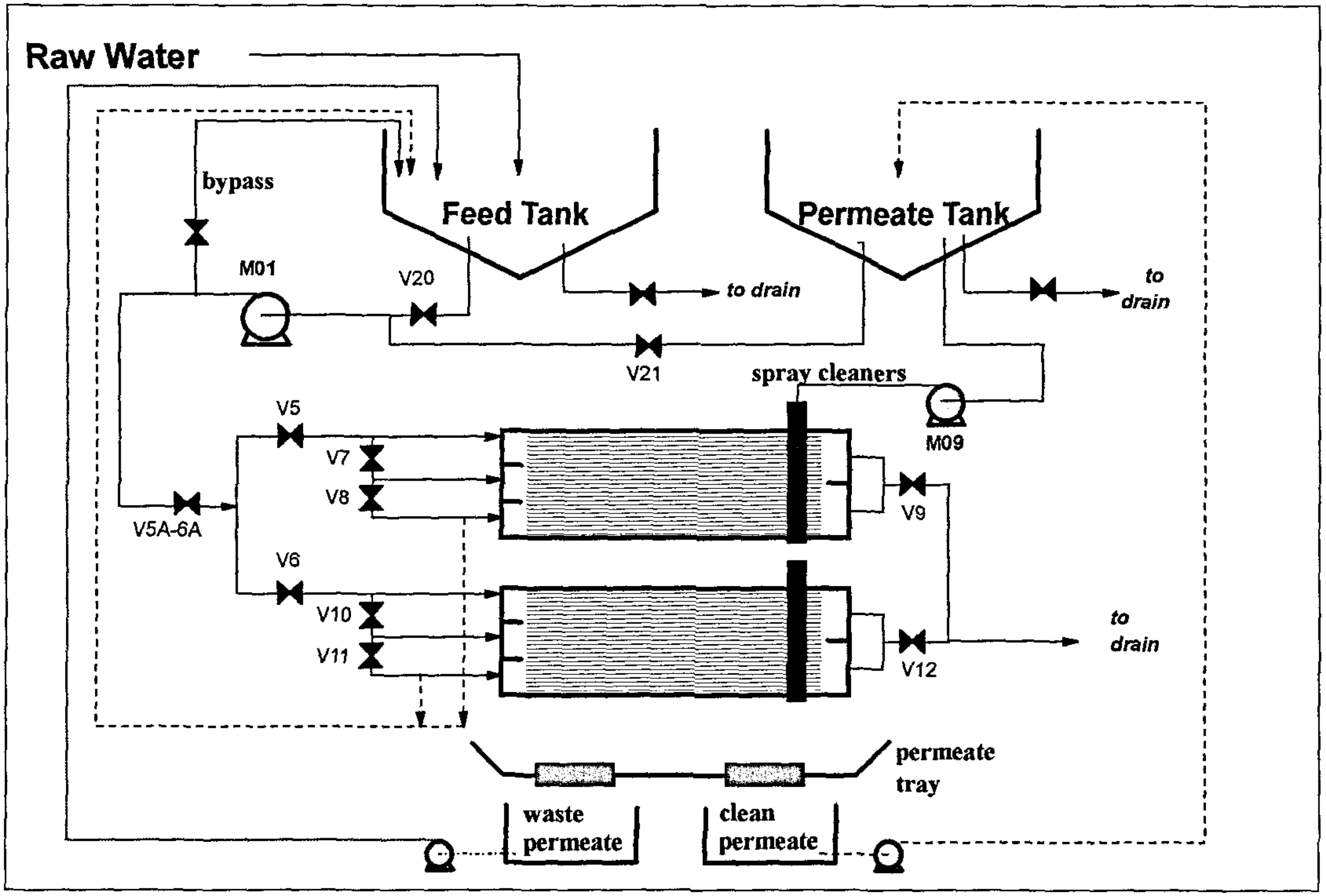


Figure 2 - Process and Instrumentation Diagram of EXXFLOW Unit (as commissioned)

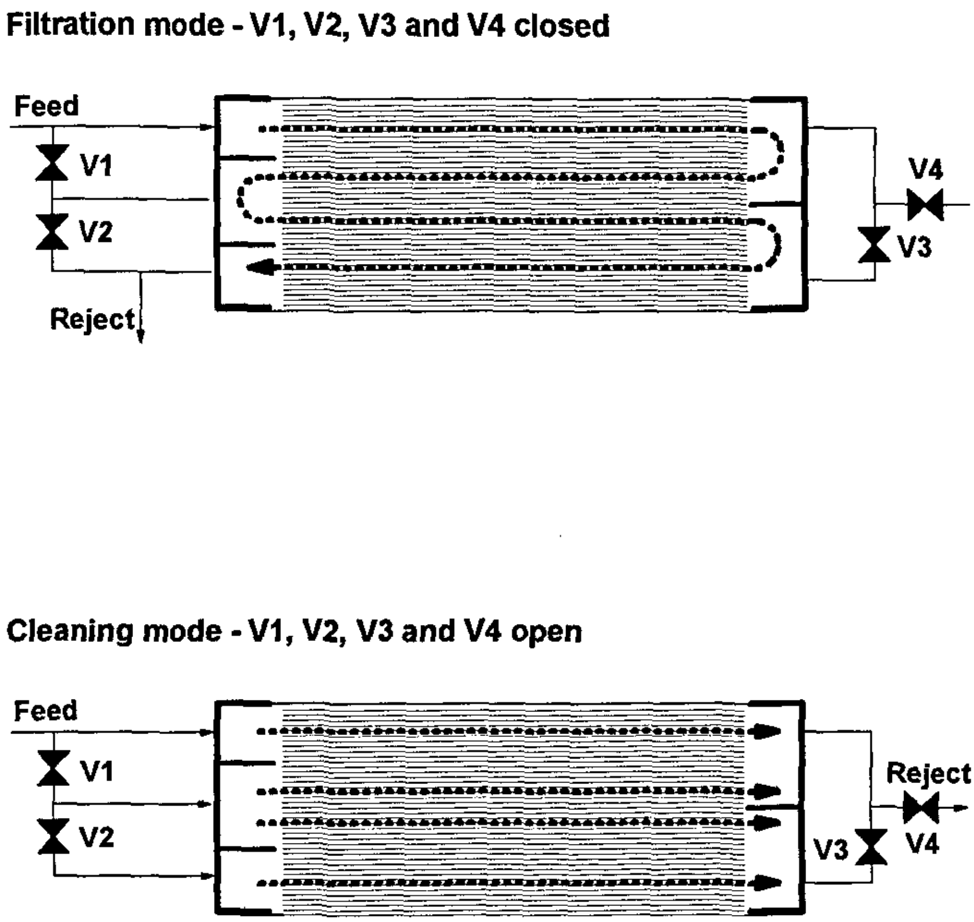


Figure 3 : Flow Distribution Through Curtains During Filtration and Cleaning

The feed to the unit is raw water from the head of the main water works, i.e. before any ozonation or chemical addition has occurred.

During the filtration cycle, raw water is pumped by the main feed pump into the four curtains operated in parallel. The valves at the inlet and outlet of the manifolds are arranged to give four passes through each curtain. The reject stream exits at the bottom of each curtain and is either returned to the feed tank or discarded to drain, depending on the operational configuration (see Table 1). The permeate pours down the side of the curtain and accumulates in the permeate collection tray. For a short while after startup, when the permeate quality is not within specifications, the permeate is collected in a waste permeate tank and pumped back to the feed tank. Once the permeate reaches a specified quality, it accumulates in the clean permeat tank and is pumped to the permeate storage tank. The waste permeate and clean permeate pumps are actuated by level probes in the waste permeate and clean permeate accummulation tanks respectively.

During the cleaning cycle, the valves at the inlet and outlet manifolds are changed so that all tubes operate in parallel (single pass). The reject stream is directed to drain. Flush water from the permeate storage tank is pumped to the curtains at a low flowrate by throttling down the main feed pump. Simultaneously, stored permeate is sprayed at high pressure onto the outside of the curtains by the spray bars. The spray carriage moves slowly along the curtain, exposing the curtains length to the spray bars. The high pressure sprays impinges onto the curtain fabric and disturbs the fibres. This dislodge foulants from the tube wall, and these are flushed out of the system to drain. At the end of the cleaning cycle, the spray carriage returns to its initial position near the control panel end of the curtain.

The unit may be operated in one of three crossflow configurations, as described in Table 1.

Table 1 : Possible Configurations in the Crossflow Mode

Crossflow Configuration	Description
semi-batch	All reject is recycled to the feed tank. All permeate is sent to a permeate storage tank. The feed tank is continually topped up with raw water. At the end of a preset period, raw water to the feed tank is stopped and contents of the feed tank are subjected to full batch concentration. In this mode, the concentration of the feed tank increases continuously during the cycle.
feed-and-bleed	A fraction of the reject is discarded so as to maintain a constant concentration in the feed tank. All permeate is sent to the permeate storage tank. In this mode, the concentration in the feed tank is higher than that of the raw water, but remains constant during the cycle.
once through	The entire reject stream is discarded. All of the permeate is pumped to the permeate storage tank. Hence the feed to the curtains is the same concentration as the raw water.

The semi-batch mode yields the highest water recovery, while the once-through mode yields the lowest recovery. Conversely, in the semi-batch mode the curtains are exposed to a progressively increasing concentration, whereas in the once-through mode the concentration is constant. Since permeate flux decreases with increasing concentration [Pillay 1992], this indicates that the permeate production rate would be the highest in the once-through mode, and the lowest for the semi-batch mode. The once-through mode would be most appropriate in circumstances where the source of raw water is abundant, e.g. if the unit was positioned next to a river.

In all experiments conducted in this study, the unit was operated in the semi-batch mode only. The main reason for this was that operating in the feed-and-bleed or once through modes would have required a significantly greater flowrate of raw water, with a low water recovery bein achieved. The raw water supply lines from the head of the Wiggins Water Treatment Plant to the Process Evaluation Facility would have been incapable of providing the unit with these higher flowrates. Further, this would have been unacceptable to the Process Evaluation Facility due to the significant wastage that would have occurred.

4.2.2. Operating Conditions

(i) Pressure - The inlet pressure to the curtains is 4 bar, and the outlet pressure is 2 bar.

(ii) Velocity - The nominal velocity in the tubes during the filtration cycle is 1,41 m/s (calculated from actual flow measurements).

4.3. Commissioning

Due to a delay in delivery of flow measuring equipment and building and plumbing alterations at the Process Evaluation Facility, commissioning trials, under operator supervision, could only commence at the beginning of September 1992.

A series of test runs lasting approximately five hours each were performed under close supervision. During these trials the plant operated at an inlet pressure of 400 kPa and an outlet pressure of 200 kPa, which represents a pressure drop of 50 kPa per pass. Two sets of trials were performed, viz. semi-batch mode without a filter-aid addition, and semi-batch mode with the addition of a filter-aid.

The starting fluxes obtained in these runs were highly repeatible, indicating that the high pressure spray cleaning technique coupled with flushing of the modules was successful in removing accumulated deposits from the tube walls. This technique requires approximately 5 kℓ of permeate for the two modules in use.

During the commisioning trials, a side-stream of permeate was recycled to the feed tank during the first half hour of operation, due to there being insufficient raw water during this period. Construction of an additional raw water supply to the Process Evaluation Facility had been initiated at that time but had not yet been completed.

At the end of these trials in November 1992, some changes were made to the process flow sheet, and further automation was implemented to allow continuous, unattended operation of the plant. The process changes were :

(i) alterations to the pipe work at the inlet to the modules to enable isolation of individual modules during the cleaning cycle.

(ii) alteraions to the permeate distribution system, including increased pumping capacity.

(iii) automation of the cleaning cycle.

These alterations were completed during February 1993, and operation on a continuous, fully automated basis was commenced during March 1993.

5 UNIT RELIABILITY

5.1. History of Plant Uptime:

For the period April 1993 to December 1994, the unit was to have operated continuously, under full PLC control, with minimal operator input. However, this operation was interrupted by various periods of unscheduled downtime. The actual filtration hours during this period was approximately 4000, and unscheduled downtime accounted for approximately 50 % of the project time in this period. The reasons for the downtime may be classed into five categories : mechanical failure, tube rupture, interruptions to utility supplies, holidays/leave and modifications/maintenance.

The percentage uptime in each week, and the reasons for downtime are depicted in Figure 4 (a) to (d). The maximum period of uptime in each week has been specified as 96 hours, based on the following :

(i) the unit was not operated over weekends

(ii) a maximum of four 24-hour runs could be performed in the precoat mode in each week (see Section 6.6.1). Hence the maximum uptime of 4 x 24 hours.

It is seen that unscheduled downtime was experienced for a considerable part of the project period, indicative of poor reliability. In the main this was due to mechanical breakdowns associated with inherent flaws in the unit. In particular, significant problems were experienced with gasket failures, and tube blockages associated with poor manifolding. Interruptions to utility supplies were beyond the control of the project. The mechanical problems, and the corrective actions taken, are discussed in Section 5.2.

[NB : *In some instances the % uptime and the downtime adds to greater than 100 %. This is due to rounding off of downtime to the nearest day, as well extended runs (> 24 hours) and runs that extended into weekends.*]

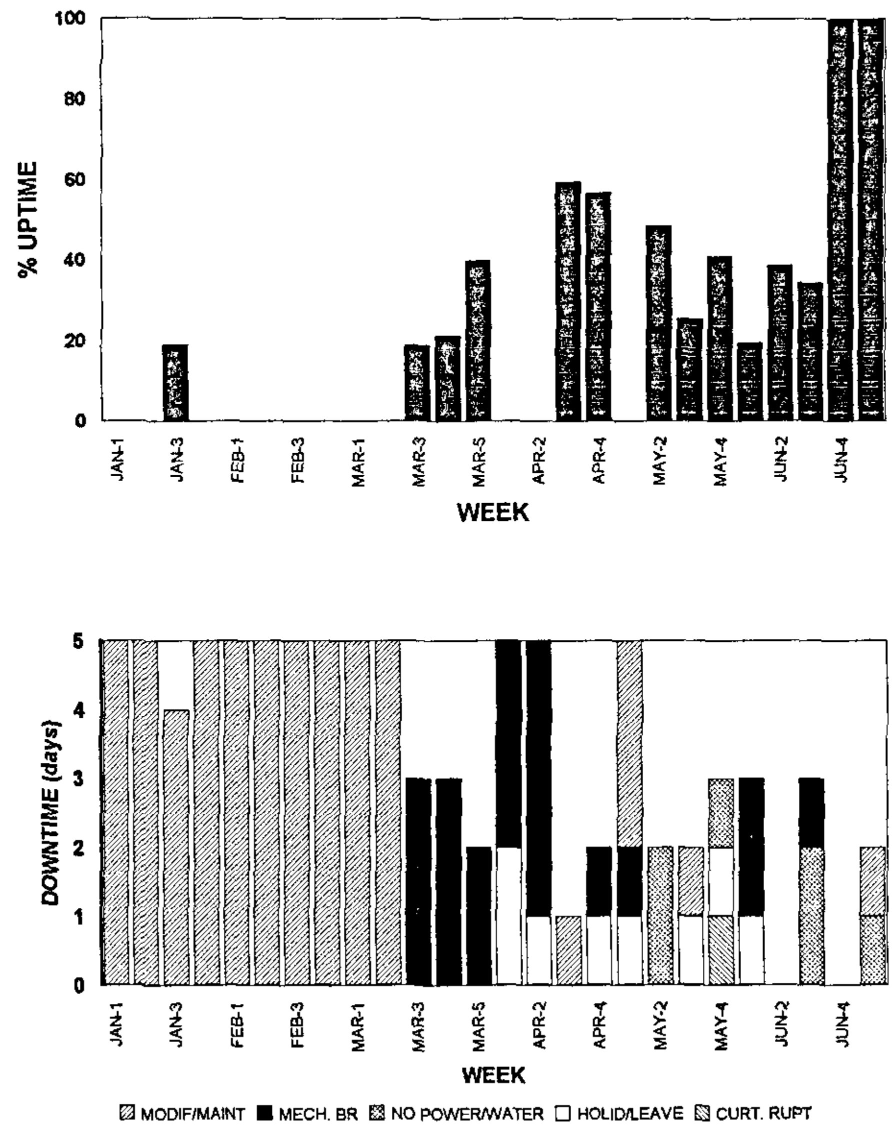


Figure 4 (a) : Percentage Uptime and Reasons for Downtime - January to June 1993

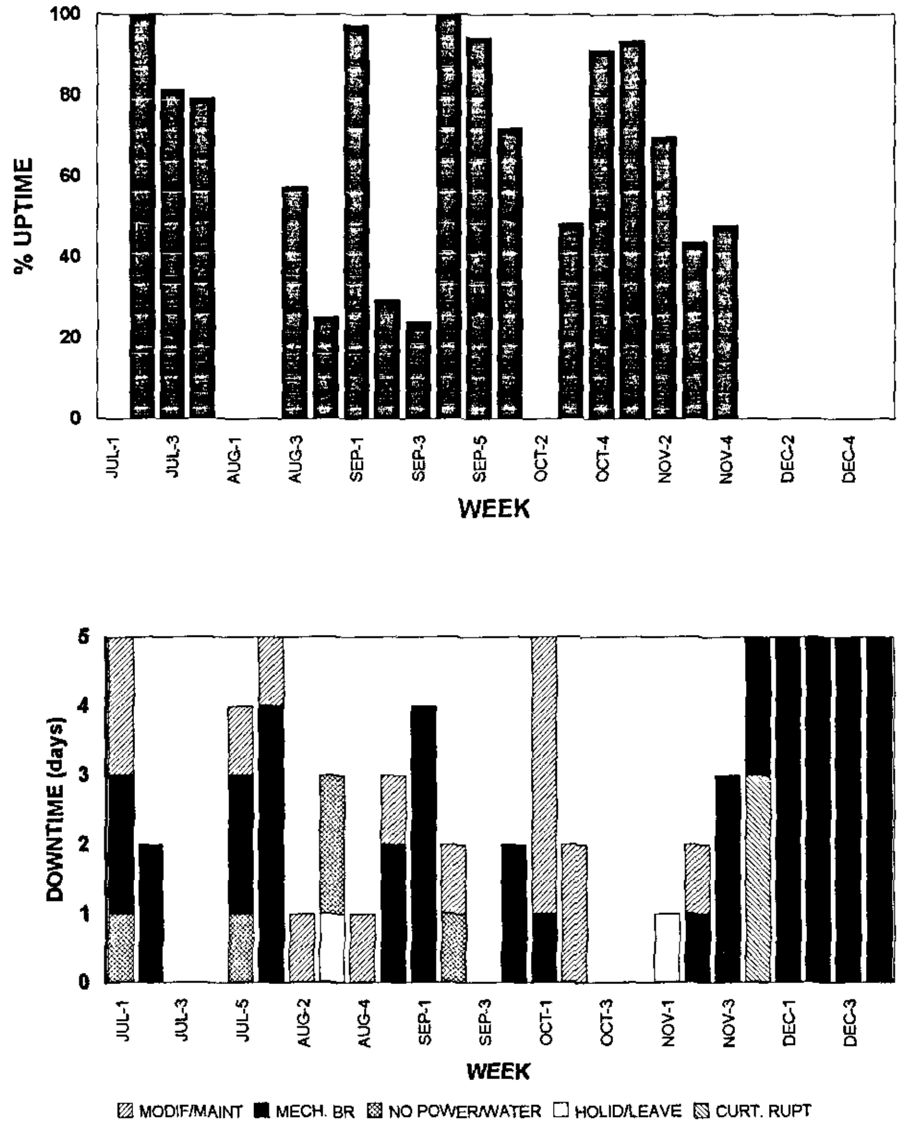
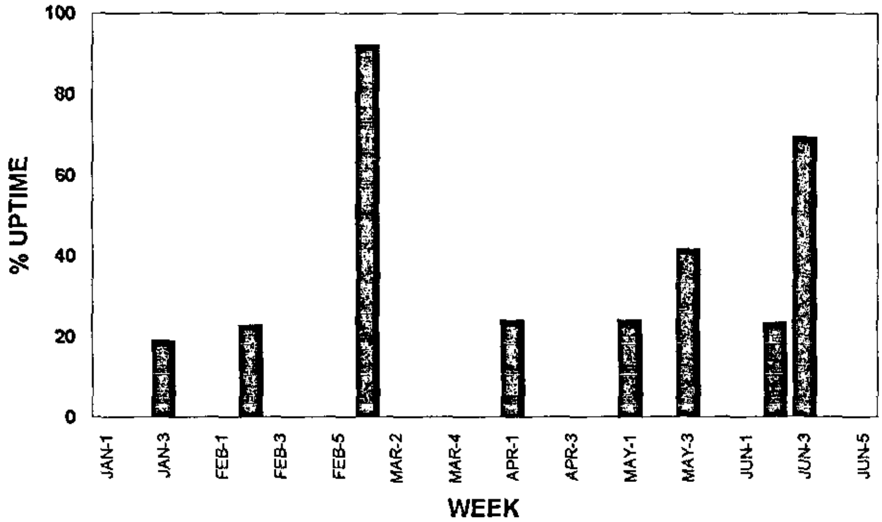


Figure 4 (b) : Percentage Uptime and Reasons for Downtime - July to December 1993



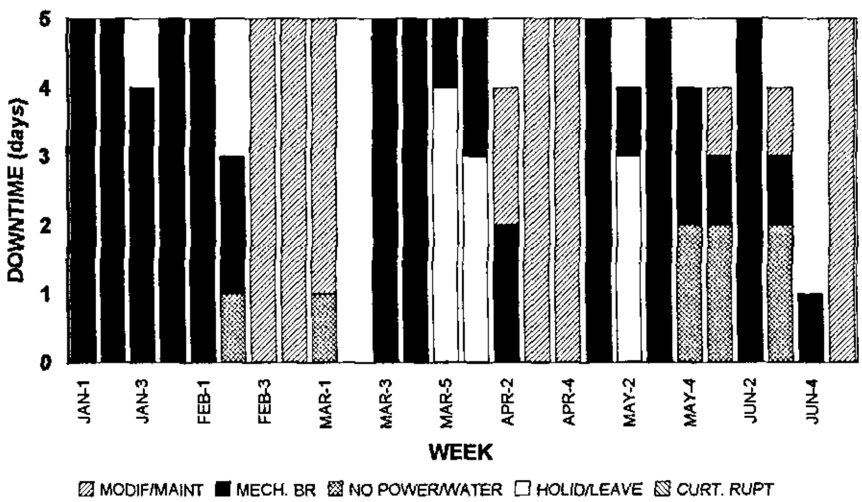


Figure 4 (c) : Percentage Uptime and Reasons for Downtime - January to June 1994

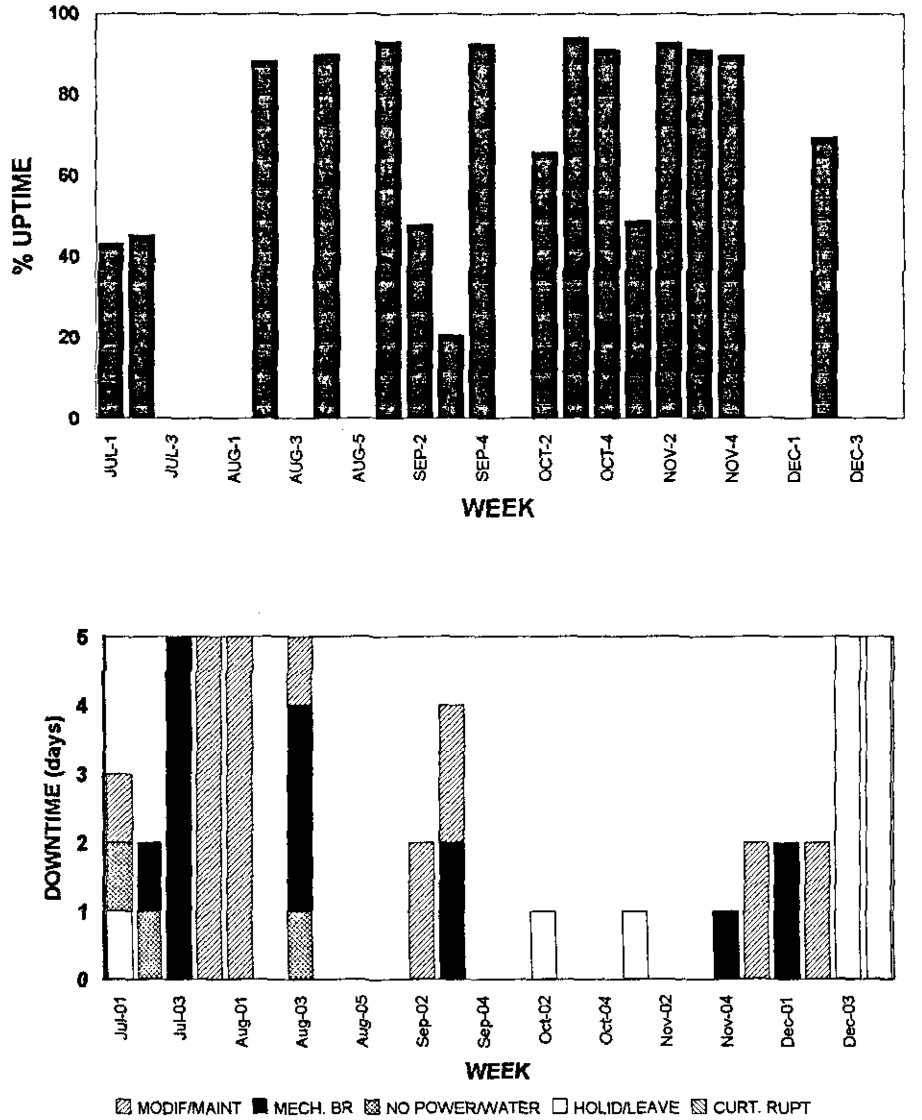


Figure 4 (d) : Percentage Uptime and Reasons for Downtime - July to December 1994

5.2. Mechanical Problems Experienced on Unit

5.2.1. Gasket Failure

From March 1993, significant problems were experienced with gaskets blowing out from between the curtain endblocks and the flow distribution manifolds, necessitating the shut-down of the unit. The endblocks, manifolds and gaskets were original equipment supplied by High Tech Water HTW NV. The problem was first experienced on the feed manifold to the second module. This was solved by placing a tight fitting metal box around the manifold and endblock The problem was subsequently experienced on the other manifolds and was solved by gluing the gasket to the endblock. It was perceived that the gluing of the gaskets to the endblocks was a permanent solution to the problem.

Following the cleaning of the tubes after the blockages experienced in March 1994, the metal plate was removed from the feed manifold on module 2 and the gasket was glued to the endblock. Hewever, in the first run following this modification, the gasket blew out of the top of the manifold. It was realised that gluing of the gasket was not a permanent solution to the problem, and other possible solutions were investigated.

In the first attempt, the interior of the manifold was machined down to leave a lip 3mm wide and 1,5 mm deep along the perimeter. The gasket was then trimmed to fit within this lip. The thickness of the gasket was 3 mm, implying that 1,5 mm protruded above the lip. It was perceived that the lip would provide a lateral restriction to the gasket and hence prevent it from blowing out under pressure.

On replacing the manifold, however, it was found that a distinct gap existed between the gasket and the endblock towards the central region of the endblock, despite the fact that the screws holding the manifold to the endblock had been fully tightened. Examination of the manifold and endblock indicated that both had distorted and were now convex towards the curtain. However, the manifold was less convex than the endblock, resulting in an approximately 2 mm gap between the manifold and the endblock in the central region.

In the second attempt to solve the problem, the 3 mm gasket was replaced with a 5 mm gasket and the depth of the lip was increased to 2 mm. This left 3 mm of gasket exposed above the lip, and it was felt that this was sufficient to overcome the gap between the manifold and endblock. On replacing the manifold and restarting the plant, however, the problem ahd worsened, with fluid spraying out from around most of the manifold. In addition, it was found that the bottom left hand cornerof the endblock had cracked, presumably due to over-tightening of the manifold screws.

Further detailed investigations indicated that there was a very high probability that the screws were too long for the application. Hence, on tightening, the screws bottomed out and did not pull the manifold closer to the endblock. Further tightening merely resulted in the inserts in the endblock being displaced and hence cracking of the endblock.

The manifold screws were shortened by 3 mm. The cracked part of the endblock was glued back to the block and the manifold was reinstalled. The shortening of the screws had solved the problems of the leaks around the manifold. However, a further problem arose in that water leaked out in the region of the cracked portion of the endblock. The most probable explanation is that fluid was leaking out from the tiny groves that remained after the cracked portion had been glued back to the endblock. It was also found that the endblock had cracked in another region, once again due to over-tightening of the screws causing the inserts to be displaced.

It was perceived that the frequent removal and replacement of the manifold over the past two months had caused irreparable damage to the inserts in the endblock. In view of the significant downtime experienced over the past two months, however, it was felt that pursuing a permanent solution should be postponed. Accordingly the module was removed and replaced with a spare module. In the new module, all screws were shortened by 3 mm, and the gaskets were not glued onto the endblocks.

In July 1994, the gasket on module 1 failed. After much consultation, and taking into account the inherent flaws referred to earlier and the solution strategies attempted earlier, a new strategy was adopted. The endblocks were drilled through thus removing the brass inserts. The bolts were replaced with ones that travelled all the way through both the manifold and the endblock. These bolts were welded to backing plates and were inserted from the curtain end of the endblock, the backing plate serving to prevent the bolt from turning when tightened. The gaskets were replaced with the 5 mm one fabricated from insertion rubber. This gasket is cross-threaded, increasing its lateral strength. The gasket was not glued to the endblock, as was the previous practise. The above system ensures that the manifold and endblock can be drawn quite tightly together, thus holding the gasket in place. To date, no further gasket failures have occurred. It is confidently believed that the above approach is the solution to the gasket problem.

5.2.2. Tube Blockages

There were three significant occurrances of tube blockages necessitating dismantling of the manifolds and manual cleaning of the tubes. These occurred in October 1993, March 1994 and May 1994. The tubes that were blocked and the relation to the geometry of the manifolds are shown in Appendix I.

In October 1993, 14 tubes were blocked. All the blockages occurred at or near the horizontal dividers in the manifolds. Examination of the manifolds indicated the following :-

(i) the interior of the manifolds had not been properly contoured. As a result, the exit flows from tubes near the horizontal flow dividers impinged directly onto perpendicular surfaces very close to the ends of the tubes. Thus fluid would have preferentially flown down other tubes, prompting stagnation and blockage of the tubes near the horizontal dividers.

(ii) the sections of the gasket that were over the horizontal dividers were too wide, resulting in some tubes being partially covered. This was the direct cause of the blockages of tubes 1 to 2, 16 to 19, 33 to 37, 51 to 54 and 69 to 70.

The interiors of the manifolds were machined to reduce problem (i) and gaskets were trimmed and contoured to reduce problem (ii).

In March 1994, it was found that most of the blocked tubes occurred away from the manifold horizontal dividers, and generally occurred on the second pass through the curtains. Investigations indicated that the blockages were most probably due to operator error. A few weeks previously, limestone was pumped through the system to identify leaks in fittings. On the same day, the spray cleaning system was dismantled for servicing and hence there was a significant amount of residual limestone in the system. This limestone would have dried and formed larger flakes during the period that the plant was inoperative. When the plant was reassembled, the system was not cleaned prior to starting the precoat stage, hence it seems that the residual limestone flakes were carried into the second pass, causing the blockages.

During the cleaning of the tubes, some pieces of plastic sheeting and what seemed to be bits of a skeleton were found in the tubes. It is most likely that this foreign matter entered the system by falling into the uncovered feed tank. To reduce this, a cover has been installed over the feed tank.

In October 1993, the tubes were cleaned by pumping raw water at high pressure through a one quarter inch POLYFLO tube and forcing the tubes into the blocked tubes. This was a very arduous and time-consuming process. In March 1994, a jet effect nozzle was fabricatd and fitted onto the end of the POLYFLO tube. The nozzle has one orifice which faces forward and four which faces backward. This nozzle considerably reduced the effort required to clean blockd tubes.

In May 1994, some of the blocked tubes were located near the manifold horizontal dividers while curtains 1 and 2 had some blockages towards the centre of the tubes in the first and second pass. The cause of these blockages are not clear.

In general, the occurrances of blockages has been relatively low and is most probably due to mechanical causes, i.e. poor manifolding, rather than being an inherent process problem. Nevertheless, the unblocking of tubes is a timeconsuming and labour intensive task, and would be unacceptable in a rural or peri-urban environment where skilled labour is at a premium. It is believed that redesign of the manifolds and endblocks will contribute greatly towards the reduction of blockages.

5.2.3. Valve Actuators

In September 1994, it was observed that one of the feed valves did not open in response to PLC instructions. The problem was identified as a faulty micro switch in the electric valve actuator, which seemingly had corroded. This was perturbing since the majority of the valves on the unit employ electric actuators, and all, including the faulty one, were well sealed. The operation of all the electrically actuated valves are being closely monitored to establish whether this is an inherent problem.
Electrically actuated valves were installed on the unit due to their lower cost, and the fact that they were specified in the original unit plans. However, if corrosion of the delicate internal mechanism is likely to result in valve failure, this would be unacceptable on a unit designed to be a low maintenence unit. The feasibility of utilising more robust pressure actuated valves should be investigated in future designs.

5.2.4. Blockage of cleaning nozzles

In September 1993, an abnormally high pressure in the line to the spray cleaners indicated that significant numbers of the spray nozzles were blocked. The spray heads were thus removed and the spray nozzles were cleaned. Following the cleaning and reinstallation of the spray heads, the off-take from the permeate tank was modified. Previously, permeate for the spray nozzles was withdrawn from the bottom of the tank. In order to minimise settleable foreign matter from being drawn into the spraying system, the off-take was moved to the side of the permeate tank. In December 1994 the cleaning heads were removed and it was observed that approximately 20 % of the nozzles were blocked. The heads were cleaned and reinstalled.

Although the nozzles are easily cleaned, a significant time is required to remove and replace the cleaning heads, contributing to a high downtime. Proposals to alleviate the problem included installation of an in line filter, and improved design of the nozzles. A subsequent proposal was to change the design of the piping to the cleaning heads to enable the system to be flushed regularly, thus removing any foreign material that may eventually clog nozzles.

The high pressure spray cleaning systems has proven to be effective in that there is no long term degradation in flux. However, the system is not robust. The spray nozzles are prone to blockages and a high time and labour input is required for their cleaning. The installation of a filter system to ensure a contaminant free supply of permeate to the spray heads would be expensive, and probably not an economically viable option.

The spray system and the nozzles need to be redesigned if the reliability of the unit is to improve.

5.2.5. Tube rupture

In November 1993, holes developed in two of the tubes on curtain 3, causing raw water to spray from the curtains. Initially, it as believed that this was due to failure of the curtain fabric. Examination of the curtain indicated the presence of brown spots in the centre of each tube, at the same location as the stationary position of the spray cleaners. This seemed to indicate that foreign matter (eg. rust) in the spray lines was being sprayed onto the curtains at the start-up of the cleaning cycle, effectively sand-blasting the curtains and causing holes to develop in the tubes. Since the pipes from the permeate tank to the spray heads are fabricated of either PVC or stainless steel, these were discountered as possible sources of rust. The mostly likely source, therefore, was the municipal water supply which is used to top up the permeate tank prior to start-up after week-ends. To reduce contamination of the permeate tank from this source, a system of cartridge filters was installed on the municipal line of the permeate tank.

The holes in the curtain was patched with the same adhesive that is used to seal tube seams, VAW 595 from GENKEM. The adhesive was then applied in a vertical column across all tubes, and in all curtains, in order to protect this region from the sandblasting effect.

While the application of the adhesive has temporarily solved the problem, this is not viewed as a long term solution. It is expected that after some time the high momemtum transmitted to the curtain when the spray cleaners are started up will degrade the adhesive as well. This aspect requires further attention.

5.2.6. Rusting of nuts, screws and bolts

One problem which significantly increased the time and effort required to effect repairs to the plant was rusting of nuts, screws and bolts. A particular problem was experienced where mild steel screws and nuts had been inserted into threaded holes in the frame of the plant. On attempting to temove these, the rusted heads invariably broke, necessitating time consuming repairs. The problem would be alleviated by replacing these with stainless steel screws, or nuts and bolts where appropriate.

5.3. Summary Of Changes Made to Original Design

5.3.1. Gaskets

In the original design, the manifold-endblock assembly is held together by bolts which travel through the manifolds and screw into brass inserts in the endblock. With time, the endblock and/or manifold undergoes a degree of warping, leading to the gaskets being blown out. Attempts to tighten the bolts, so as to close the gap between the manifold and endblock results in the brass inserts being pulled out of the endblock with the endblock subsequently cracking.

The final solution adopted here, which has worked to date, is to drill out the brass inserts and drill holes through the entire width of the endblock. A backing plate with bolts welded to it is then attached to the rear of the endblock, the bolts travelling all the way through the endblock. Careful attention has to be paid to the fabrication of the backing plate, since the bolts have to line up exactly with the holes in the endblock. The bolts are then inserted all the way through the holes ain the manifold and tightened down with nuts and washers. Using this approach, the bolts may be tightened as much as is required without any damage to the endblock or manifold.

5.3.2. Manifolds

The major problem experienced with respect to the manifolds was tube blockages arising from basic flaws in the manifold. These flaws include :

(i) the interiors of the manifold have not been properly contoured

(ii) the arrangement of the tubes does not take into account the horizontal separators in the manifolds.

(iii) the manifold and endblock distort with time.

In the current project, the former was solved by machining out the interior of the manifolds, so as to ensure a smooth flow path for all tubes. The latter flaw was addressed by trimming the gaskets on the horizontal dividers. However, this is not a permanent solution to the problem, since a small part of the tubes on either size of each divider are still blocked by the divider. One option would be to permanently block off those tubes that fall under the horizontal separators. The distortion of the manifold and endblock with time could be alleviated by using a metal frame to support them.

Clearly the design of the manifold and endblocks have not been approached holistically, i.e. the manifold design seems to have been developed without a knowledge of the geometry of the endblock and curtains. This area would certainly benefit from further development.

5.3.3. Spray Cleaners

The major problem experienced with the spray cleaners was the blockage of the spray nozzles. Besides reducing the efficiency of the cleaning cycle, the a considerable effort in terms of time and manpower is required to clean out the nozzles.

During the project the problem was not solved. It was alleviated by changing the offtake from the permeate storage tank and filtering the municipal water that was used to top up the permeate storage tank.

One proposal for solving the problem was to install a filter just before the spray bars. However initial cost estimates indicate that such a filter, operating at high pressures, would be extremely expensive. Other approaches would be to improve the design of the nozzles themselves, to reduce their blocking potential, or to install appropriate valves so that the spray lines could be flushed out prior to the sprays being engaged.

5.3.4. Tubes

The only problem experienced in terms of tube failure was that small holes developed in the tube due to the sandblasting effect from the spray nozzles when the sprays are started up. Flushing out the spray lines to remove particulate contaminants prior to engaging the sprays should alleviate this. Other options include covering the affected region of the curtain with a resistant layer, and ramping up the flow to the spray bars slowly, so as to alleviate the sandblasting effect.

5.3.5. Electrically Actuated Valves

Problems have been experienced with valves failing to respond to PLC instruction, due to corrosion of the delicate internal mechanism of the valves.

It is recommended that in future designs the viability of installing more rpbust pressure actuated valves be investigated.

5.4. Plant Response to Upset Conditions

On 23 September, 1993, the turbidity of the raw water entering the Wiggins Water Works suddenly increased from the usual 10 to 30 NTU to over 3500 NTU, due to a problem with the raw water supply. The main water works plant and the rest of the test units at the Process Evaluation Facility were shut down, and the only plant that operated successfully was the Exxflow unit.

The flux was considerably reduced, as was to be expected from the high feed concentration. Following a clean, it emerged that the tubes were not blocked as expected, and the plant subsequently performed as normal.

This experience indicated the ability of the plant to cope with upset conditions with no detrimental effects to its long term performance. It also indicates the ability of the unit to recover from inadvertant operator error. This would be of particular significance in rural and peri-urban areas, where operator error could be higher due to lower skills levels.

6 UNIT PERFORMANCE

6.1. Choice of Operating Modes

As indicated in Section 4.1, in woven fibre microfiltration, the fouling layer is the actual separating barrier. This fouling layer may be formed from the foulants inherent in the raw water, or it may be artificially formed by the introduction of particulate material into the raw water. This leads to three **modes of operation** :

(i) Operation on raw water only - here the fouling layer forms from the foulants in the raw water.

(ii) Operation with a filter aid - here a mineral powder, e.g. limetone, kaolin or diatomaceous earth, is added to the raw water. The fouling layer consists of both filter aid particles and foulants from the raw water.

(iii) Operation with a precoat - here a fouling layer or cake is formed on the tube wall before the raw water is pumped into the system. This is effected by circulating a suspension of the precoat material through the curtains for some time and then switching the feed over to the raw water.

Previous studies have indicated that the performance of a microfiltration system can be greatly improved by operating with a filter aid or a precoat. Accordingly all three modes of operation, viz. raw water only, filter aid and precoating were investigated in this project. In addition, 4 different types of precoat were investigated, viz. two grades of limestone (Kulu 5, and Kulu 2), diatomaceous earth and kaolin.

The procedures for operating in the different modes are described in Table 2. The performance in the different modes are described in the relevant sections, Section 6.2 to 6.6.

Table 2 : Operating Cycles for the Different Operating Modes

Mode	**Cycle**
raw water only	Charging - The feed tank is charged with raw water (15 minutes) Mixing - The feed tank is mixed via the feed pump and bypass line. (5 minutes) Filtration A - The feed pump is started. The permeate is is collected in the waste permeate accummulation tray and returned to the feed tank, together with the reject (3 minutes). Filtration B - the permeate is collected and pumped to the permeate storage tank. The feed tank is continually topped up with raw water (5 hours). Concentration - as Filtration B, but the raw water supply to the feed tank is stopped, and the feed tank undergoes full batch concentration (25 to 45 minutes) Discharge of feed contents to drain and cleaning cycle (5 minutes).
filter aid	Charging - as "Raw Water" Dosing - a measured quantity of limestone suspension is fed from dosing tank into feed tank. Mixing - *thereafter similar to "Raw Water"*
precoat	Charging - feed tank is filled with municipal water. Maesured quantity of precoat material introduced into feed tank, and contents mixed via feed tank and bypass line. Precoating - precoat suspension circulated through curtain (4 pass configuration). Reject and permeate returned to feed tank (20 to 30 minutes) Switchover - drain valve on feed tank opened and contents dropped to about half. Tank refilled with raw water. All the time contents continue being circulated through curtains. Draining and refilling continued until most of precoating suspension removed from system (usually 5 cycles). Filtration - permeate sent to permeate storage. Reject returned to feed tank (about 24 hours). *Thereafter, as for "Raw Water"*

6.2. Performance indicators monitored :

(i) Turbidity - regular measurements of the raw water, feed tank and permeate turbidities were performed using a standard turbidity meter. The turbidity was measured in nephelometric turbidity units (NTU). The raw water sample was taken from a sample port on the raw water supply line. The feed tank sample was taken from a sample point just before the main feed pump. This represents the actual turbidity that the curtain is exposed to. Due to the concentration effect of operating in the semi-batch mode, the feed tank turbidity progressively increases with filtration time, while the raw water may not change significantly. The permeate sample was taken directly from the permeate stream that flows off the curtain.

(ii) Microbiological analyses - four sets of microbiological analyses were performed by the Umgeni Water Laboratories on samples of the raw water, feed tank and permeate. The samples were taken as in (i) above. The following analyses were performed as per Umgeni Water's standard methods :

- Coliforms
- E.Coli
- Fecal Streptococci
- CC37 (colony count at 37 °C)
- CC22 (colony count at 22 °C)
- Algae
- CHLA

(iii) Overall chemical analysis - The samples taken for (ii) above were also analysed for the the various parameters indicated in Table 4, as per Umgeni Water's standard methods.

(iv) Permeate production - Permeate fluxes were measured on an hourly basis, where possible. An hourmeter was installed onto the main feed pump and a cumulative flowmeter was installed on the line between the clean permeate pump and the permeate storage tank. Successive differences between the flowmeter and hourmeter readings indicated the net permeate production and the period of production respectively, whence the permeate flux could be calculated.

The nominal filtration area of four tubes is 80 m^2. However, a fraction of the tube area near the endblocks is not pervious, due to the glue used to attach the curtain to the endblock. The **active filtration area was estimated as 78 m^2**, and this value was used in flux calculations.

6.3. Turbidity removal

6.3.1. Effect of Operating mode on turbidity removal

The turbidity-time profiles obtained in the different operating modes are depicted in Figure 5. The turbidity of the raw water ranged from approximately 5 to 20 NTU. The turbidity in the feed tank increases from the raw water turbidity up to 100 NTU during the course of a filtration cycle, due to the concentration effect.

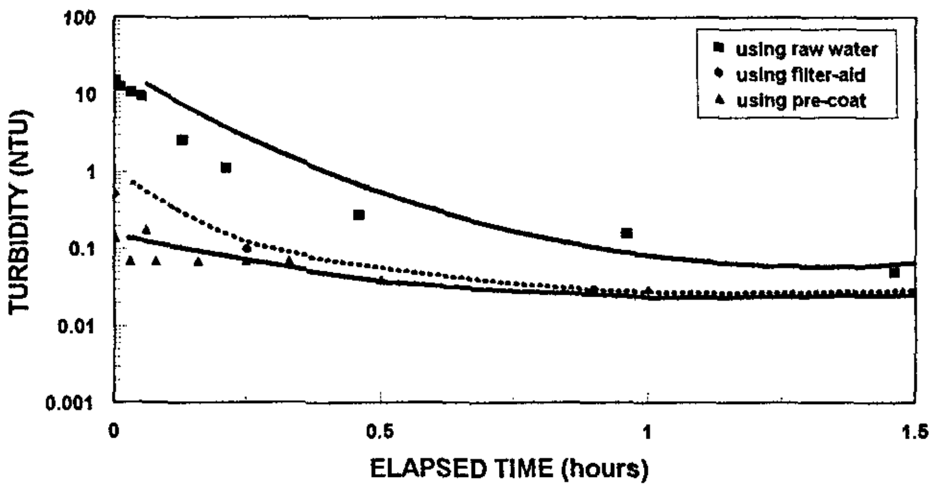


Figure 5 : Effect of Operating Mode on Permeate Turbidity - Time Profiles

When operating on raw water only, the permeate turbidity typically takes up to a hour before it drops to below 0,1 NTU, whereafter it remains below this value. In the filter-aid mode of operation, the permeate turbidity typically takes ten to fifteen minutes to drop to below 0,1 NTU. For the run with a precoat, the turbidity is about 0,1 NTU from the start of the filtration cycle, and remains at this value for the duration of the run.

Thus, from the point of view of turbidity rejection, the performance of the plant with a precoat is significantly superior to that in the other modes. The results also indicate that when operating on raw water only, the permeate would have to be discarded for a significant period of time before the permeate quality becomes acceptable. Unfortunately, this initial period is also the period of the highest permeate production (see Section 6.6). Thus, when operating on raw water a significant fraction of the permeate has to be discarded due to poor quality.

6.3.2. Overall turbidity removal performance

The overall turbidity removal efficiency is depicted in Figure 6.

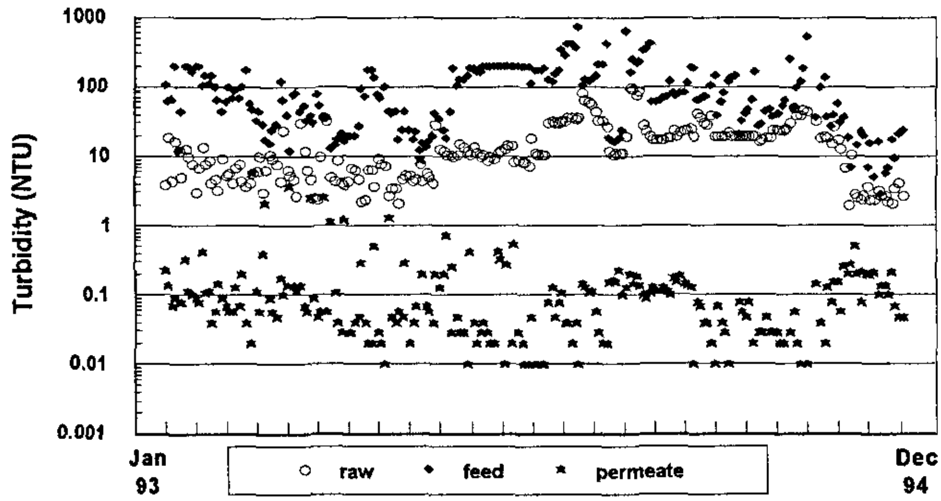


Figure 6 : Turbidity Removal History

Over the period reported in Figure 6, the raw water turbidity ranged from 3 NTU to 100 NTU and the feed tank turbidity from 10 NTU to 800 NTU. In the period May to August, runs were performed in the raw water only and in the filter aid modes. Turbidities were measured at random times during the run, including the initial period where the turbidity is known to be high for runs on raw water only (see Section 6.3.1). Accordingly, there are various points during this period where the permeate turbidity exceeded 1 NTU. From September the unit was operated solely in the precoat mode. Here, permeate turbidities are consistently below 0,5 NTU, and usually about 0,1 NTU.

It is seen that the unit consistently produced a permeate of good turbidity over an extended period of operation. The World Health Organisation (WHO) standard for drinking water is 2 NTU. The standard adopted by Umgeni Water is 0,5 NTU. Figure 6 indicates that the unit is capable of consistently producing a permeate of a turbidity well within the potable water standards.

6.4. Microbiological Removal Efficiency

Investigations into the bacteriological rejection efficiency were performed by the Pollution Research Group as well as Umgeni Water. In these investigations, the unit was not dosed with chlorine for at least a week before the tests (see Section 6.6.5).

The results obtained from the Umgeni Water Laboratories are reported in Table 3. Two sets of analyses were performed in November 1993 and three sets in November 1994. Each set consisted of three samples, viz. raw water, feed tank and permeate. Sets 1 and 3 were taken shortly after the initiation of the filtration cycle, Sets 2 and 5 were taken at 4 to 5 hours into the filtration cycle, and Set 3 was taken at the end of the filtration cycle.

The analysis indicate that in all instances > 99,9 % of coliforms, E. Coli and fecal streptococci are rejected. On comparing Sets 1 and 2, it is seen that the concentration of contaminants in the feed tank undergoes a tenfold increase in the first five hours of filtration. However, this does not affect the bacteriological rejection capabilities of the unit. Note also that the unit operated on a high contaminant level source in 1993 (Cleremont Pump Station) and a low contaminant level source in 1994 (Inanda Dam). In both instances, the rejection capabilities of the unit was equally as good.

Accordingly, an excellent bacteriological rejection efficiency is exhibited by the plant. This, combined with the very good permeate turbidities indicates that the unit consistently produced an excellent quality of water.

6.5. Overall Chemical Analysis

Overall chemical analyses were performed at the same time that the microbiological tests were done. The results are presented in Table 4.

It is seen that there is a significant removal of Fe and Mn. Since microfiltration is essentially a physical separation process, it must be concluded that the decrease in these metals is most probably due to metal adsorption onto colloidal material which is retained by the microfilter.

It is also seen that there is a significant decrease in Ca and a slight decrease in alkalinity. This indicates that the limestone precoat is not being progressively dissolved by the permeate.

Table 3 : Microbiological Analyses

		SET 1			SET 2			SET 3			SET 4			SET 5		
		Clermont Pump Station 25 November 1993 t = 0 hours			Clermont Pump Station 25 November 1993 t = 5 hours			Inanda Dam 1 November 1994 t = 23 hours			Inanda Dam 17 November 1994 t = 0 hours			Inanda Dam 18 November 1994 t = 4 hours		
	Units	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**
COLI	counts/ 100 mℓ	264	460	**0**	460	4 980	**0**	6	30	**0**	8	1	**0**	0	16	**0**
E.Coli	counts/ 100 mℓ	260	440	**0**	314	4 900	**0**	2	30	**0**	8	1	**0**	0	4	**0**
F.Strep	counts/ 100 mℓ	4	14	**0**	2	80	**0**	0	16	**0**	nd	nd	**nd**	0	4	**0**
CC37	counts/ mℓ	296	240	**0**	260	504	**0**	258	2 192	**5**	404	1 212	**3**	156	260	**28**
CC22	counts/ mℓ	2 210	2 470	**0**	2 600	1 000	**0**	624	4 144	**7**	nd	nd	**nd**	784	2 472	**378**
ALG	ug/ℓ	609	320	**1**	461	TB	**0**	334	6 488	**0**						
CHLA	ug/ℓ	2.67	2.8	0	3 031	TB	**0**									

Table 4 : Chemical Analyses

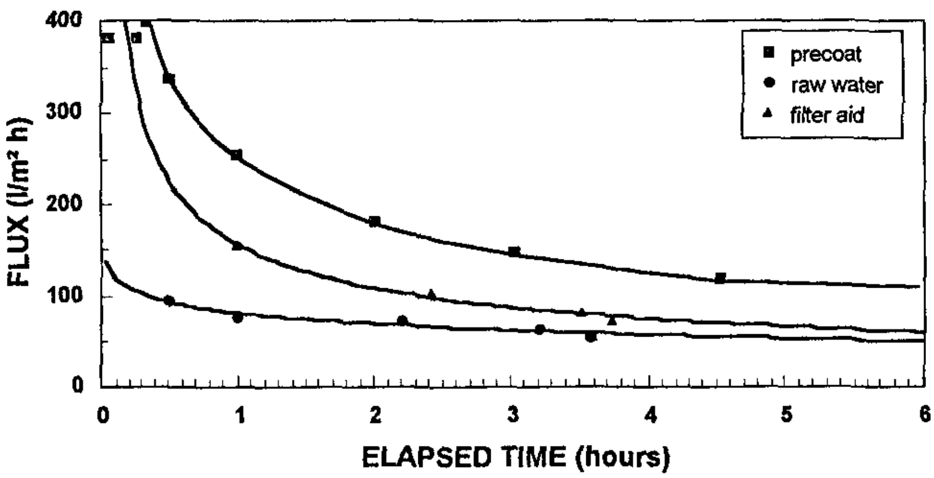
		SET 1			SET 2			SET 4			SET 5		
		Clermont Pump Station 25 November 1993 t = 0 hours			Clermont Pump Station 25 November 1993 t = 5 hours			Inanda Dam 17 November 1994 t = 0 hours			Inanda Dam 18 November 1994 t = 4 hours		
	Units	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**	**raw**	**feed**	**perm**
Colour	Hazens	6.81	6.9	5.08	7.47	8.73	6.45	3.13	4.5	2.2	3.09	5.58	2.57
Turbidity	NTU	36.6	69.1	0.26	32.1	328	0.13	2.6	22.7	0.08	2.9	22.3	0.02
Conductivity	mS/m	27.3	28.2	27.1	27.4	33.5	27.6	28.1	28.1	27.3	28.3	33.3	28.2
pH								7.9	8.1	8.1	7.9	8	8.1
Odour								nil	vmveg	nil			
AL T	ug/mℓ	269	300	40	260	OR	OR						
ALK	as $CaCO_3$	60.4	69	62	60	78.9	60	65.8	97.6	68.4	65.8	86.8	67.9
Fe	mg/ℓ	0.6	0.67	0.02	0.65	3.04	0.02	0.15	0.19	< 0.02	0.11	0.75	< 0.02
Mn	mg/ℓ	0.28	0.35	0.01	0.24	1.96	0.01	0.03	0.05	< 0.01	0.02	0.24	< 0.01
NO_3	mg/ℓ	0.44	0.46	0.44	0.5	0.65	R						
NO_2	mg/ℓ	0.05	0.05	0.05	0.05	0.05	R						
NH_3	mg/ℓ	0.1	0.2	0.2	0.1	0.1	0.1	0.02	0.02	0.02	0.01	0.01	0.01
Cl	mg/ℓ	46.4	46.8	45.1	47.3	55.3	R						
SO_4	mg/ℓ	15.7	15.7	14.5	15.7	22.1	R						
TP		25	30	< 15	20	23	R						
SRP	ug/ℓ	13	8	6	5	10	L						
TDS	mg/ℓ	142	49.5	123	95	166	124						

		SET 1			SET 2			SET 4			SET 5		
		Clermont Pump Station 25 November 1993 t = 0 hours			Clermont Pump Station 25 November 1993 t = 5 hours			Inanda Dam 17 November 1994 t = 0 hours			Inanda Dam 18 November 1994 t = 4 hours		
SS	mg/ℓ	54	191	4	77.3	414	9						
TOC	mg/ℓ	3.15	3.25	3.08	3.23	4.43	2.09				< 0.7	2.48	< 0.7
TKN	mg/ℓ	0.64	1.23	0.73	0.94	1.89	2.07	0.86	0.63	0.49	< 0.2	2.31	0.29
AL (T)		269	300	40	260	2 138	33						
AL (s)		< 10	< 10	< 10	< 10	< 10	< 10						
Total hard		65.2	106	62.7	65.5	118	64.4						
Ca		13.4	29.4	13.5	13.4	31.3	13.5	13.8	28.3	15.4	15.3	24.5	15.4
Mg		7.63	7.98	6.99	7.7	10.5	7.37	7.14	7.15	6.64	7.67	8.96	7.46
Na								29.4	28.5	27.8	29.9	32.8	29.4
K								3.73	3.78	3.57	3.87	4.84	3.83
Cu											0.08	< 0.05	0.07
Zn											< 0.02	0.03	< 0.02

6.6. Permeate Production

6.6.1. Effect of Operating Mode

The effect of operating mode on permeate production is shown in Figure 7 (a) and (b), where the point permeate flux profile with time is depicted.



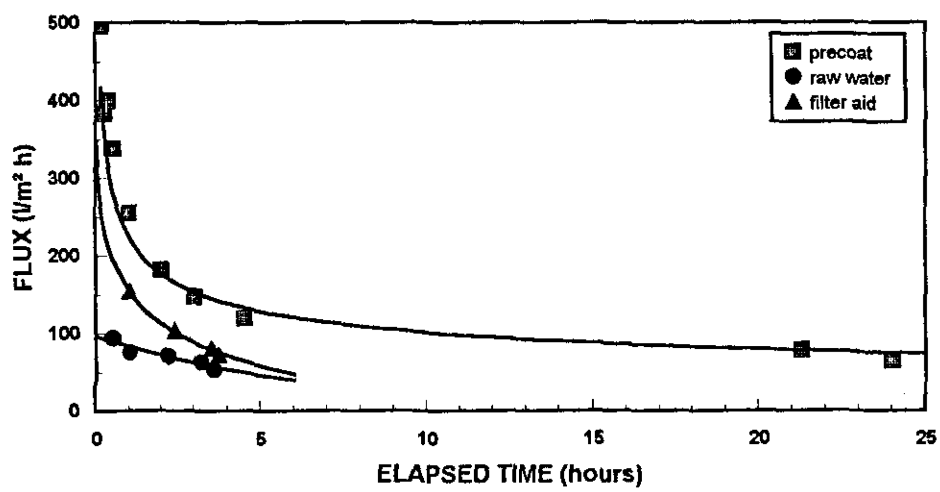


Figure 7 (a) and (b) : Effect of Operating Mode on Permeate Flux - Time Profile

When operating on raw water only, the flux starts off at a relatively low value and declines to around 50 ℓ /m2h. within four hours. The flux obtained with a filter-aid starts off at a significantly higher value and declines to about 75 ℓ /m2h after 4 hours. The flux obtained with a precoat is significantly greater than that obtained on raw water only or with a filter-aid. After

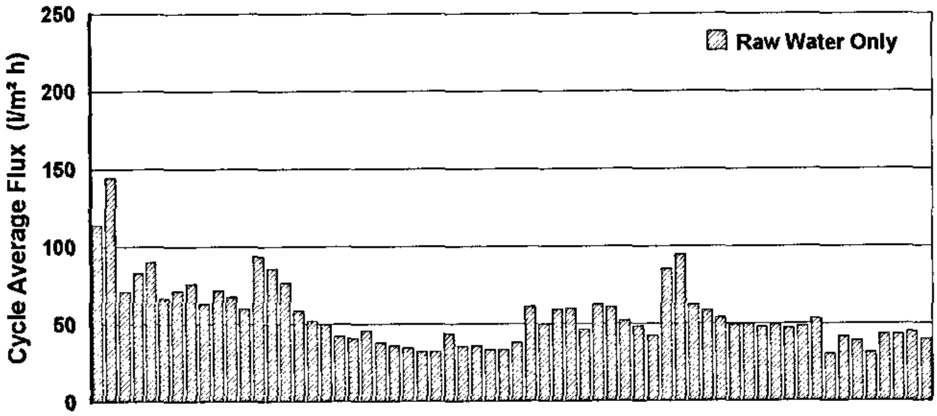
2 hours the flux obtained with a precoat is twice that obtained on raw water only, and approximately 1,5 *times that obtained with a filter-aid. After 4 hours, the flux obtained with a* precoat is approximately twice that obtained on raw water only and with a filter aid. After 24 hours of operation with a precoat, the flux is similar the that obtained after 4 hours of operation with a filter-aid.

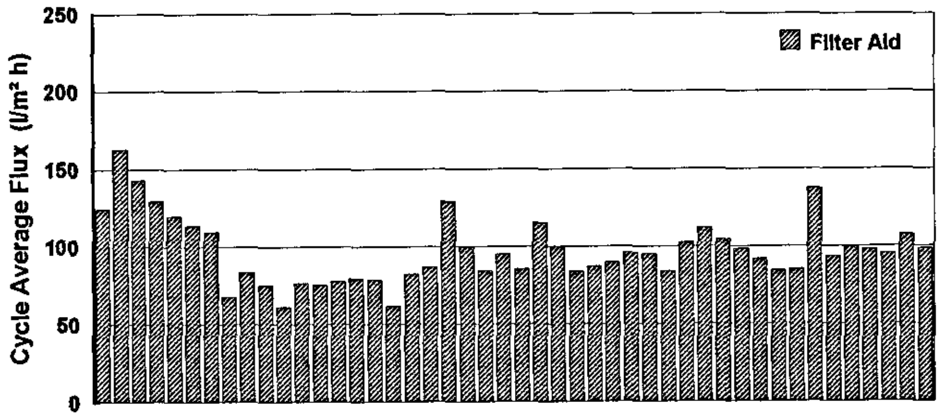
Due to the rapid decline in flux in the raw water and filter aid modes, the filtration cycle times for these modes was set to 6 hours. The filtration cycle time for the precoat runs was set to 24 hours. This significant difference in cycle times affects the frequency of cleaning cycles for each mode, and hence affects the net production per day, as discussed in Section 6.6.4.

Cycle average fluxes for each run were calculated from the total permeate production during the filtration cycle and the total filtration cycle period. The downtime required for cleaning was not included in the cycle time.

The cycle average fluxes obtained with a precoat are compared to those obtained with raw water only and with a filter-aid in Figure 8 (a) to (e). In those figures, all data obtained during the project for each mode has been depicted. As noted above, the cycle times for the runs with a precoat was significantly longer than the cycle times for runs withraw water only and with a filter-aid. To enable a comparison, cycle average fluxes for runs with runs with a precoat have been calculated for three cycle times :- approximately 3 hours (Figure 8c), approximately 6 hours (Figure 8d) and for the full cycle of approximately 24 hours (Figure 8e)

The cycle average fluxes are a long term confirmation of the trends exhibited in Figure 7 (a) and (b), i.e. that operating in the precoat mode produces a significantly greater permeate production than operation in the other modes.





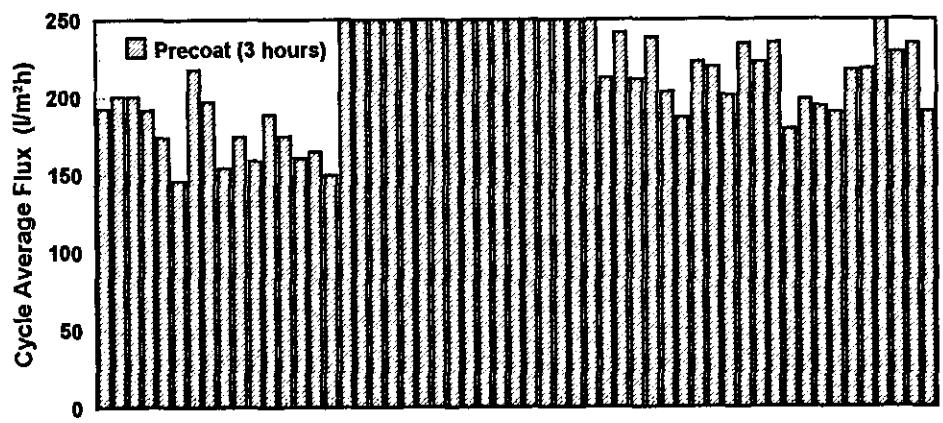


Figure 8 (a), (b) and (c) : Effect of Operating Mode on Cycle Average Fluxes

Raw Water Only, Filter Aid and Precoat at 3 hours

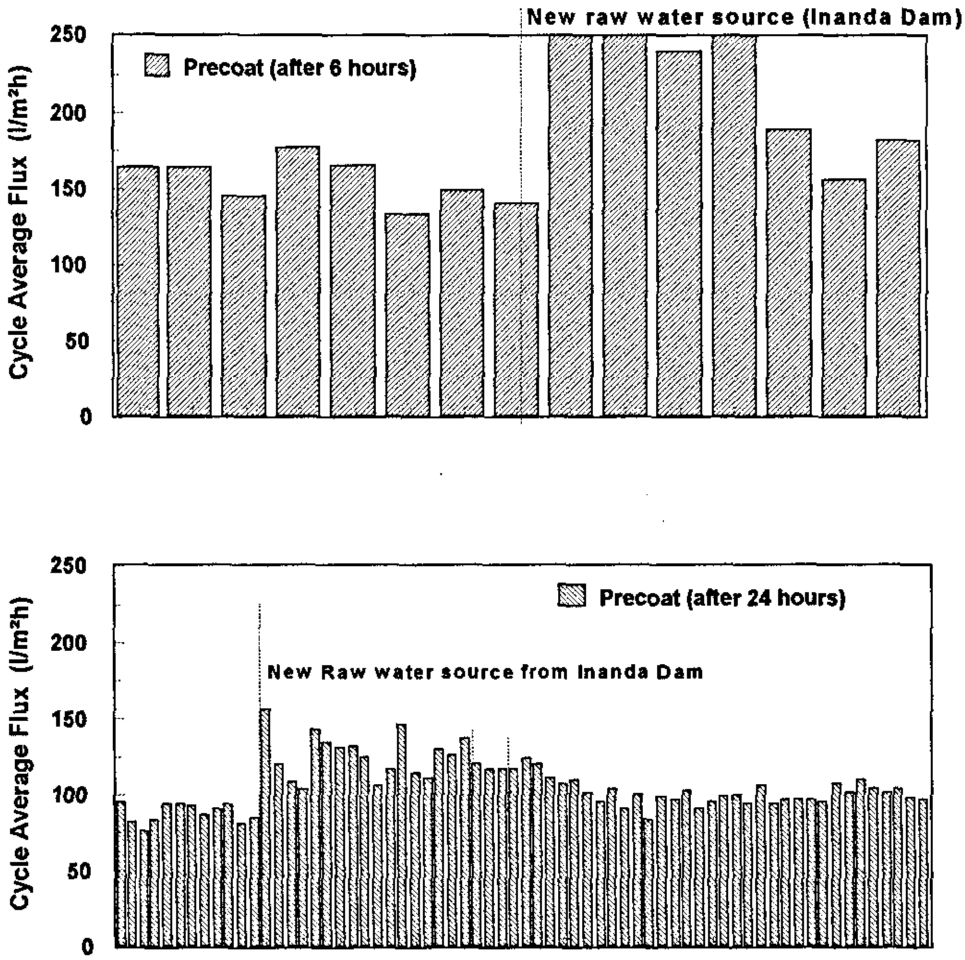


Figure 8 (d) and (e) : Effect of Operating Mode on Cycle Average Fluxes
Precoat Mode at 6 hours and approximately 24 hours

6.6.2. Comparison of Precoat Types

Four precoats were investigated, viz. two sizes of limestone (5 microns - Kulu 5 and 2 microns - Kulu 2), kaolin and diatomaceous earth. In each instance, the initial concentration of the precoat suspension and the precoat period were the same. Flux time curves obtained for each precoat are shown in Figure 9. The curves obtained with Kulu5 and the more expensive Kulu 2 are similar. The flux obtained with diatomaceous earth is less than that obtained with limestone. The flux for kaolin is initially notably less than that obtained with limestone, but this difference diminishes with time. Figure 9 indicates that the kaolin curve is significantly flatter than others. This may indicate that for runs of very long periods, very much longer than 24 hours, kaolin may yield the highest average flux. This will be investigated in the future.

In general, the above investigation indicated that there was no significant reason to change the precoat from the currently used Kulu 5.

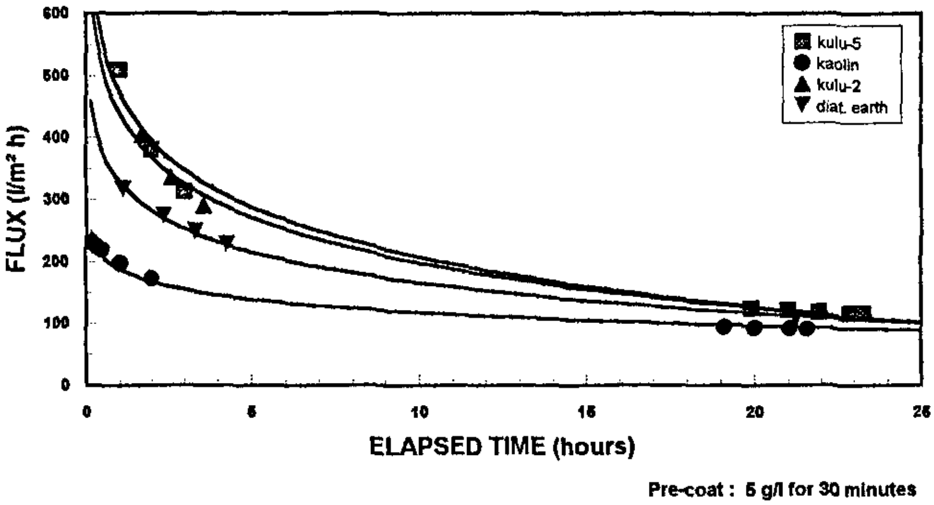


Figure 9 : Effect of Precoat Type on Flux - Time Profile

6.6.3. Overall Permeate Production Performance

The weekly average fluxes for the entire project are depicted in Figure 10. These were calculated from the total permeate production and the total filtration hours in each week.

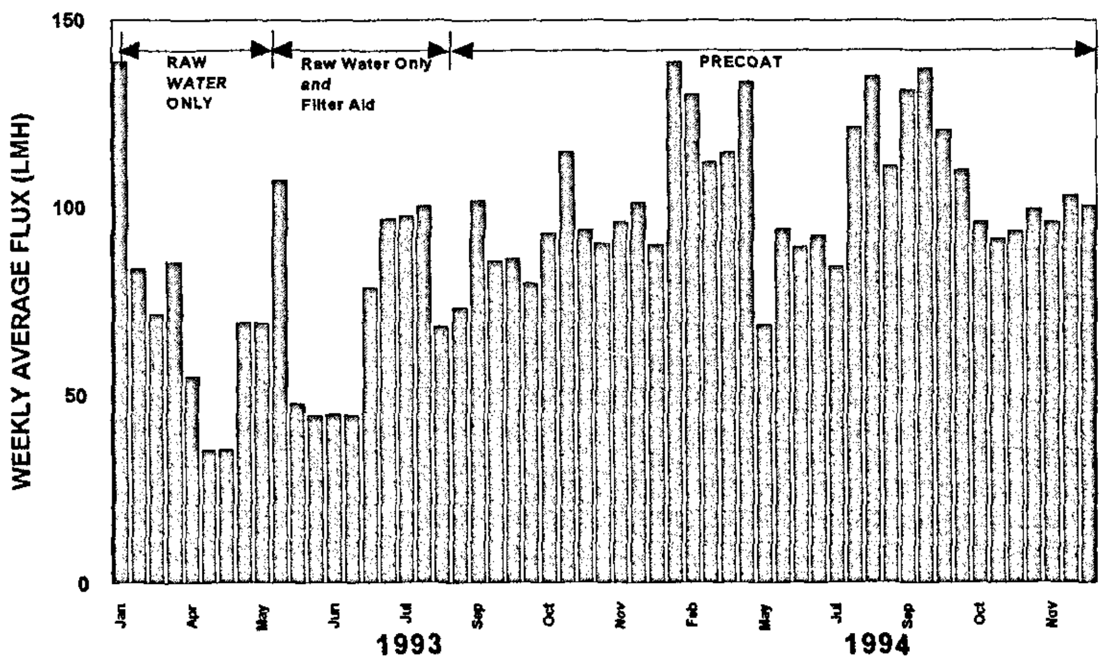


Figure 10 : Weekly Average Fluxes over Project Period

As expected, there is a progressive increase from runs performed on raw water only, to runs performed with a filter aid and precoat runs. On examining the precoat runs, which span sixteen months, the following are clear :

(i) there is no long term decline in flux

(ii) the unit has consistently produced a weekly average flux of approximately 90 ℓ/m²h.

This overview of the permeate production performence indicates clearly that the unit is capable of producing the higher fluxes associatd with precoating over an extended period.

6.6.4. Net Production and Water Recovery

The daily net production is calculated in Table 6, using the assumptions of Table 5.

The water recovery is calculated as follows :

Volume of water dumped to drain = 5 m^3 (max remaining in feed tank at end of run)

Total volume of raw water drawn = 5 + total daily permeate production

Water Recovery = (total daily permeate production)/(5 + total daily production)

Table 5 : Data for Calculation of Daily Production

Mode	Average daily flux (ℓ/m^2h)	Filtration cycle period (hours)	Filtration hours per day	Number of cleans per day	Volume of permeate used in each clean
raw water	50	6	22	3	5
filter aid	75	6	22	3	5
precoat	90	22	22	1	5

Table 6 : Net Daily Production and Water Recovery

Mode	Total permeate production per day (m^3)	Total volume permeate used in cleans (m^3)	Net permeate production per day (m^3)	Water Recovery
raw water	85.8	15	70.8	94.5
filter aid	128.7	15	113.7	95.8
precoat	154.4	5	149.4	96.9

Thus the production capability in the precoat mode, and at 97 % water recovery, is as follows :

Installed (4 curtains)	=	0,15 Mℓ/day
Full Capacity (8 curtains)	=	0,3 Mℓ/day

Assuming a potable water requirement of 200 ℓ per household per day, the unit would be capable of servicing a town of 1 500 households.

6.6.5 Loss of Performance due to Bacterial Activity

In initial semi-batch runs without filter-aid, the average permeate flux for each filtration cycle was approximately 50 to 65 ℓ/m^{2}h. In the period late April to early May, this declined to an average cycle flux of approximately 35 ℓ/m^{2}h. Investigations indicated that this flux degradation was most probably due to the growth of bacteria in the system. Subsequently, chlorine was continually dosed into the feed tank, with a commercial swimming pool chlorine dispenser. With the chorine dose, the average cycle flux was restored to about 60 ℓ/m^{2}h.

When operating in the filter aid and precoat modes, continuous dosing of chlorine was stopped. On an occasional basis, usually one in every two weeks, chlorine was added to the permeate during the cleaning cycle. It was found that this occasional "spiking" of the permeate was sufficient to keep the curtains and permeate trays free of bacterial growth.

6.7. Summary of Unit Performance

The performance of the unit in the precoat mode is significantly better than the performance on raw water only or with a filter aid, both from the point of view of permeate quality and permeate production.

In the precoat mode, the unit exhibits an excellent turbidity rejection, producing permeate of a turbidity < 0,5 NTU, and usually around 0,1 NTU, for feed turbidities ranging from 5 NTU to > 800 NTU. The bacteriological rejection is also good and in tests performed by Umgeni Water's laboratories, 100 % of coliforms, E. Coli and fecal streptococci are rejected. The unit was also able to remove some Fe and Mn. Overall, the unit has produced an excellent quality of permeate that was well within the potable water standards and guidelines in terms of the parameters tested.

Over the course of the project, the daily permeate production rate was virtually doubled, from 0,07 Mℓ/day (raw water only) to 0,15 Mℓ/day (precoat). The unit has consistently produced the higher fluxes over a period of sixteen months, with no long term decline in performance.

7 OPERATOR REQUIREMENTS AND ECONOMICS

7.1. Manpower Requirements

The operation of the unit requires very little attention due to the fact that it is fully automated and controlled by PLC.

Duing the course of the project significant operator and technical input was required to cope with the various mechanical problems experienced on the unit that lead to unscheduled downtime. On the assumption that all inherent mechanical flaws would be solved in a redesign of the unit, the regular, scheduled, manpower input required to operate and maintain the unit is estimated in Table 7.

Table 7 : Manpower Requirement for Regular Operation and Maintenance

Work	Description	Hours	Skills Level
Routine operation	Daily sampling Turbidity and flowrate measurements Makeup of precoat suspension	2 per day	Operator
Maintanance and Repair	Pump maintenance, repair of leaks Curtain and PLC checks	4 per month	Technician

It is assumed that the operator would have at least a standard eight certificate (or equivalent) and a technical aptitude. The main function would be to monitor the daily performance of the unit and ensure that the unit is performing as expected. The technican would have to be a skilled artisan, preferrably with an electrical or mechanical background.

7.2. Capital Cost

The plant produces approximately 150 m^3/day on two modules, but was designed for 300 m^3/day (4 modules). The approximate cost of a unit as initially commissioned was R 150 000 (in 1991 Rands). A costing exercise on the unit in 1997 indicated that to rebuild the unit, as originally commissioned, would cost approximately R 250 000.

This translates into a general capital cost of R 833 /(m^3/day).

7.3. Operating Costs

The chemical costs are based on actual costs incurred when operating on two modules. Since the unit was designed for four modules, the power, labour and maintenance costs are based on the expected production rate with four modules (300 m^3 /day).

7.3.1. Chemical Cost

The unit requires limestone for precoating and chlorine for occasional "spike" disinfection.

The unit is precoated with 5 m^3 of a 5 g/ℓ limestone suspension every 24 hours. This requires 25 kg of limestone per day, since all the limestone is wasted to drain. The cost of limestone is approximately R 0,80 per kilogram, and approximately 150 m^3 of permeate is produced per day.

Thus, the cost of limestone is R 0,13 per m^3.

A very low concentration of commercial disinfectant is used for occasional disinfection of the curtains and permeate tray. The cost is estimated to be R 0,0001 /m^3 and is considered to be negligible.

The **overall chemical cost** is thus **approximately R 0,13 /m^3**.

Note that this high chemical cost is due to the fact that all the precoat is wasted at the end of the precoating stage. If a separate precoating system were installed, it is estimated that 80 % of the precoat could be reused. This would reduce the chemical costs substantially.

7.3.2. Power

The unit requires a three-phase 380 V power supply. It is estimated that the power requirement is between 37 kW and 50 kW (based on power drawn mainly by pumps).

Based on a consumption of 2,5 kWh/m^3 at a rate of R 0,2643/kWh, the **energy cost** is **approximately R 0,66/m^3**.

7.3.3. Labour Cost

Based on 2 hours per day of operator input at a rate of R 7 /h, the **labour cost** is **R 0,036 /m^3**.

7.3.4. Maintenance Cost

It is assumed that 5 % of the capital cost per annum would be used for materials. Based on a downtime of 10 % (worst case scenario), the cost of materials is therefore R 0,13 /m^3.

The skilled labour required for maintenance is estimated at 4 hours per month. Assuming a labour cost of R 75 /h, the labour cost of maintenance is R 0,04 /m^3.

The **total maintenance cost** is therefore **R 0,17 /m^3**.

7.3.5. Summary of Operating Costs

Component Cost	Estimated Specific Cost (R/m^3)
Chemicals	0.13
Power	0.66
Labour	0.04
Maintenance	0.17
TOTAL	**1.00**

8 TECHNOLOGY TRANSFER

8.1. Plant Demonstrations

The plant has been demonstrated to the following personnel:

(i) The past and current personnel director of Lever Brothers. The scientific Director of Umgeni Water was also present at this demonstration.

(ii) Personnel from the Projects Department of the gold division of Anglo America Corporation.

(iii) The post-conference tour following the WISA 93 conference in Durban.

(iv) Messrs W. N. Richards and D. Kerdachi from Umgeni Water

(v) Delegates on the post-conference tour following the IAWQ Inyternational Symposium on Anaerobic Digestion held in Cape Town in January 1994.

(vi) Professor Grabouw from the University of Pretoria

(vii) Visitors from Sastech and Explochem.

8.2. Conferences

Three papers concerning allied cross-flow microfiltration projects were presented at the IMSTEC'93 conference in Sydney, Australia in November 1992, by Mr A.. F. Swart and Dr Pillay. In the ensuing discussions with conference delegates, the Exxflow plant was described and generated significant interest. Dr Pillay also described the Exxflow plant in meetings held with research and development personnel from the Sydney Water Board. A considerable interest was shown, and they indicated that they would like to be informed of future progress.

Dr Pillay presented a paper on the results obtained on the Exxflow unit from 1993 to 1994 at the IMSTEC'96 conference in Sydney, Australia, in November 1996. Once again, a significant interest was shown in the process based on the excellent quality of water produced.

Local presentations on the project were made at the WISA-MTD workshop at Badplaas, and the WISA'96 conference in Port Elizabeth.

8.3. Training of Operators

In the initial project plan, the unit was to be commissioned and operated for a short while by a skilled operator, whereafter a low skills level was to be employed. Ms S Govender, a graduate engineer from the University of Natal, was trained as the skilled operator, and operated the unit for the duration of this project.

Unfortunately, due to the various mechanical breakdowns that occurred, it was not possible to hand the unit's operation over to a low skills level operator. The aspect of operator training and the performance of the unit under the care of a low skills level operator will have to be undertaken in the future.

9 CONCLUSION

The objective of the project is to assess the applicability of the EXXFLOW process for the production of potable water in rural and peri-urban areas.

A full-scale EXXFLOW unit was constructed and relocated to the Process Evaluation Facility at Umgeni Water's Wiggins Water Treatment Works. The unit utilises woven fibre microfilter curtains of length 8 m and consisting of 70 x 12 mm tubes arranged in a vertical array. The unit was designed for eight curtains (filtration area of 160 m^2), but the project was conducted on four curtains (filtration area of 80 m^2). A high pressure spray system is utilised for cleaning the tubes. The unit is fully automated and controlled by a programmable logic controller (PLC).

Over a two year period, 1993 to 1994, the unit was operated in a semi-batch mode and the performance and reliability of the unit was monitored. In this period the unit operated in the filtration cycle for 4021 hours, and produced 29 737 m^3 of permeate.

Unscheduled downtime was experienced for a significant part of the project. In the main this was due to inherent mechanical flaws in the original design of the unit. The main problems concerned poor manifolding, poor design of the manifolds and endblocks, and blockages of the spray nozzles. Corrective action was taken during the course of the project in order to keep the unit operational. However, all the mechanical problems experienced to date have not been solved.

The performance criteria monitored included turbidity removal, microbiological removal efficiency and permeate production rates. Three modes of operation were investigated - raw water only, raw water with a filter aid, and raw water with a precoat. The performance with a precoat was vastly superior to that obtained on raw water only or with a filter aid. When operating on raw water only, the permeate turbidity is initially > 5 NTU and takes about an hour to drop to 0,1 NTU. With a filter aid, the permeate turbidity takes up to 15 minutes to drop to 0,1 NTU, while with a precoat a turbidity of 0,1 NTU is obtained from the start of the filtration cycle. The permeate production rates with a precoat are up to three times greater than that obtained on raw water only, and up to twice that obtained with a filter aid.

Overall, the unit shows an excellent turbidity rejection. In the precoat mode the permeate turbidity is usually around 0,1 NTU for feed turbidities ranging from 5 NTU to > 800 NTU. The unit consistently produced this high turbidity removal over the project period. The bacteriological rejection capabilities are also very good. In tests conducted by Umgeni Water's laboratories, a > 99,9 % removal of coliforms, E.Coli and Fecal Streptococci was reported. The ability of the unit to remove viruses was not tested during the project.

In the precoat mode the unit produced a weekly average flux of 90 ℓ/m^2h at a water recovery of 97 %. The unit produced this output consistently over a sixteen month period, with no long term decline in productivity. This translates into a production capability of 0,15 Ml/day (with 4 curtains installed) and 0,3 Ml/day (at full capacity, 8 curtains). Assuming a daily allowance of 200 ℓ of potable water per household, the unit is capable of servicing a town of 1 500 households.

Overall, therefore, the unit consistently produces a very good quality of water that is well within the potable water standards and guidelines in terms of the parameters tested. The permeate production rate has been increased significantly during the course of the project and the unit has maintained this higher level of production over an extended period, with no long term decline. The unit is fully automated, and very little attention is required during normal operation.

However the unit cannot at present be regarded as a reliable one, due to the various mechanical problems that exist. Further improvements to the mechanical reliability are necessary before the unit may be regarded as a viable one for the production of potable water in rural and peri-urban areas.

10 RECOMMENDATIONS

Recommendations for future work on the EXXFLOW process are as follows :

(i) Solution of the mechanical problems identified in the current project

The problems experienced and proposed solutions are summarised in Section 5.3.

(ii) Improvements to the cleaning system

The high pressure cleaning system, with its associated controls, is the "Achilles Heel" of the unit, and the subsystem that is most prone to failure in an environment where a low skills level exists. The simplification of this system must be investigated.

(iii) Installation of a dedicated precoating system

At present the majority of the precoat suspension is wasted, inflating the chemical costs. The installation of a separate precoating system, that would enable reuse of the precoat suspension, should be investigated.

(iv) Investigation into other operational configurations

As noted in Section 4.2 the semi-batch configuration, which was used in this study, is expected to yield the lowest fluxes but the highest water recovery. The other operational configurations, i.e. once-through, feed-and-bleed, have specific applications and should be evaluated.

Laboratory studies have indicated that for low turbidity suspensions, typical of most surface waters, the dead-end mode of operation may yield a similar performance to crossflow microfiltration. If so, the dead-end mode could be economically attractive, since the energy and capital requirements are significantly lower than the crossflow mode. Accordingly, the performance in the dead-end mode should be investigated.

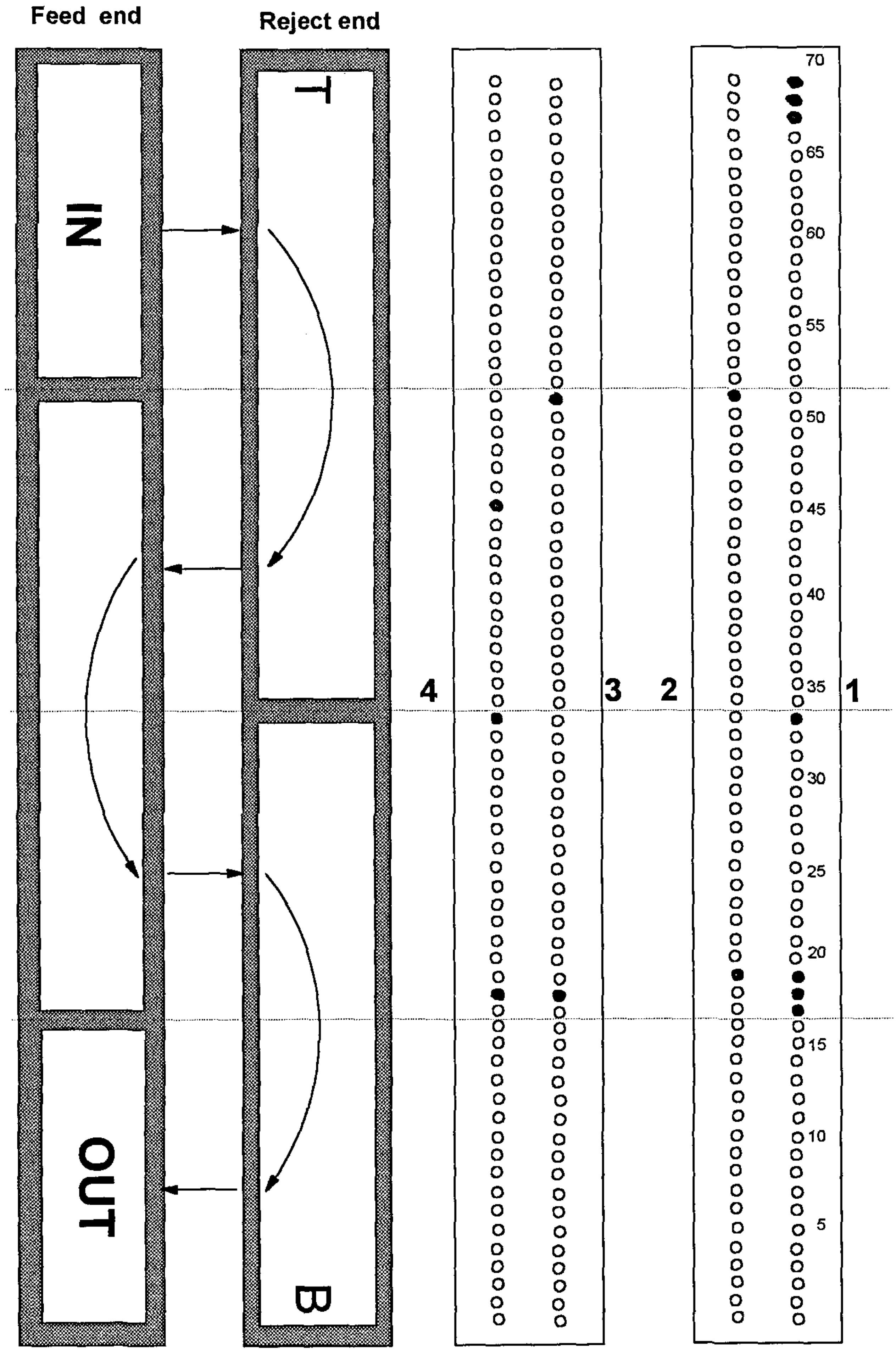
(v) Microbiological and Viral Removal Efficiencies

A limited number of microbiological tests were done in the current project. The microbiological removal efficiency should be assessed more frequently over a longer period. The effect of operator error, e.g. failing to make up a proper precoat suspension, on this efficiency should be investigated.

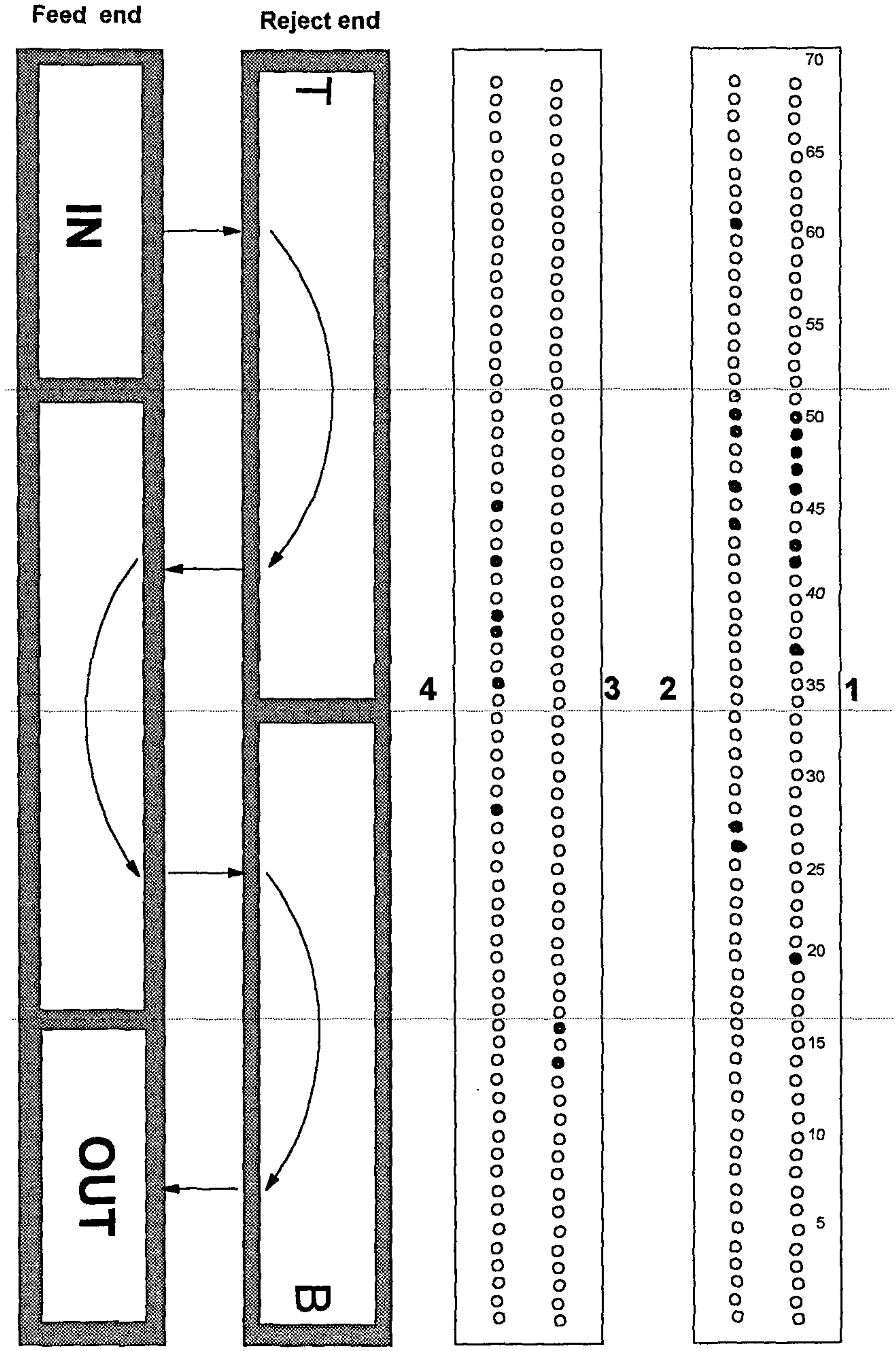
It is not expected that a microfilter would remove viruses to any significant extent. Nevertheless, in view of the excellent turbidity removal, the ability of the unit to remove viruses should be tested.

APPENDIX I

OCCURRENCE OF TUBE BLOCKAGES



<u>**Tube Blockages - October 1993**</u>



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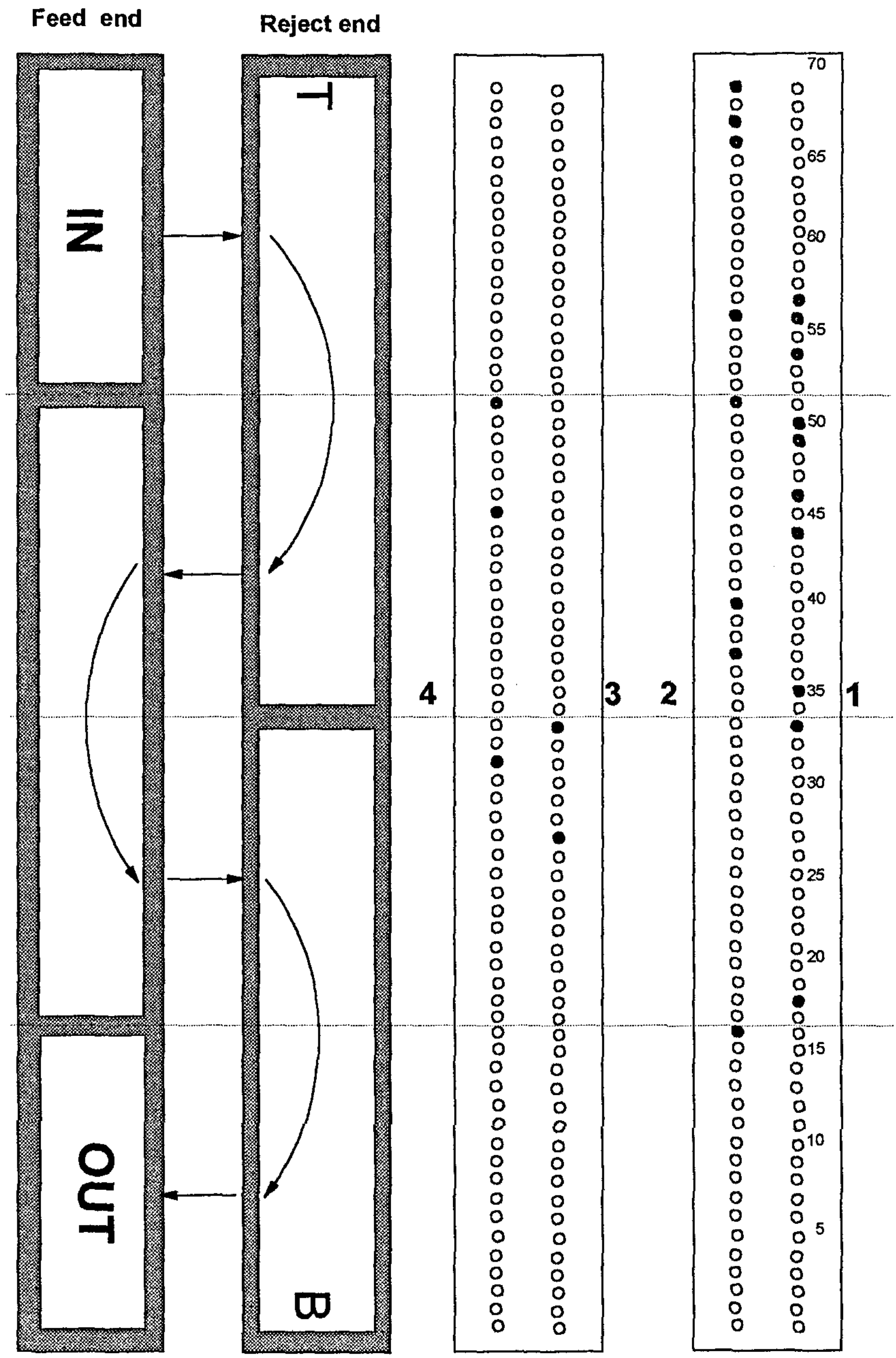

Tube Blockages - May 1994