EVALUATION AND OPTIMISATION OF A CROSSFLOW MICROFILTER FOR THE PRODUCTION OF POTABLE WATER IN RURAL AND PERI-URBAN AREAS

VL Pillay • CA Buckley

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Water Research Commission

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Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The supply of potable water to rural and peri-urban areas is a national development priority. Package, or preconstructed, water treatment plants have various advantages over conventional water treatment plants, and could have a major role to play in the rapid provision of potable water. This project concerns the evaluation of **woven fibre crossflow microfiltration** (WFMF) as a package treatment process for the production of potable water in rural and peri-urban areas.

Water Research Commission Project No. 386, "*The Development of a Crossflow Microfilter for Rural Water Supply*" was established to assess the applicability of the the WFMF process for the production of potable water in rural and peri-urban areas [Pillay (1998)]. The project concerned only the *crossflow* mode of operation, and characterised WFMF performance in the crossflow mode on raw water only, with a filter aid, and with a precoat. Investigations indicated that a very high quality of permeate could be produced when operated in the crossflow mode with a precoat, with a turbidity of less than 0,5 NTU and a bacteriological rejection of greater than 99 %. Changes in the operational strategy yielded a threefold increase in the permeate production rate. The unit also demonstrated the ability to cope with upset conditions in the form of extremely high input turbidities.

However, various mechanical flaws with the unit progressively became apparent. These resulted in significant periods of downtime, and indicated that the unit could not be regarded as a reliable and easily operable one. It was also found that the cleaning system was inefficient and warranted further improvement and optimisation. Overall, therefore, Project No. 386 indicated that the WFMF process was capable of producing a high quality of water, but that further improvements in the mechanical aspects of the unit were essential.

This project is a follow up to WRC Project No 386, and concerns the further development of the woven fibre microfiltration system for potable water production in rural and peri-urban areas. The specfic objectives are :

(i) To improve and optimise the cleaning system on the WFMF unit.

(ii) To establish a reliable, easily operable and fully automated demonstration unit for the process.

(iii) To evaluate the performance of the WFMF unit operated in the dead-end mode (DEMF).

<u>Improvements to the cleaning system</u>

The unit was initially constructed with a spray cleaning system, consisting of a high pressure pump, spray bars, a motorised carriage, and associated piping and control valves. During the cleaning cycle, the valves at the inlet and outlet manifolds of the curtains 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.

As noted in Project 386, the spray cleaning system adds considerably to the complexity of the rig and control circuitry. Also, major problems were experienced with frequent blockage of the spray nozzles. Besides reducing the efficiency of the cleaning cycle, a considerable effort in terms of time and manpower is required to clean out the nozzles. Thus, in Project 386, the cleaning system was identified as being the part of the rig that is most prone to failure.

In this project a new **pulse cleaning** technique was investigated. In initial investigations the curtains were pulsed by starting and stopping the feed pump, and subsequently allowed to dry for 24 hours. The pulsing causes the curtains to alternately inflate and deflate, presumably destroying the fouling layer which is then swept out by subsequent pulses. The drying phase was expected to cause the remaining foulants to dry and fall off the tube wall. It was found that the daily average fluxes so obtained were 10 % to 20 % lower than that obtained with the spray cleaning system. However, there was no long term decline in the daily average flux, indicating that the pulse cleaning technique was indeed effective.

In subsequent improvements to the pulsing technique, it was found that the drying phase was not necessary. The curtains could be pulsed and a new filtration cycle started immediately thereafter, with no obvious detriment to permeate production. Following further investigations the final pulsing strategy adopted was to pulse the curtains three times for 30 s each.

The implications for the process as a whole are tremendous. If redesigned from scratch, the rig would consist essentially of a feed pump and curtains, with the associated valves, piping and a control system of greatly reduced complexity. The exclusion of the spray system would reduce the capital cost of the rig significantly. In additional the general robustness and reliability of the rig would also improve significantly. The maintenance requirement would decrease and the level of skill required by the operator would also be reduced dramatically.

It is expected that the process would now be economically viable in various applications where it was previously viewed as being expensive, and could be viable in applications where it was previously viewed as being too sophisticated for the existing operator skills levels.

Improvements to Reliability and Operability

In Project 386, the following areas were identified as requiring improvement :

(i) The method of fixing the manifolds to the endbocks

(ii) The precoating system

Manifold System

In Project 386, a significant down-time was caused by mechanical problems experienced with the module endblocks and manifolds. It was proposed that this could be alleviated if the method of fastening the endblock to the manifold was improved.

The original fastening system entailed inserting bolts through holes in the manifold and into threaded brass inserts in the endblocks. The brass inserts were removed from the endblocks, and holes corresponding to those on the manifold were drilled all the way through the endblock. Bolts were then welded to a single backing plate which was to have been inserted from the rear of the endblock all the way through the gasket and the manifold. However, it was found that it was extremely difficult to align all twenty bolts with the drilled holes. One unsucessful attempt resulted in an endblock cracking. The singl backing plate was then cut into smaller backing plates, each with five bolts, which could be inserted individually. This proved sucessful. The soft gaskets that were previously used were replaced by a firmer gasket made of inertion rubber, and hat had cross-threads to improve its lateral strength.

The combination of the new fastening method and the new gasket proved extremely sucessful, and problems with leaking gaskets were not experienced during the project. It is confidently stated that the problems with the leaks from manifolds have now been solved.

Precoating System

In Project 386, it was shown that operating in the crossflow mode with a precoat yielded a vastly superior performance than operating on raw water only, or with a filter aid. In that project, there was no separate precoating system, and the feed tank was also used as a precoating tank. It was also identified that using the feed tank for precoating was laborious, time consuming, and resulted in a significant waste of precoat suspension.

To improve the operability of the unit, as well as facilitate the reuse of unspent precoat suspension, a separate precoating system was installed. This entailed installation of a precoat tank with a mixer, and modifications to the feed, reject and permeate lines.

The installation of a separate precoating system has greatly simplified the precoating sequence, as well as facilitated the reuse of the precoat suspension.

Investigations into the Dead-end Mode of Operation

The unit's performance in the crossflow mode on raw water only, with a filter aid, and with a precoat had been established in Project 386, for operation on 12 mm curtains. The workplan for this project entailed evaluating the unit's performance in the dead-end mode, and comparing this to the crossflow performance obtained previously.

However, just prior to commencement of dead-end investigations, the project team decided that dead-end operation on 12 mm curtains would not be viable due to the increased possibility of tube blockages, and that the system should be changed to 25 mm curtains. It was also realised that dead-end results from 25 mm curtains could not be compared with crossflow results from 12 mm curtains, since the relationship between performance and tube diameter was not known. Hence, it was decided that baseline studies would be performed on the 25 mm curtains in the crossflow mode, prior to commencing dead-end investigations.

Three modes of operation were investigated in this project : crossflow with a precoat; crossflow without a precoat on high turbidity waters; and dead-end without a precoat.

Operation in crossflow with a precoat continues to yield the best performance, with high daily average fluxes, low permeate turbidities and long filtration cycles. Filtration cycles of 24 hours were performed. Daily average fluxes were very dependant on the operating conditions, and ranged from 60 LMH (2 bar, 1.3 m/s) to 140 LMH (2 bar, 2 m/s). The permeate turbidities were < 0.3 NTU for raw water turbidities ranging from 10 NTU to over 100 NTU. The bacteriological rejection was also very good, with > 99 % of indicator microorganisms being rejected. The crossflow mode with a precoat is thus the most suitable for potable water production.

Operating in crossflow without a precoat on high turbidity waters yields average run fluxes of 38 LMH to 110 LMH (2 bar, 2 m/s), and permeate turbidities ranging from about 3 NTU at the start of the filtration cycle to 0.2 NTU at the end of the cycle. The filtration cycles were limited to between 5 and 6 hours, due to very low fluxes at the end of this period. This mode would probably be the most appropriate as a pretreatment step for high turbidity waters.

Operating in the dead-end mode without a precoat yields a very poor permeate turbidity, ranging from 10 NTU to about 2 NTU, and relatively low fluxes. The filtration cycles in this mode were also restricted to 6 hours, and average run fluxes of approximately 80 LMH were obtained.

The energy requirements for each operating mode were calculated, based on the operating conditions and configurations used in this study. Operating in the crossflow mode with a precoat required 2.33 kWh/m^3. The crossflow mode without a precoat draws 28.75 kWh/m^3, while the dead-end mode requires 0.14 kWh/m^3. The extremely high energy requirement for crossflow without a precoat is due to the very low production in that mode - over 60 % of the permeate produced is used in each clean, giving a very low net permeate production.

In overview, operating in the crossflow mode with a precoat produces an excellent quality of permeate at high production rates, while the dead-end mode of operation produces a very poor quality of permeate at reduced production rates. However, the energy requirement for the dead-end mode is about two orders of magnitude less than that required for crossflow with precoat. Operating in crossflow without a precoat produces an intermediate quality of permeate, but at an energy requirement ten times greater than crossflow with a precoat. Accordingly, the crossflow with a precoat mode would be the most appropriate in applications where a high quality of permeate is required, whereas the dead-end mode would probably be the most suitable for pretreatment applications where energy is a major consideration.

Recommendations for future work

Improvements to the woven fabric to reduce the permeability should be investigated. This could be achieved by a tighter weave or impregnating the fabric with a resin. A tighter fabric could improve the performance in the dead-end mode without a precoat, resulting in an inexpensive pretreatment process.

Investigate starting up in the crossflow mode and switching over to dead-end (high turbidities feeds only). This may result in a tighter cake forming during the crossflow startup, which would give a better separation and better product qualities during the dead-end filtration period. Whilst this would not reduce the capital costs, it could result in a significant saving in energy requirements.

Identify possible niche markets for each operating mode : The product qualities and energy requirements are significantly different for each operating mode, and in general the energy requirement increases with product quality. An analysis of market needs should be performed to match product qualities in each operating mode with specific applications.

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1.1. Package Water Treatment Units

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)].

1.2. The Woven Fibre Microfiltration Process

This project concerns the evaluation of **woven fibre crossflow microfiltration** (WFMF) as a package treatment process for the production of potable water in rural and peri-urban areas.

Microfiltration is a separation process that enables the removal of contaminants down to the sub-micron size range. Microfiltration is capable of removing suspended solids, colloidal contaminants, as well as bacterological contaminants, and hence has potentially widespread applicability in the treatment of water for potable use as well as the treatment of waste waters.

The first microfilters were of the depth filter type and the particles and microbes in the feed water were trapped within the internal structure of the microfilter. Once breakthrough of particles occurred or a specified pressure drop was attained, the microfilters had to be discarded. Due to this requirement for regular replacement, depth filtration microfilters have limited application in large scale water treatment processes. In contrast, *microfiltration membranes* effect the removal of particles according to their retention on the membrane surface. Thus no "break-through" can occur, and the fouling layer may be easily removed, restoring the permeability of the membrane. Membrane microfiltration (MMF), therefore, offers various advantages over the depth filter microfilters, and can potentially be applied to high volume applications such as water treatment.

Membrane microfiltration is the "loosest" of the pressure-driven membrane process, where the pore size of the membrane ranges from 0.05 to 5 μm (micron). Porous supports utilised in MMF include stainless steel, ceramic, rigid plastic and woven fibre tubes [Henry (1972), Kraus (1974)]. Woven fibre 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 eighties. The major advantage of stainless steel, ceramic and rigid plastic tubes is that they maintain their geometric integrity and can thus be back-flushed. They also enable operation at elevated pressures. Woven fibre tubes can be produced relatively inexpensively in large lengths [Dalheimer et al. (1970), Kraus (1974)]. This potentially extends the economic viability of MMF to large-scale high-volume applications.

In considering the rigid tubes, the tube wall is usually the filtration barrier, and the formation of a fouling layer or *cake* is undesirable. In the woven fibre tubes the actual filtration barrier is invariably the cake that forms on the tube wall. The close packing of the cake can enable the retention of particles that are often orders of 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, whilst the foulng layer is undesirable in rigid microfiltration membranes, it is exploited as a *dynamic membrane* in the woven fibre microfiltration (WFMF) system.

The use of dynamic membranes has been widely reported [Bhave (1991), Murkes and Carlsson (1988)], and is not unique to the WFMF system. Much of the initial work on these dynamic membranes revolved around hydrous zirconium(IV) oxide and the hydrous zirconium (IV) oxide / polyacrylic acid composite membranes. In these studies the dynamic membranes were used to alter the surface properties of the manufactured membrane or porous substrate, giving the microporous structure rejection characteristics similar to those usually expected of ultrafiltration or nanofiltration membranes.

The advantages of using dynamic membranes to alter the rejection capabilities of preformed membranes are as follows [Murkes and Carlsson (1988)] :

- The membranes become tighter, the rejection of the macromolecules and particles becomes better than that of 'naked' supporting membranes.
- The relatively open membrane rejects much finer particles / molecules than pore openings themselves would allow.
- The flux is stabilized on a relatively satisfactory level and remains almost constant with a very slow decline as the process goes on.
- An adequate secondary membrane protects the support against plugging by particles and contributes therefore to a higher and more stable flux.

In the WFMF system, situations might arise where the suspended solids in the feed forms an inadequate dynamic membrane. Under these circumstances, a dynamic membrane can be artificially laid down by *precoating* the fabric tubes with another suspension such as limestone or fumed silica prior to the introduction of the feed. This is usually carried out by running the WFMF system in crossflow mode first with the precoating suspension and then switching to the feed [Pillay (1992a)]. In some cases the precoating material is added to the feed tank to enhance the membrane-forming properties of the feed suspension.

Membrane microfiltration may be carried out in either of two distinct operating modes, crossflow microfiltration (CFMF) and dead-end microfiltration (DEMF). In the crossflow mode, the feed suspension is pumped at a high velocity tangential to the membrane surface (Figure 1). This high tangential velocity serves to scour the surface of the fouling layer and hence restrict the growth of the fouling layer. The net effect is that a higher permeate flux is obtained. The crossflow mode of operation has been modelled by Pillay [Pillay (1992)].

In the dead-end mode there is no significant fluid velocity tangential to the membrane surface (Figure 2). The fouling layer thus grows much quicker and continuously, resulting in a permeate flux that decreases rapidly with time. The CFMF mode, however, requires a greater pumping requirement and is significantly more energy intensive, due to the high velocities that have to be attained.

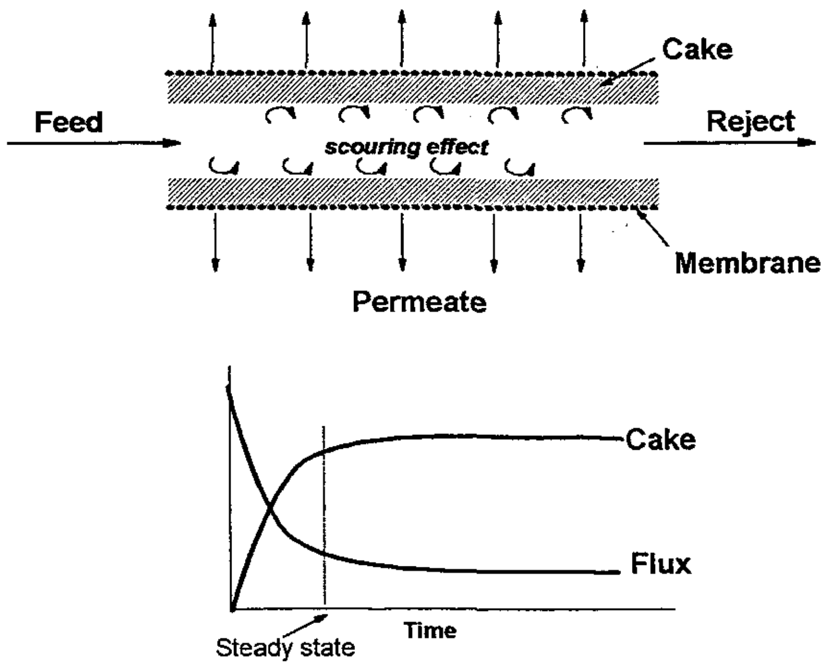


Figure 1 - Crossflow Mode of Operation

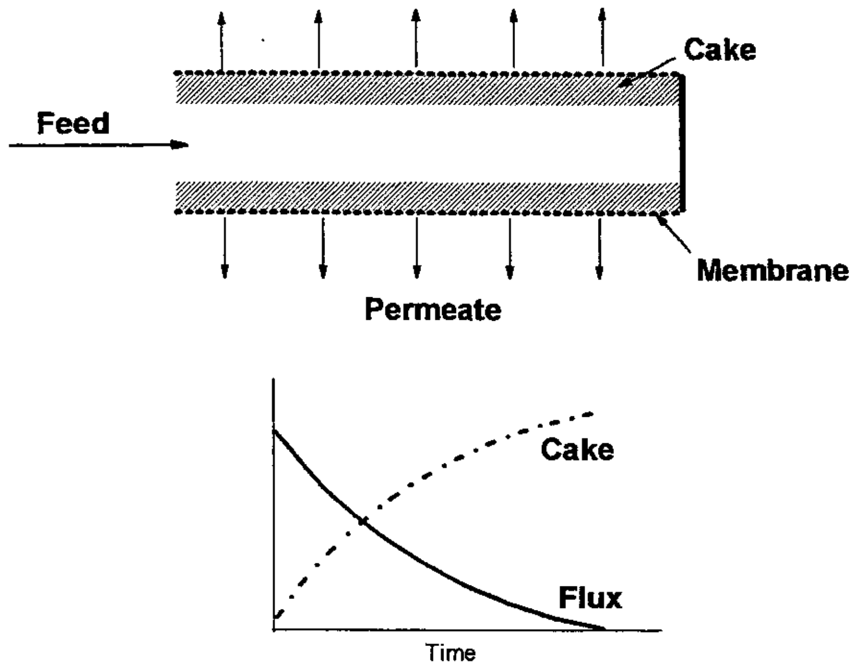


Figure 2 - Dead-end Mode of Operation

The operation of fabric tube filters in a cross-flow mode (CFMF) has traditionally been used for the production of a high quality permeate from a turbid feed while operation in a dead-end mode (DEMF) has been used for the recovery of a spadeable cake. Operation in the cross-flow mode is generally expected to give significantly higher fluxes than operation in the dead-end mode, albeit at the expense of higher pumping and energy requirements. There are indications however that for low turbidity waters, typical of many surface and sub-surface waters, operation in the dead-end mode may yield similar permeate fluxes to cross-flow operation [Swart (1993)]. If so, it would be advantageous to operate in the dead-end mode due to the reduced energy and pumping costs.

1.3. Previous Investigations into WFMF

Water Research Commission Project No. 386, "*The Development of a Crossflow Microfilter for Rural Water Supply*" was established to assess the applicability of the the WFMF process for the production of potable water in rural and peri-urban areas [Pillay (1998)]. The project concerned only the *crossflow* mode of operation, and characterised WFMF performance in the crossflow mode on raw water only, with a filter aid, and with a precoat. Investigations indicated that a very high quality of permeate could be produced when operated in the crossflow mode with a precoat, with a turbidity of less than 0,5 NTU and a bacteriological rejection of greater than 99 %. Changes in the operational strategy yielded a threefold increase in the permeate production rate. The unit also demonstrated the ability to cope with upset conditions in the form of extremely high input turbidities.

However, various mechanical flaws with the unit progressively became apparent. These resulted in significant periods of downtime, and indicated that the unit could not be regarded as a reliable and easily operable one. It was also found that the cleaning system was inefficient and warranted further improvement and optimisation. Overall, therefore, Project No. 386 indicated that the WFMF process was capable of producing a high quality of water, but that further improvements in the mechanical aspects of the unit were essential.

1.4. Objectives of the Current Project

The current project was initiated in January 1995, as a follow up to Project 386. The objectives of the project are as follows :

(i) To evaluate the performance of the WFMF unit operated in the dead-end mode (DEMF).

(ii) To improve and optimise the cleaning system on the WFMF unit.

(iii) To establish a reliable, easily operable and fully automated demonstration unit for the process.

All work was performed on the WFMF unit situated at the Umgeni Water Process Evaluation Facility, Wiggens Water Works, Durban.

2 Description of the Woven Fibre Microfiltration Unit

2.1. Process and Instrumentation Diagram

The process and instrumentation diagram of the WFMF unit, as constructed, is shown in Figure 3. 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 - centrifugal, with 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.

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

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

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

(vii) curtains. At the start of the current project, the unit was fitted with 12 mm curtains. During the course of the project, the 12 mm curtains were replaced with one 25 mm curtain, to facilitate investigations into the dead-end mode of operation.
When operating on the 12 mm curtains, the unit had two 12 mm "duplex" curtain modules, i.e. two curtains are attached to a common endblock. Each curtain had a length of 8 m, and contained 70 x 12 mm tubes arranged in a vertical array. This yielded a nominal filtration area of 80 m^2. Valves on the inlet and outlet manifolds enabled the tubes of the curtain to either operate in parallel (single pass) or in a four pass mode. In the single pass mode the path length is 8 m and in the four pass mode the path length is 32 m.
When operating with 25 mm curtains, the unit was fitted with a single 25 m curtain, containing 30 tubes. The nominal filtration here was 18 m^2.

(viii) high pressure cleaning system - At the start of the project, the unit included a high pressure cleaning system, consisting of a high pressure spray pump, spray bars and spray carriage. This was changed during the project, as discussed in Section 4.

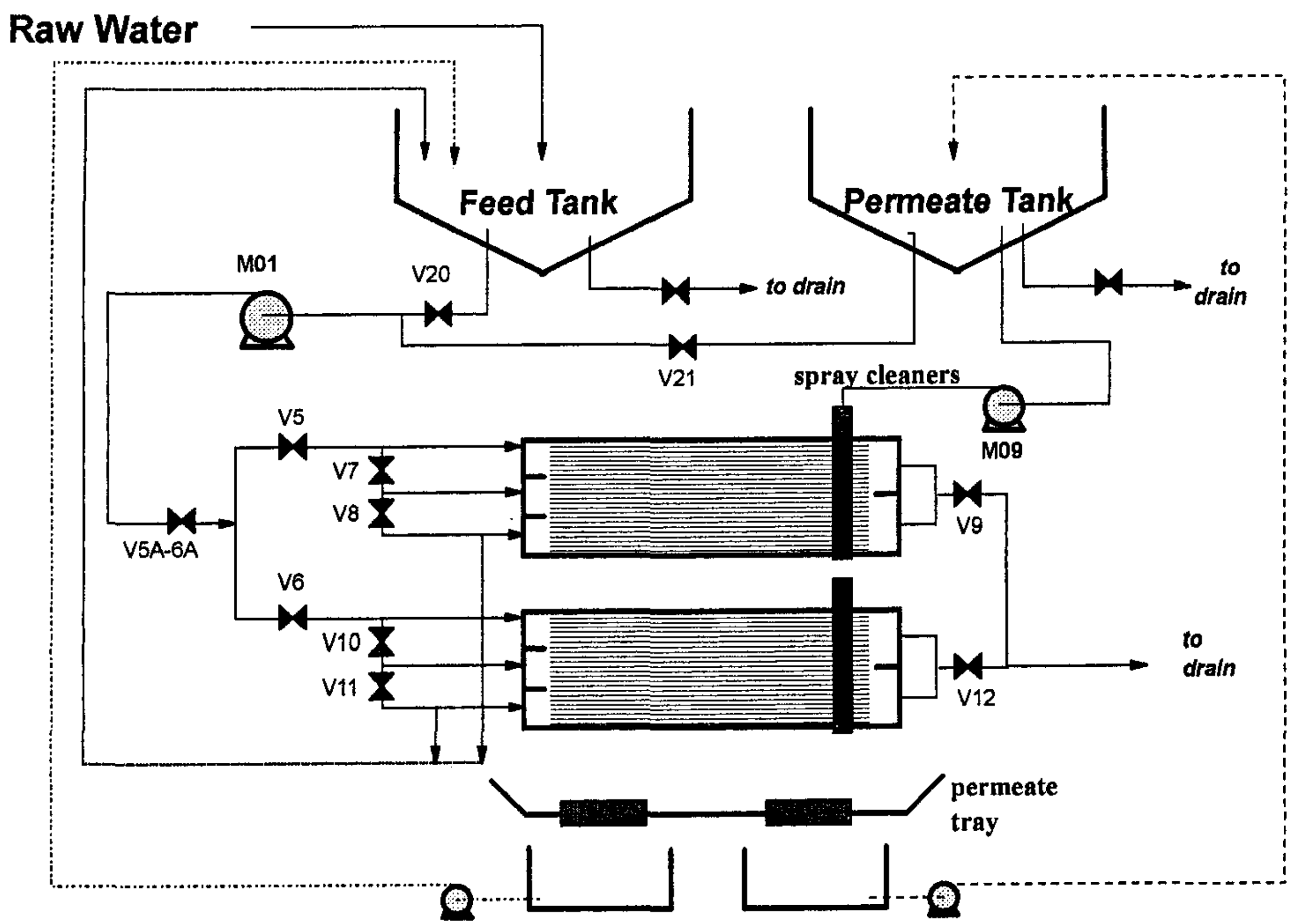


Figure 3 - Process and Instrumentation Diagram of Unit as Installed

2.2. Unit operation

2.2.1. Choice of Operating Options

As indicated in Section 1.2, 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 **operating options** :

(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.

In this study, two modes of operation were used - operating on raw water only, and operating with a precoat. The procedures for operating in the different modes are described in Table 1.

Table 1 : Operating Cycles for the Different Operating Options

Mode	Cycle
raw water only	Charging - The feed tank is charged with raw water Filtration - the permeate is collected and pumped to the permeate storage tank. The feed tank is continually topped up with raw water (4 to 6 hours). Discharge of feed contents to drain and cleaning cycle (5 minutes).
precoat	At the onset of the project, the unit did not have a separate precoating system. Hence, the operating sequence for the precoating mode was as follows : Charging - feed tank is filled with municipal water. A measured 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"* During the course of the project, a separate precoating system was installed. This is discussed in Section 3.1.

2.3. Operating configurations

The unit may be operated in one of four configurations, as described in Table 2.

Table 2 : Possible Operating Configurations

Configuration	Description
crossflow - 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.
crossflow - 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.
crossflow - 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.
dead-end	Here, the exit valves from the curtain are closed and there is no reject stream. The feed to the curtain is the same concentration as in the feed tank.

In all crossflow 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.

2.4. Operating Variables

The two operating variables for the crossflow operation unit are tube velocity (feed flowrate), and operating pressure. Since a centrifugal feed pump was used, these variables were not totally independant of each other. In the crossflow mode of operation, the operating pressure and tube velocity were set by manipulation of the reject valve and the bypass valve. However, the pressure drop across the reject piping restricted the velocity/pressure combinations that could be achieved.

In the dead-end mode of operation, the only operating variable is the operating pressure. This was set by manipulation of the bypass valve. Once again, the operating characteristics of the pump limited the minimum pressures that could be attained.

The velocities and operating pressures used are reported in Section 5.1.

2.5. 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 - microbiological analyses were performed by the Department of Biological Sciences, M L Sultan Technikon, on samples of the raw water, feed tank and permeate. The samples were taken as in (i) above. The following analyses were performed:

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

(iii) 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.

3 Improvements to Unit Reliability and Operability

3.1. Precoat System

In Project 386, it was shown that operating in the crossflow mode with a precoat yielded a vastly superior performance than operating on raw water only, or with a filter aid. This was from a point of view of turbidity rejection, bacteriological rejection and permeate production. However, it was also identified that the precoating stage, as described in Table 2, was laborious, time consuming, and resulted in a significant waste of precoat suspension.

To improve the operability of the unit, as well as facilitate the reuse of unspent precoat suspension, a separate precoating system was installed. This entailed installation of a precoat tank with a mixer, and modifications to the feed, reject and permeate lines. The modified process and instrumentation diagram for the unit is shown in Figure 4.

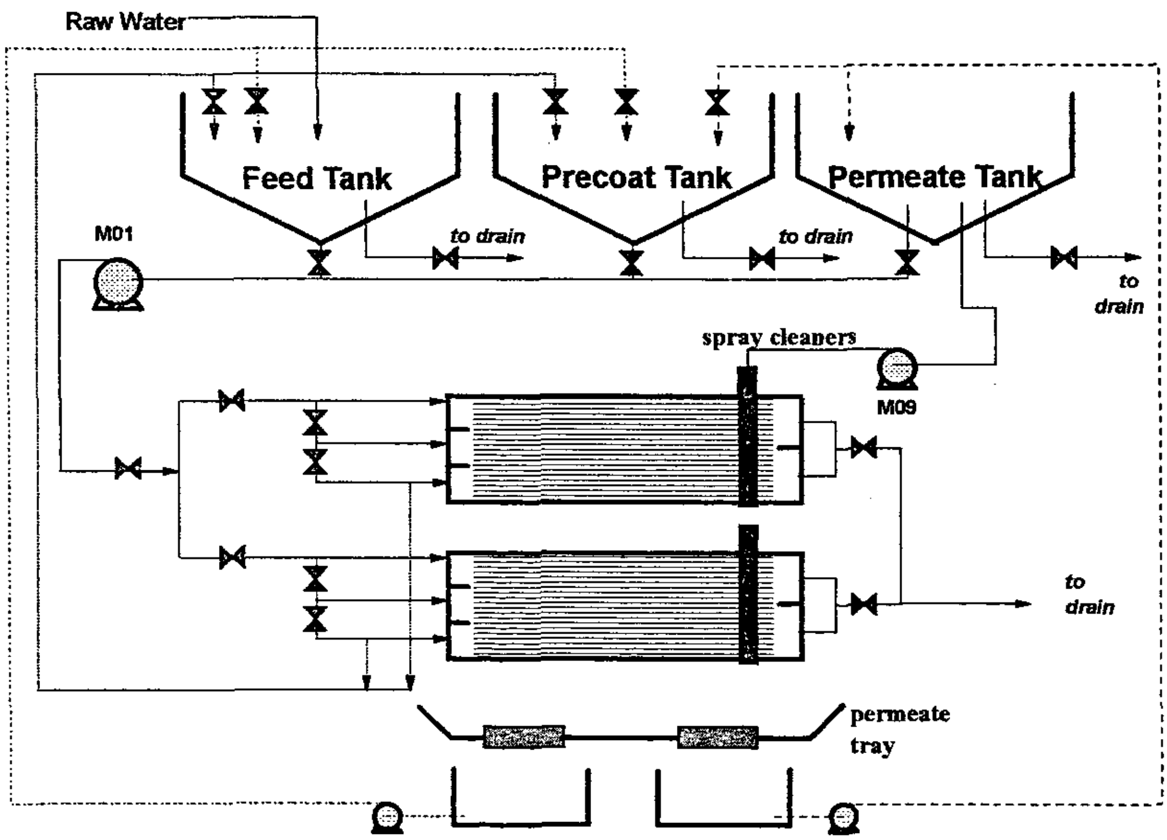


Figure 4 - P&I diagram of unit after addition of precoating system

The operating sequence for the precoat mode is shown in below. :

(i) Precoat makeup - The precoat suspension is made up in the precoat tank, by mixing municipal water with the measured amount of the desired precoat material. (After each precoat sequence, approximately 80 % of the precoat suspension is recovered in the precoat tank. Makeup thus resolves to topping up the tank with municipal water, and adding an amount of precoat material calculated to give the desired precoat suspension. In general, the precoat suspension could be reused for up to a month, before being discarded due to excessive contamination).

(ii) Precoating - The precoat suspension is circulated through curtain. Reject and permeate returned to feed tank (20 to 30 minutes)

(iii) Switchover - The feed stream is switched from the precoat tank to the raw water tank. The reject and permeate streams are switched from the precoat tank to the raw water tank and the permeate tank respectively. During the switchover, it is ensured that the curtains do not depressurise.

(iv) Filtration - The permeate sent to permeate storage, and the reject is returned to the feed tank (about 24 hours). The feed concentration increases with time.

(v) Cleaning - The cleaning sequence is initiated.

It is seen that the installation of a separate precoat system greatly simplifies the precoating sequence, as well as results in a reuse of the precoat suspension.

3.2. Manifolds

In Project 386, a significant down-time was caused by mechanical problems experienced with the module endblocks and manifolds. These are detailed in Pillay (1998). It was proposed that this could be alleviated if the method of fastening the endblock to the manifold was improved.

The original fastening system entailed inserting bolts through holes in the manifold and into threaded brass inserts in the endblocks. The brass inserts were removed from the endblocks, and holes corresponding to those on the manifold were drilled all the way through the endblock. Bolts were then welded to a single backing plate which was to have been inserted from the rear of the endblock all the way through the gasket and the manifold. However, it was found that it was extremely difficult to align all twenty bolts with the drilled holes. One unsucessful attempt resulted in an endblock cracking. The single backing plate was then cut into smaller backing plates, each with five bolts, which could be inserted individually. This proved sucessful. The soft gaskets that were previously used were replaced by a firmer gasket made of inertion rubber, and hat had cross-threads to improve its lateral strength.

The combination of the new fastening method and the new gasket proved extremely sucessful, and problems with leaking gaskets were not experienced during the project. It is confidently stated that the problems with the manifolds have now been solved.

4 Improvements to Cleaning System

The unit was initially constructed with a spray cleaning system, consisting of a high pressure pump, spray bars, a motorised carriage, and associated piping and control valves. During the cleaning cycle, the valves at the inlet and outlet manifolds of the curtains 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.

As noted in previous reports, the spray cleaning system adds considerably to the complexity of the rig, requiring a high pressure pump, a moving carriage, various control valves and control circuitry. Also, major problems were experienced with the blockage of the spray nozzles. Besides reducing the efficiency of the cleaning cycle, a considerable effort in terms of time and manpower is required to clean out the nozzles. Thus, in Project 386, the cleaning system was identified as being the part of the rig that is most prone to failure.

Proposals to improve the cleaning system included :

(i) installing a filter just upstream of the spray bars to reduce blockage of the spray nozzles

(ii) redesigning the spray nozzles

(iii) installing a roller cleaning system, similar to the Tubular Filter Press.

The option of installing a filter was investigated. However initial cost estimates indicate that such a filter, operating at high pressures, would be extremely expensive, and this option was subsequently discounted.

In the initial workplan for this project, it was stated that rod cleaners ("squeegees") would be evaluated. Subsequent experience on an allied project, WRC Project No. 560 **Research on the Development of a Cross-flow Microfilter to Improve the Performance of Anaerobic Digestors Waste Water Treatment Works,** has revealed significant problems with the existing rod cleaner design. Accordingly the rod cleaners, in their present form, were not considered in this project. Experience on Project 560 did however indicated that low pressure sprays may be just as effective in cleaning the tubes as high pressure sprays. Thus, low pressure sprays were chosen as the most viable option to investigate to improve the cleaning system.

In 1996, it was brought to the attention of the project team that Renovexx, a company that fabricated WFMF systems in England, had experienced great success with using a pulsing and drying technique for cleaning. At the end of the filtration cycle, fluid is pulsed through the curtain, allowing the curtain to rapidly pressurise and collapse. Thereafter, the curtain was allowed to dry for 24 hours, whereafter the pulsing was repeated. It was decided that the pulsing and drying technique should be investigated prior to any mechanical change to the cleaning system.

In April 1996, preliminary tests were done on the pulsing and drying cleaning method. At the time the unit operated on two "duplex" modules with 12 mm curtains. The operating conditions were the same as that used in Project 386 (tube velocity of 1.6 m/s and average operating pressure of 3 bar). This entailed pulsing fluid through curtains for about ten seconds, allowing the curtains to collapse completely, and repeating the pulsing for 3 to 5 times. Thereafter the curtains were allowed to dry overnight before beginning the next filtration cycle.

The average daily fluxes obtained with the spray cleaners during the course of the project was 90 LMH to 100 LMH. The coverage daily fluxes obtained with the pulsing was lower, about 70 LMH to 90 LMH. This was extremely promising, and the technique was investigated further. The fluxes obtained with the various techniques are shown in Figure 5.

From the beginning of May to the beginning of June, the spray cleaning method was stopped, and only the pulse cleaning method was used. Each module was pulsed individually 10 times for about tens seconds per pulse. Thereafter the curtains were allowed to dry overnight before beginning the filtration cycle. The mean daily average flux was about 80 LMH.

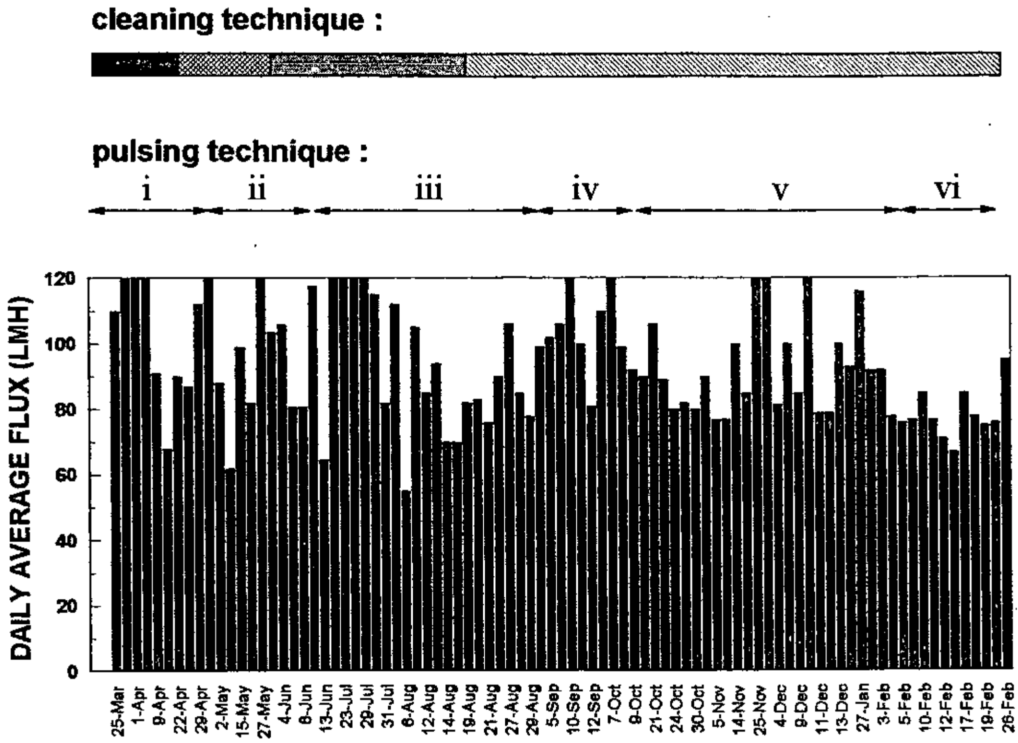
Due to the number of days lost while the curtains were drying, the technique was changed at the beginning of June. Then, one module was run in the filtration mode while the other was allowed to dry. The feed valves etc. were adjusted to ensure that the flow to each module was the same as when the modules were run together. The mean daily average flux here was also about 80 LMH.

Towards the middle of August, it was decided to investigate the contributions that the pulsing and the drying individually made to the cleaning. The modules were pulsed and a filtration cycle was started without any drying. The daily average fluxes were no different from that obtained with drying. This had significant implications for total permeate production rates and accordingly drying was abandoned, and the mode of operation was to pulse the curtains at the end of a filtration cycle and immediately begin the next precoating cycle.

At the beginning of October, an investigation indicated that a 10s was probably too short to carry contaminants out of the tube, and that a minimum of a 30s pulse was required. Th pulsing method was then changed to 5 pulses of 30s each. Fluxes were marginally higher than with the previous pulsing sequences. In this pulsing sequence, a total of 5 m^3 of permeate is used to clean both modules. This is the same as the volume of wash water used in the spray cleaning mode, and implies that about 3,5 % of the permeate produced is used in the wash cycle.

At the beginning of February 1997, the pulses were reduced to 3 pulses for 30s. There was no discernible decrease in flux. However, this sequence needs to be evaluated over a longer period. In this sequence only about 2 % to 2,5 % of the permeate produced is used as wash water.

In overview, the unit was evaluated for about 10 months with pulse cleaning, and has returned fluxes about 10 % to 20 % lower than that obtained with sprays. This indicates unequivocally that the pulse cleaning system was giving the required performance.



cleaning technique :

comparing sprays and pulsing with drying. pulse both modules and dry for 24 hours.

pulsing with drying. pulse both modules and dry for 24 hours

pulsing with drying. pulse one modules and dry for 24 hours, while other is running

pulsing only. pulse both modules and immediately start filtration, without drying

pulsing technique :

i pulse 3 to 5 times for 10 s
ii pulse 10 times for 10 s
iii pulse 4 times for 10 s
iv pulse 8 times for 10 s
v pulse 5 times for 30 s
vi pulse 3 times for 30 s

<u>Figure 5 - Evaluation of Different Pulse Cleaning Strategies</u>

The implications for the process as a whole are tremendous. If redesigned from scratch, the rig would consist essentially of a feed pump and curtains, with the associated valves, piping and a control system of greatly reduced complexity. The exclusion of the spray system would reduce the capital cost of the rig significantly. In additional the general robustness and reliability of the rig would also improve significantly. The maintenance requirement would decrease and the level of skill required by the operator would also be reduced dramatically.

It is expected that the process would now be economically viable in various applications where it was previously viewed as being expensive, and could be viable in applications where it was previously viewed as being too sophisticated for the existing operator skills levels.

5 . Evaluation of Different Operating Modes

5.1. Historical Overview

The unit's performance in the crossflow mode on raw water only, with a filter aid, and with a precoat had been established in Project 386, for operation on 12 mm curtains. The workplan for this project entailed evaluating the unit's performance in the dead-end mode, and comparing this to the crossflow performance obtained previously.

However, just prior to commencement of dead-end investigations, the project team decided that dead-end operation on 12 mm curtains would not be viable due to the increased possibility of tube blockages, and that the system should be changed to 25 mm curtains. This was based on recent experiences with tube blockages on allied crossflow and tubular filter press projects. It was also realised that dead-end results from 25 mm curtains could not be compared with crossflow results from 12 mm curtains, since the relationship between performance and tube diameter was not known. Hence, it was decided that baseline studies would be performed on the 25 mm curtains in the crossflow mode, prior to commencing dead-end investigations. In view of the fact that poor results were obtained in Project 386 on raw water only and with a filter aid, it was decided that dead-end operation would be compared to cross-flow operation with a precoat.

The operating points originally chosen for each mode were as follows :

crossflow with a precoat	**2 m/s and 2 bar**
dead-end	**2 bar.**

A new single 25 mm curtain containing 30 tubes was procured and duly installed, and investigations were initiated into the crossflow mode with a precoat [1]. However, it was found that the desired operating point of 2 m/s and 2 bar could not be attained. Due to the high pressure drop across the reject pipework, the operating pressure at a velocity of 2 m/s was approximately 3.8 bar. Conversely, at an operating pressure of 2 bar, the maximum tube velocity that could be obtained was 1.3 m/s.

The pressure drop across the reject pipework was slightly reduced by improving the flowpath. However, calculations indicated that for the desired operating point to be obtained, the entire reject pipework and reject manifolding would have to be redesigned with larger diameters. This was beyond the financial scope of the project.

The project team then decided that the most viable solution would be to halve the number of tubes in the curtain from 30 to 15. This would reduce the flowrate in the system, and hence decrease the reject pressure drop. This solution was subsequently implemented, and it was found that the desired operating point of 2 m/s and 2 bar could be easily obtained.

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[1] The first 25 mm module that was installed had various flaws, resulting in leaks and poor performance. This was subsequently replaced by a second module which gave good performance

Switching from 30 tubes to 15 tubes also enabled the project team to establish whether operation at a specified tube velocity and pressure gave the same performance irrespective of the number of tubes/curtains employed. This had previously not been tested. The results are discussed in Section 5.2.

During 1999, the raw water turbidities into the Wiggens Water Works reached extremely high values (> 200 NTU), presumably due to high rainfalls. The project team had previously postulated that the performance in the crossflow mode without a precoat would be dependant on the feed turbidity. With a low feed turbidity, the rejection was expected to be poor, due to insufficient foulants to form a stable dynamic membrane. With high raw water turbidities, the rejection was expected to improve, since the dynamic membrane would form substantially faster. In Project 386, the raw water turbidities were relatively low (10 to 30 NTU), hence the poor performance. The high raw water turbidities in 1999 provided the opportunity to test the above hypothesis. Hence, although operating in the crossflow mode on raw water only was not a part of the project workplan, the workplan was modified to accommodate this investigation. The results of operating in the crossflow mode on raw water only is presented in Section 5.3.

Following the baseline studies (crossflow with a precoat), and the investigations into crossflow on raw water only, dead-end investigations were initiated. In the dead-end runs, the flow through the bypass line was continually adjusted to give the desired operating pressure in the curtain. However, it emerged that the feed pump could not operate stably at the desired operating pressure of 2 bar. The pump tripped on numerous occasions during runs. These trips could not be correlated with any particular events during the runs. Further, the problem could not be solved by an electrician who had been called in.

During the filtration cycle, most of the flow is via the bypass line. On the assumption that the pressure drop across the line was too great, causing an overload, a second bypass line was installed. This did not resolve the matter.

Further proposed solutions included :

(i) changing the impeller of the pump for a smaller one .

(ii) performing the dead-end runs at a pressure where the pump operated stabily, i.e. 3.5 bar to 4 bar.

Due to time and financial constraints, the first option was rejected, especially since the cause of the trips had not been identified, and there was no guarantee that changing the impeller would solve the problem. It was recognised that operation in the dead-end mode at 3.5 bar to 4 bar could not unequivocally be compared to crossflow runs at 2 bar. However, as noted above, three sets of crossflow results were available for the 25 mm tubes, i.e.

(i) crossflow with a precoat at 2 m/s and 3.5 bar (curtain with 30 tubes)

(ii) crossflow with a precoat at 2 m/s and 2 bar (curtain with 15 tubes)

(iii) crossflow on raw water only at 2 m/s and 2 bar (curtain with 15 tubes).

On the assumption that increasing the operating pressure changes the permeate flux, but does not significantly change the rejection, the *rejection* obtained in the dead-end mode at 3.5 bar to 4 bar could be compared to the *rejection* obtained in set (iii) above.

Accordingly, the dead-end runs were performed at an approximate pressure of 3.5 bar. The results are presented in Section 5.4.

5.2. Crossflow with Precoat - 25 mm tubes

5.2.1. Operation at 2 bar and 1.3 m/s - 30 tubes

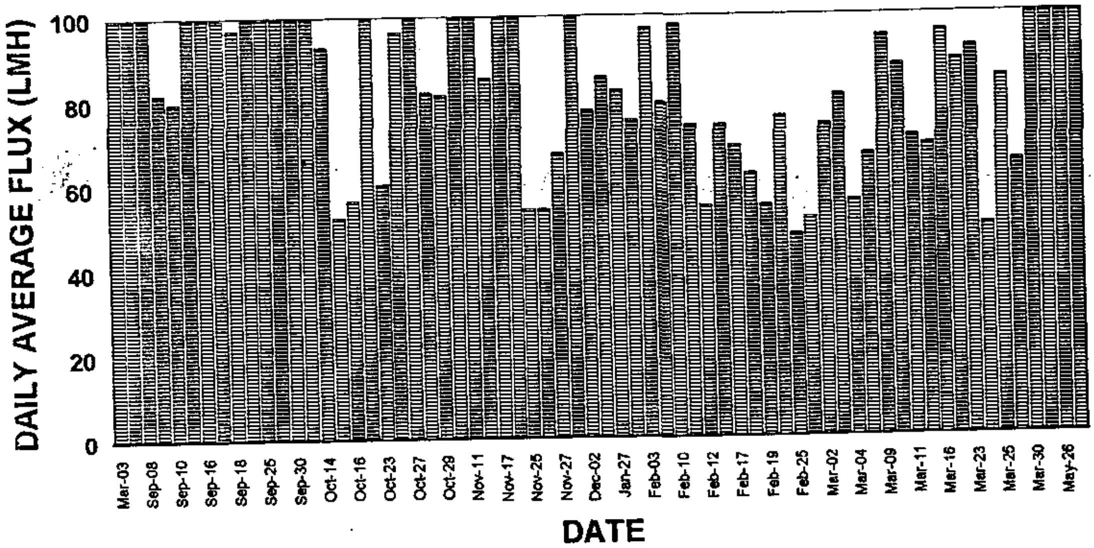


Figure 6 - Daily Average Fluxes: 1.3 m/s and 2 bar (30 tubes)

When operating on the 12 mm modules a daily average flux of approximately 90 LMH was obtained over extended periods of operation (see Figure 5). Figure 6 indicates that the fluxes obtained with the 25 mm tubes are significantly less (approximately 60 LMH), and a lot more erratic.

The difference could most probably be attributed to a difference in operating conditions. At present, there is no indication of the similarity parameters between different tube sizes. The 12 mm tubes were operated at an average trans-membrane pressure of 3 bar, and a tube velocity of 1,4 m/s. In the runs reported in Figure 3, the 25 mm tubes were operated at an average transmembrane pressure of 2 bar and a tube velocity of 1,3 m/s (these conditions were specified by piping constraints). Thus, the results from the 12 mm tubes cannot be directly compared with those from the 25 mm tubes.

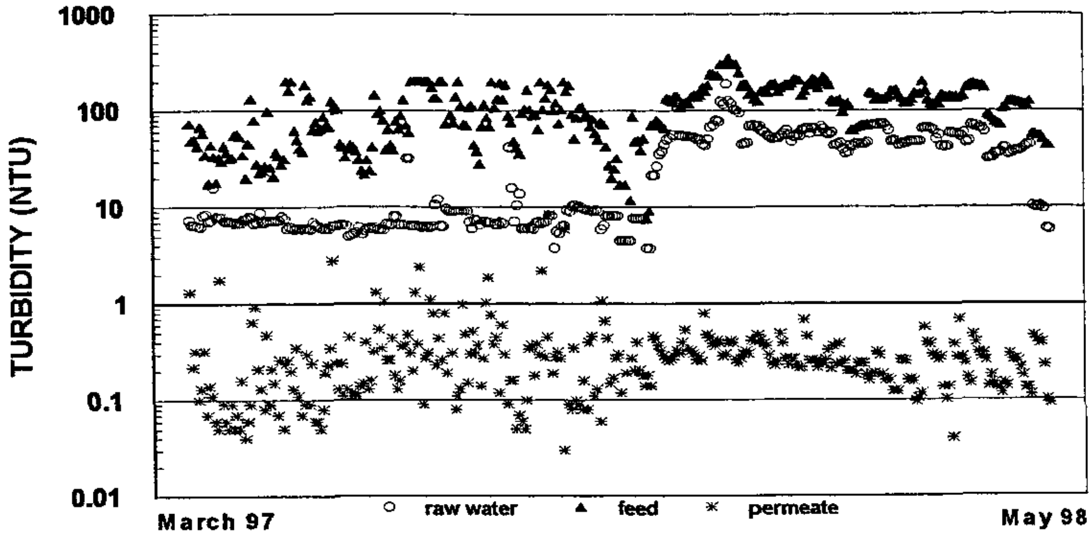


Figure 7 - History of Turbidity Rejection: 1.3 m/s and 2 bar (30 tubes)

Over the report period, the raw water turbidity ranged from 8 NTU to 80 NTU. The feed turbidity ranged from 20 NTU to 300 NTU. The permeate turbidity ranged from 0,1 NTU to 3 NTU, and was generally around 0,3 NTU.

Note that the turbidities are higher than those obtained previously, using 12 mm modules. The above runs were performed on a 25 mm module that subsequently turned out to be flawed. It is not known whether the above results are due to some effect of tube diameter, or whether they were affected by the numerous leaks that developed in the curtain.

5.2.2. Operation at 1.9 m/s and 3.8 bar - 30 tubes and 15 tubes

The daily average fluxes obtained at 1.9 m/s and 3.8 bar on both 30 tubes and 15 tubes are shown in Figure 8.

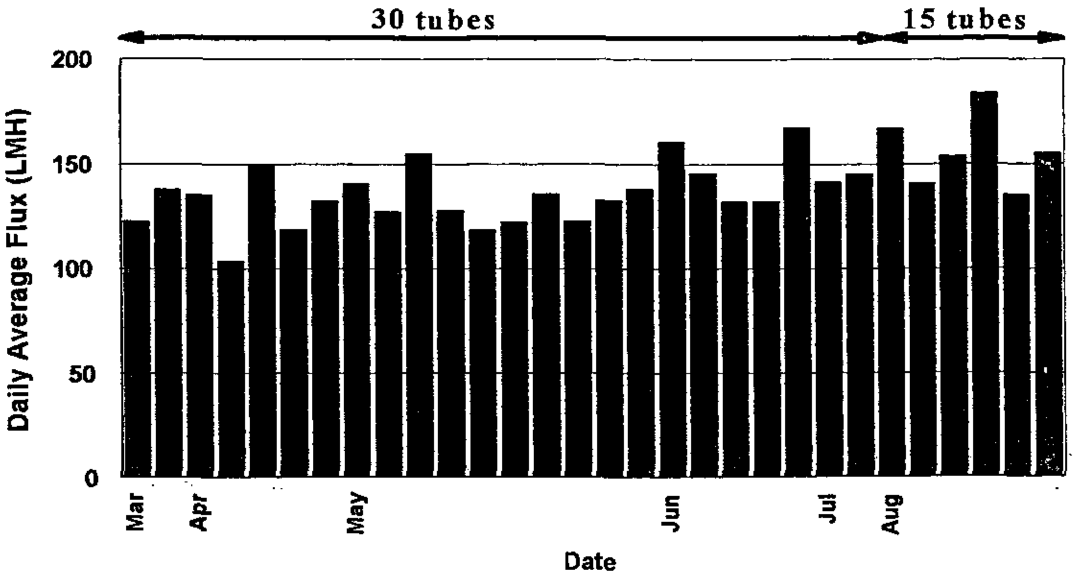


Figure 8 - Daily Average Fluxes: 1.9 m/s and 3.8 bar (30 tubes and 15 tubes)

The average flux is approximately 125 LMH. Figure 8 also indicates that operating at similar conditions on the full and half curtains yields similar fluxes. This is the first time that the influence of number of tubes on performance has been investigated. The results indicate that the results obtained on half a curtain may be applied to a full curtain with confidence.

The turbidity removal history is shown in Figure 9.

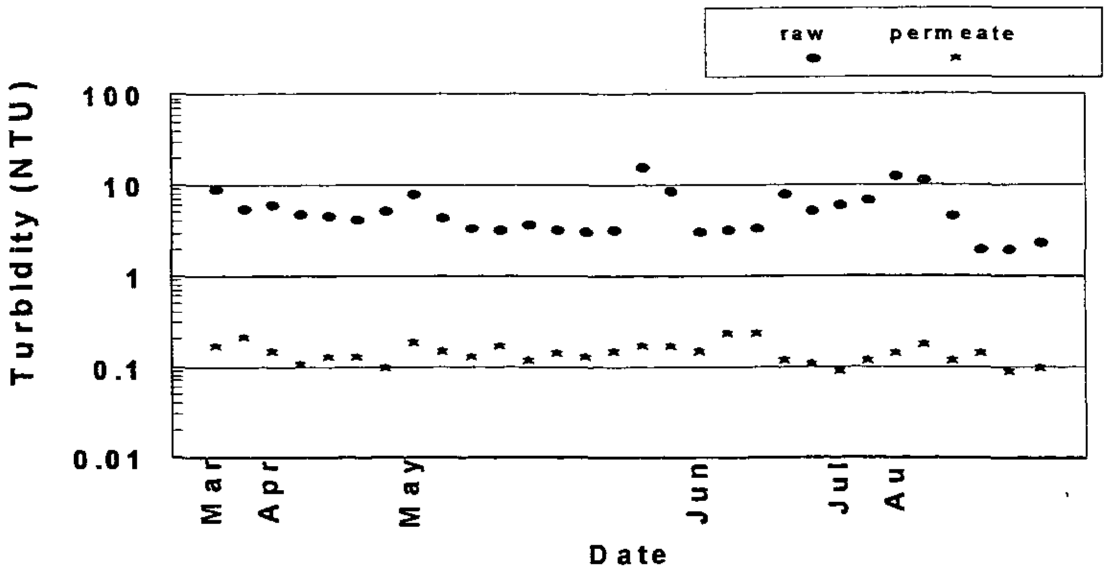


Figure 9 : Turbidity Removal History: 1.9 m/s and 3.8 bar

Over the report period, the raw water turbidity ranged from 5 NTU to 14 NTU. The performance in terms of turbidity removal continues to be excellent, with permeate turbidities ranged from 0,1 NTU to 0,3 NTU, and was generally around 0,2 NTU.

In Section 5.2.1 it was noted that that the permeate turbidities obtained on the initial 25 mm module were higher than those obtained previously using 12 mm modules. It was not known whether this is due to some effect of tube diameter, or whether it is affected by the numerous leaks that developed in the 25 mm curtain. The results in Figure 9 were obtained on a new module. Thus Figure 9 indicates clearly that very low permeate turbidities may be obtained on 25 mm tubes, and that the previous higher turbidities were most probably due to faulty modules.

5.2.3. Operation at 2 m/s and 2 bar

A typical flux-time curve obtained at 2 m/s and 2 bar is shown in Figure 10.

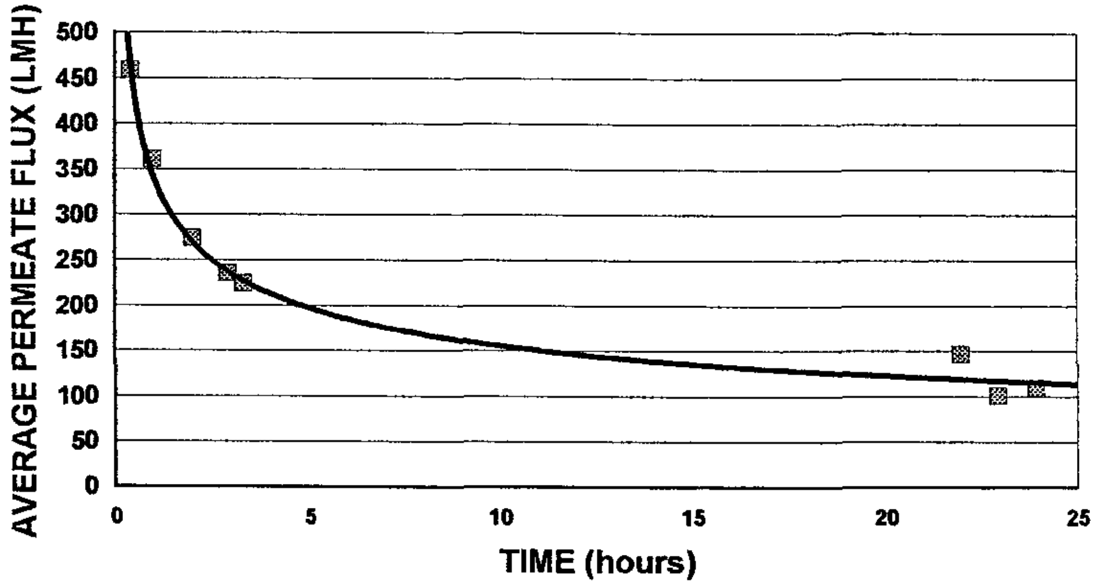


Figure 10 - Typical Flux-Time Profile : 2 m/s and 2 bar

Consistent with characteristic WFMF performance in the crossflow mode, the flux declines rapidly and then shows a slower, long-term decline with time.

A typical turbidity-time profile is shown in Figure 11.

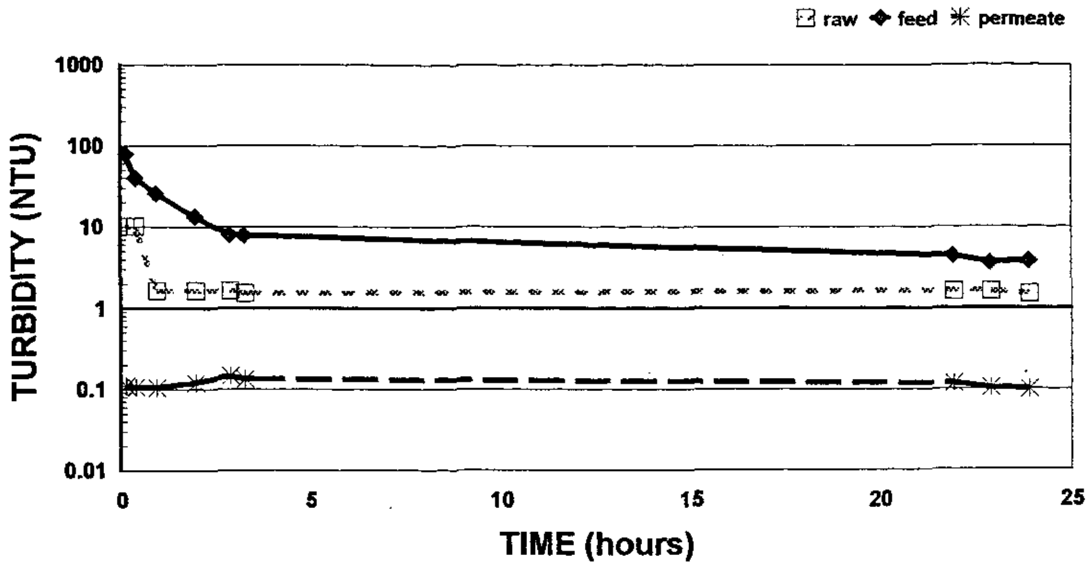


Figure 11 - Typical Turbidity-Time Profile : 2 m/s and 2 bar

In Figure 11, time 0 represents the switchover from precoat to raw water. Similar to previous results, an excellent permeate turbidity is obtained right from the start of the filtration cycle. Note that the feed turbidity exhibit a decrease with time, contrary to expectations for the semi-batch mode of operation. This is due to a high initial turbidity caused by resuspension of solids in the feed line at the start of the filtration cycle.

The daily average fluxes obtained in this mode are shown in Figure 12. The history of turbidity removal is shown in Figure 13.

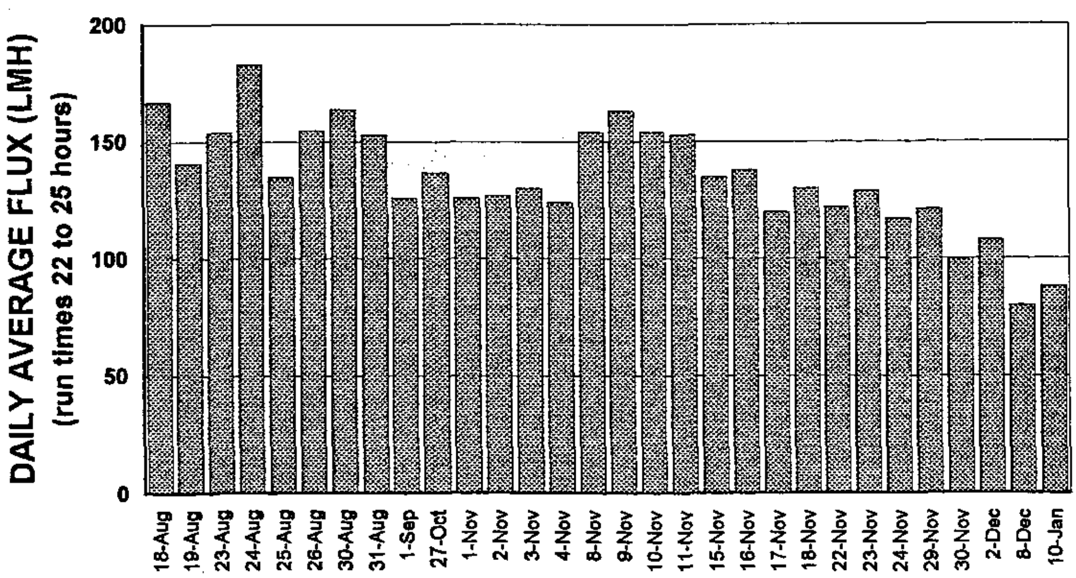


Figure 12 - Daily Average Fluxes : 2 m/s and 2 bar

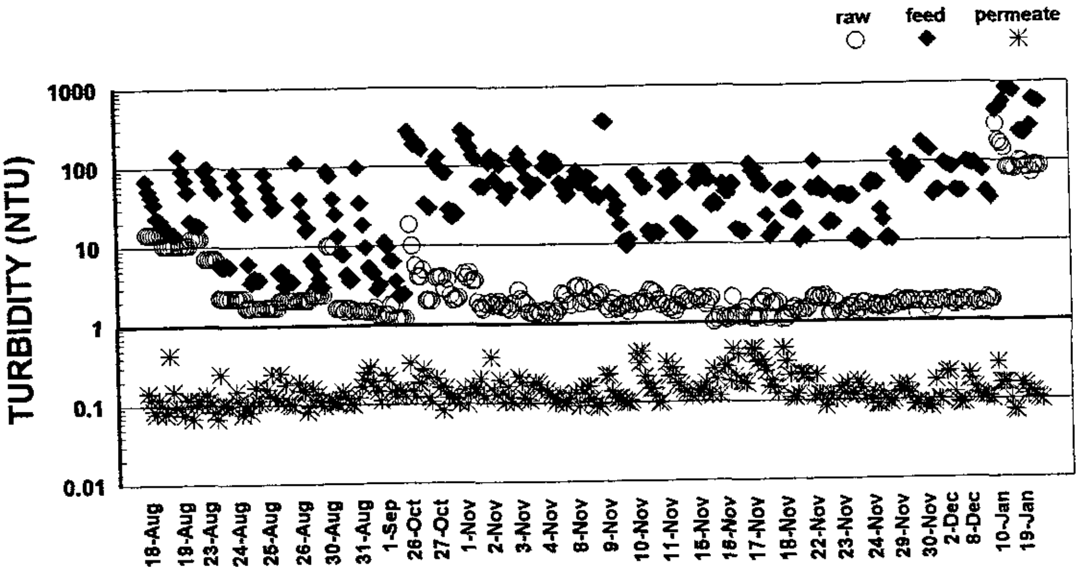


Figure 13 - Turbidity Removal History : 2 m/s and 2 bar

Consistent with previous results obtained in the crossflow mode with a precoat, fluxes are relatively high and turbidity rejection is excellent, with excellent permeate turbidities being obtained right from the start of the filtration cycle

The unit consistently produced a daily average flux of about 140 LMH, up to December 1999. Thereafter there is a noticeable decrease, probably due to the increase in raw water turbidity.

Bacteriological rejection is summarised in Table 3.

Table 3 - Bacteriological Rejection for Crossflow Operation with a Precoat : 2 m/s and 2 bar

Samples	Time from start (h)	Coliform /ml	E. Coli /ml	F. Strep /ml	colony count @ 22 °C	colony count @ 37 °C
Feed	0	500	300	<10	800	700
	4.85	600	100	<100	3000	1000
Permeate	0	2	0	2	0	0
	4.85	0	0	0	0	1
	22.4	2	2	2	1	4

A very good bacteriological rejection is obtained, with > 99 % of microbes being removed.

5.2.4. Summary of Crossflow with Precoat performance at different operating conditions and tube diameter

Set	Tube Diameter (mm)	Operating Conditions		Daily Average Flux (LMH)
		Average TM Pressure (bar)	Tube velocity (m/s)	
A	12	3	1.4	90
B	25	2	1.3	60
C	25	3.8	1.9	125
D	25	2	2	140

In overview, operation with a precoat gives excellent turbidity rejection, very good bacteriological rejection and relatively high fluxes. The table above also illustrates that the flux is significantly more sensitive to velocity, tahn to operating pressure.

5.3. Crossflow without Precoat

In initial investigations into operating in the crossflow mode without a precoat, two filtration periods were investigated : approximately 6 hours and 24 hours. It was found that when operating for a long period, cleaning was extremely difficult, with many purges required before fluxes could be restored. It was also found that the flux declined rapidly and had a very low value after 5 to 6 hours of filtration. It was subsequently decided that filtration periods will be restricted to between 5 and 6 hours.

In the initial runs performed in the crossflow mode without a precoat, permeate fluxes and the turbidity removal was fairly good. However, in March 1999 there was a sudden drastic decrease in permeate flux, accompanied by a deterioration in permeate quality. Typical flux-time profiles for a "good" and a "poor" run are shown in Figure 14. Turbidity-time profiles for a "good" and a "poor" run are shown in Figure 15 and Figure 16 respectively.

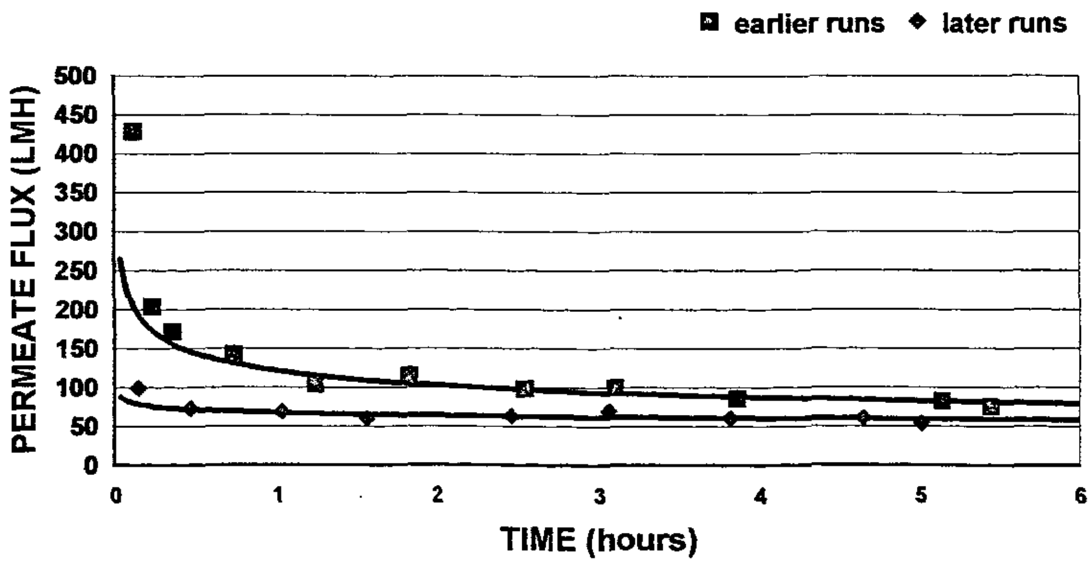


Figure 14 : Typical Moving-average Fluxes for "good" and "poor" runs

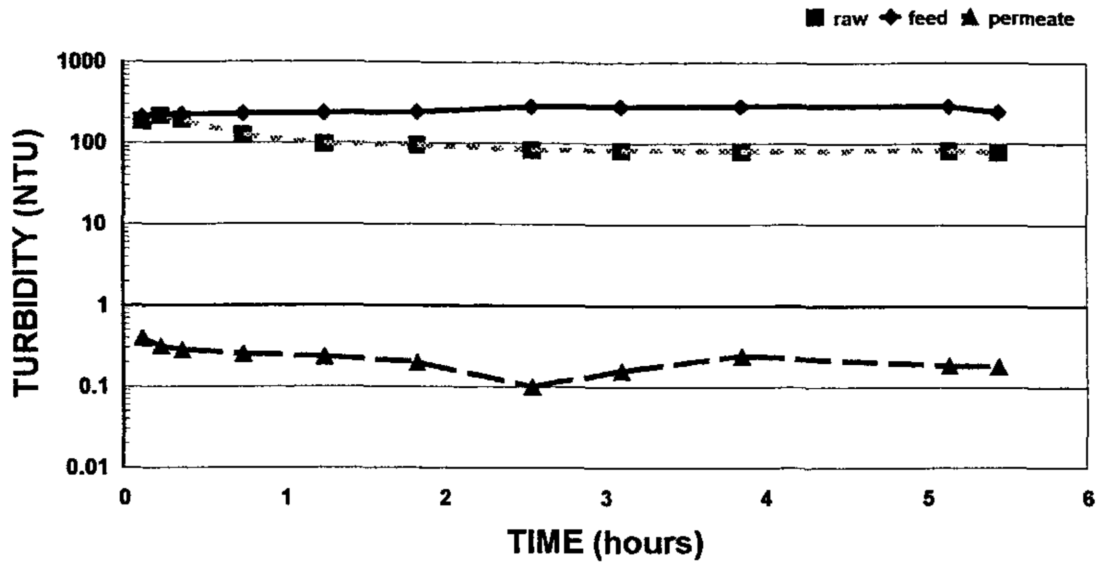


Figure 15 : Typical Turbidity-time Profiles for "good" runs

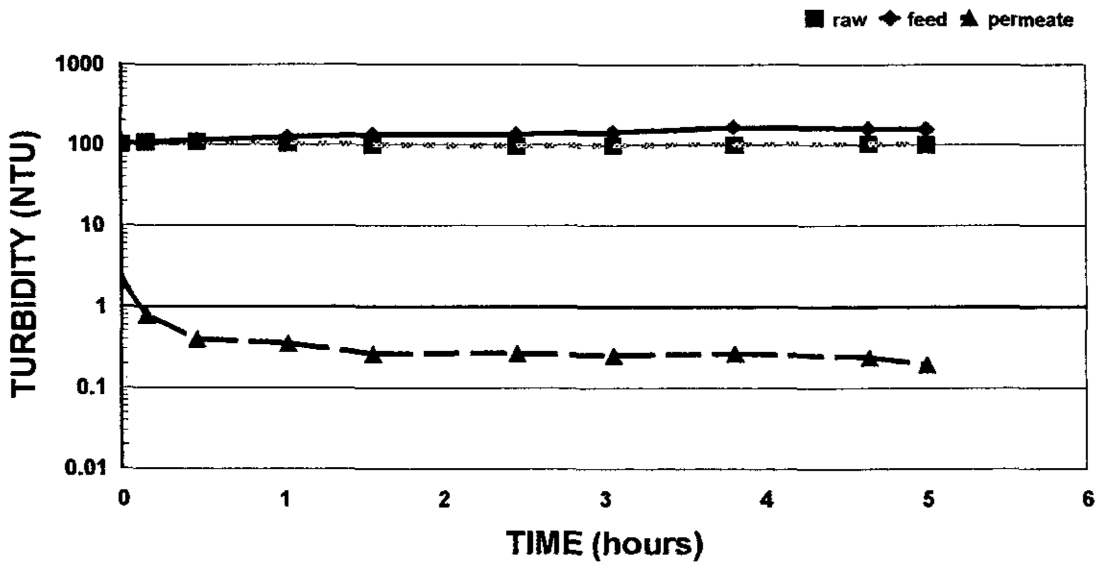


Figure 16 : Typical Turbidity-time Profile for "poor" runs

The history of average fluxes per run and turbidity removal are shown in Figures 17 and 18 respectively.

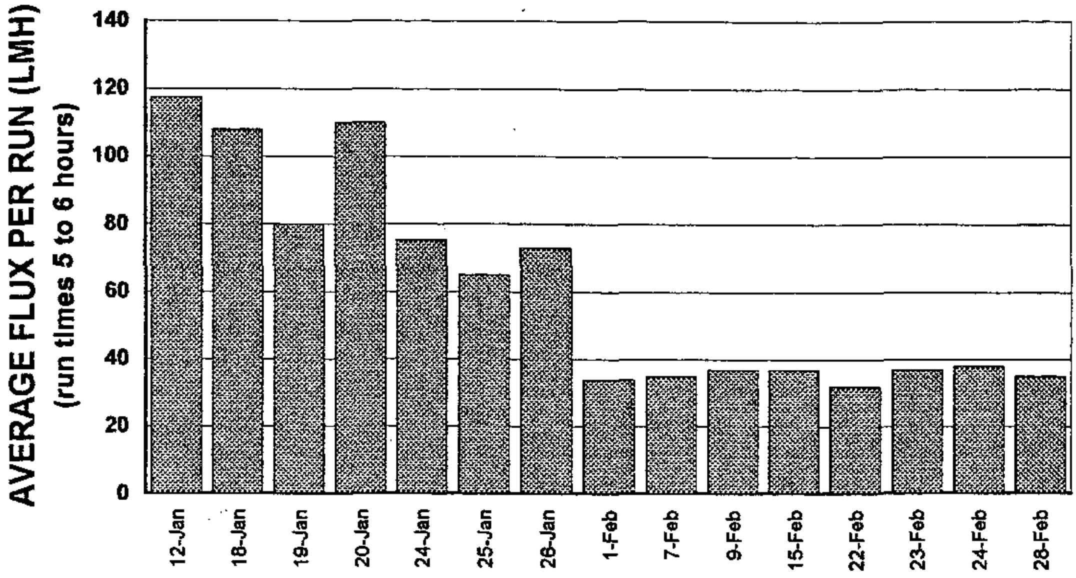


Figure 17 : History of Average Run Flux

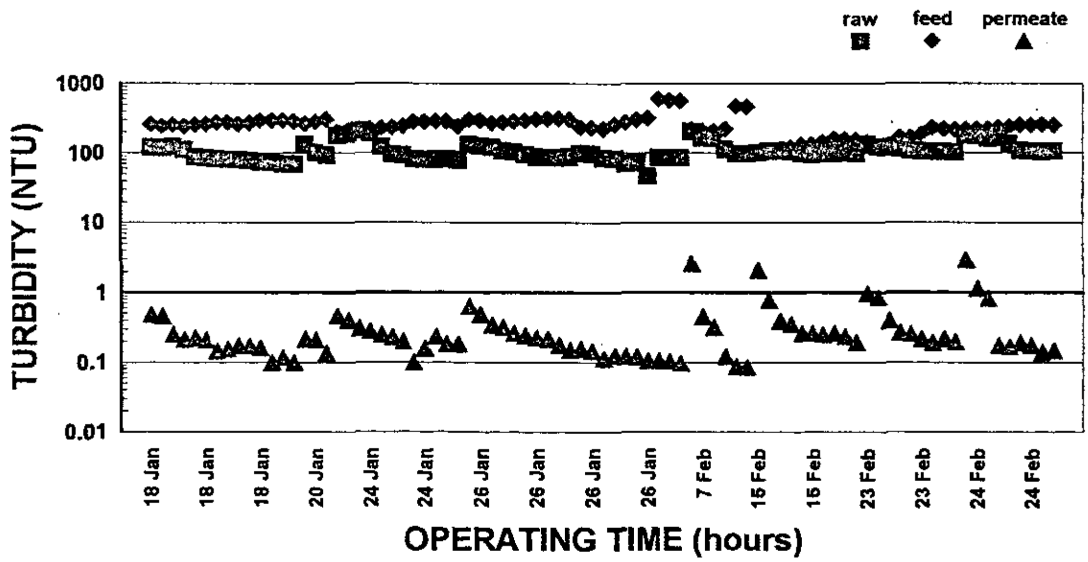


Figure 18 : History of Turbidity Removal

As can be observed, there is a significant decrease in flux towards the beginning of February, accompanied by an increase in turbidity at the beginning of each run. The reason for this is not known. It could most probably due to a change in nature of the foulants in the raw water, but this was not quantified at the time.

In overview, however, the results obtained in the crossflow mode without a precoat are fairly encouraging. Feed turbidities ranged from about 200 NTU to over 800 NTU. Permeate qualities ranging from 3 NTU down to 0,2 NTU. Whilst this permeate is certainly not of potable quality, it could provide a very good feed to a tighter membrane, e.g. UF, which would not be able to operate directly on the initial high turbidity raw water. Thus, these results indicate that WFMF in the crossflow mode without a precoat could be technically viable as a pretreatment step forhigh turbidity raw waters / effluents.

The bacteriological rejection in the crossflow mode without a precoat is shown in Table 4.

Table 4 - Bacteriological Rejection for Crossflow Operation Without a Precoat : 2 m/s and 2 bar

Sample	Time (h)	Coliform /ml	E.Coli /ml	F.Strep /ml	colony count @ 22 °C	colony count @ 37 °C
Permeate 1	0.5	0	0	0	80	256
Permeate 2	3	0	0	0	360	512
Feed 1	0.5	500	20	<100	>1000	>1000
Feed 2	3	700	16	<100	>1000	>1000
Raw Water	3	340	10	<10	>1000	>1000

The above results were obtained for a "good" run. An excellent bacteriological rejection is shown, consistent with the very good turbidity rejection.

5.4. Dead-end without Precoat - 25 mm tubes

Typical flux-time and turbidity-time curves obtained in the dead-end mode, at 2 bar, are presented in Figure 19 and Figure 20 respectively.

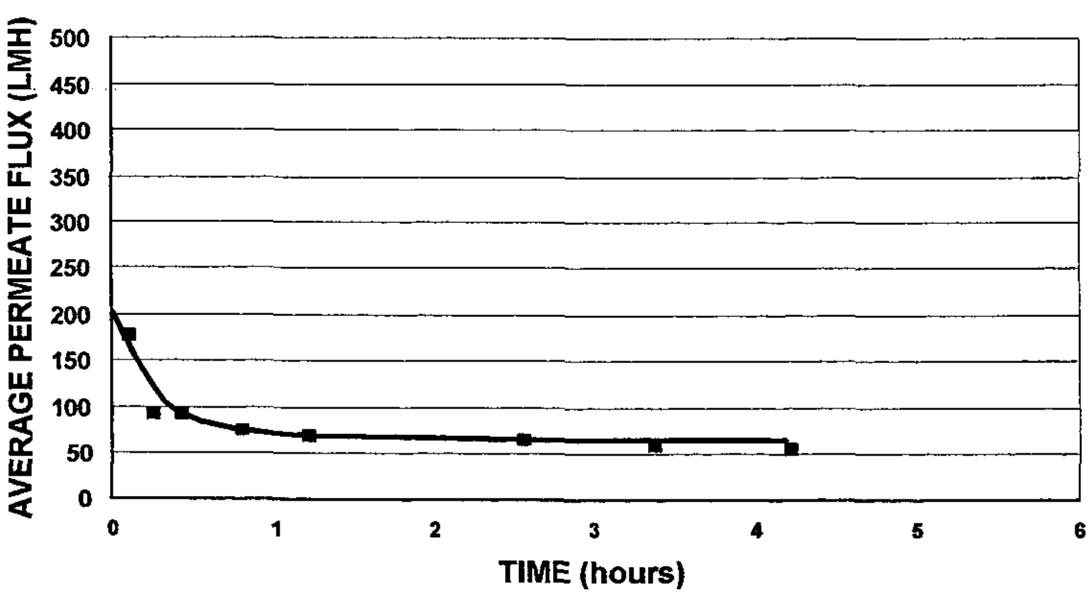
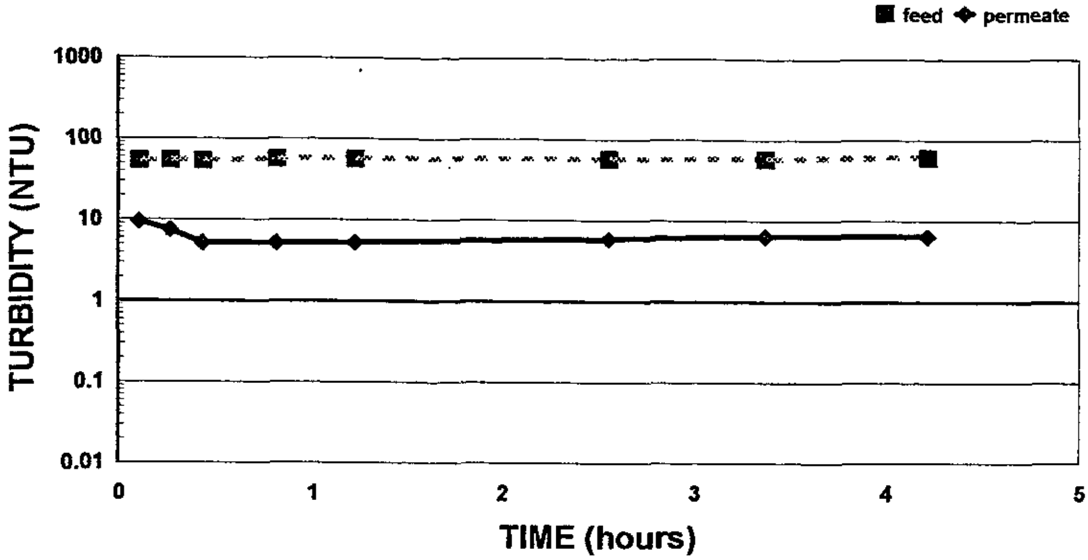


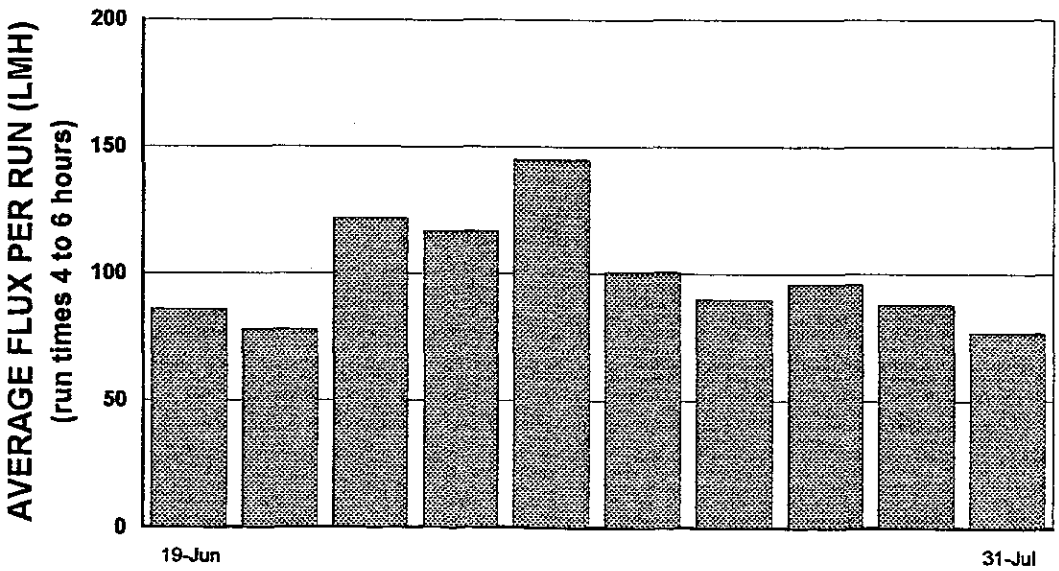
Figure 19 : Typical Flux-Time Profile



<u>**Figure 20 : Typical Turbidity Profiles - DE without Precoat**</u>

The permeate turbidities obtained in the dead-end mode were extremely poor, with turbidities of about 10 NTU obtained at the beginning of the filtration cycle, and no significant decrease thereafter.

The history of the average flux per run and the turbidity removal are presented in Figure 21 and Figure 22 respectively.



<u>**Figure 21 : History of Average Run Fluxes - DE without Precoat**</u>

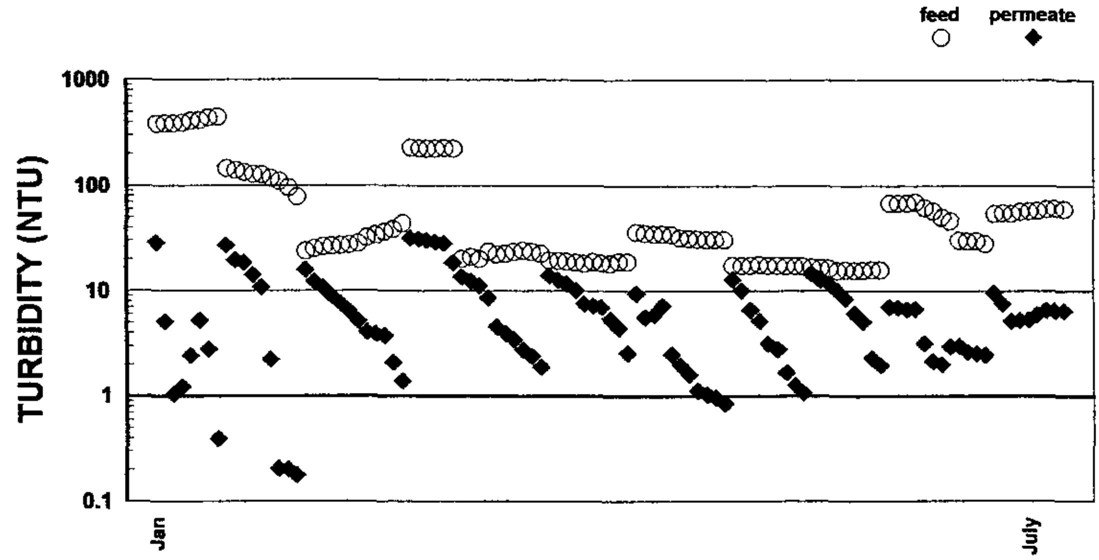


Figure 22 : History of Turbidity Removal - DE without Precoat

For the range of feed turbidities experienced, 20 NTU to 300 NTU, it is observed that the permeate turbidities are extremely poor.

During filtration cycles in the dead-end mode it was observed that there were numerous leaks from the seams between tubes. In the belief that some seams of the curtain had degraded, attempts were made to seal leaks with a glue. However, this proved to be unsuccessful, with new leaks springing up from other parts of the curtain.

To test the hypothesis that these leaks were a result of the mode of operation, and not due to curtain degradation, further runs in the crossflow mode without a precoat were performed in August 2000. These results (Figure 23 and Table 5) indicated that the poor turbidities obtained in the dead-end mode were most probably due to the mode of operation, and not to curtain degradation.

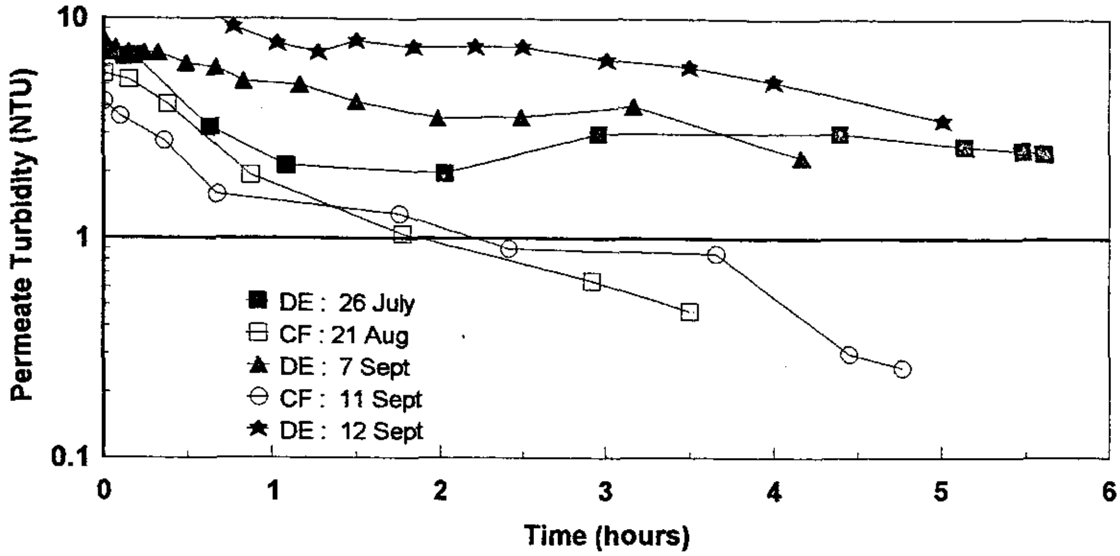


Figure 23 - Turbidity-Time Profiles for Sequential Crossflow and Dead-end Runs

Table 5 - Summary of Sequential Crossflow and Dead-end Runs

DATE	MODE	Average Flux (LMH)	Permeate Turbidity after 3 hours (NTU)
26 July	Dead-end	88	3
21 August	Cross-flow	31.7	0.6
7 September	Dead-end	85.5	3.8
11 September	Cross-flow	34	0.8
12 September	Dead-end	76	6.5

The differences between the turbidities obtained in the dead-end and crossflow modes without a precoat could probably be ascribed to the nature of the cake. In the crossflow mode the arrangement of the particles in the cake is determined by two velocity components - radial and axial [Pillay (1992)]. In the dead-end mode the particles are subjected mainly to a radial velocity component. Under the action of two perpendicular velocity components, a "tighter" cake is expected to form. This may explain the discrepancy obtained in the crossflow and dead-end modes. This explanation is supported by the higher fluxes obtained in the dead-end mode without a precoat when compared to the cross-flow mode without a precoat.

The project team is also of the opinion that operating in the dead-end mode with a precoat is of limited practical applicability. The precoating step would have to be done in the crossflow mode, to prevent settling out of the precoating material. Hence the capital equipment required is the same as that for crossflow with a precoat. It is highly unlikely that the reduced energy requirement for dead-end operation with precoat would outweigh the vastly superior performance obtained in the crossflow mode with precoat. Accordingly, dead-end operation with a precoat was not investigated in this project.

5.5. Summary of performance in the different operating modes

Three modes of operation were investigated in this project : crossflow with a precoat; crossflow without a precoat on high turbidity waters; and dead-end without a precoat. The summarised performance is shown in Table 6.

Table 6 - Summary of Performance in the Different Operating Modes

	XF with Precoat	XF without precoat		DE without Precoat
		"Good" runs	"Poor" runs	
Feed Turbidity (NTU)	10 to 400	30 to 400		30 to 400
Permeate Turbidity (NTU)	0.5 to 0.1	0.9 to 0.2	3 to 0.2	30 to 1
Average Run Flux (LMH)	140	70	35	80

5.6. Energy Requirements of the Different Operating Modes

The energy requirements of the different operating modes is illustrated below, based on the operating configuration used in this study. Note that the experimental rig was not optimised in terms of energy usage, hence the calculations below are for illustrative purposes only. The energy requirements could be significantly reduced by, for example, operating curtains in series.

5.6.1. Assumptions

(a) Cleaning cycle :

Volume of permeate used per curtain	=	2.5 m^3
Number of pulses per clean	=	5
Duration of each pulse	=	30 s
Pressure drop during clean	=	0.5 bar

(b) Operating conditions and performance data

	XF with precoat	XF without precoat	DE without precoat
tube velocity (m/s)	2	2	n/a
operating pressure (bar)	2	2	3.5
Filtration period per cycle (h)	23.5	5.5	5.5
Cleaning period per cycle (h)	0.5	0.5	0.5
Average flux per filtration period (LMH)	140	35	80

(c) Curtain geometry

tube diameter = 25 mm

tubes per curtain = 30

curtain length = 8 m

5.6.2. Energy requirements for cleaning cycle

Pressure drop = 50 000 Pa

Average flowrate = (2.5/(5*30))
= 0.0167 m^3/s

Energy per clean = (50000)(0.0167)(150/3600)(1/1000)
= 0.035 kWh/m^3

5.6.3. Energy requirements for XF with precoat

Flowrate = (3.14/4 * 0.25^2 * 30 * 2)
= 0.0295 m^3/s

Energy during filtration = (200 000 * 0.0295 * 23.5)/1000
= 138.7 kWh

Total energy per cycle = energy for filtration + energy for cleaning
= 138.7 + 0.035
= 138.74 kWh

Production per cycle = [(3.14 * 0.025 * 8 * 30) * 140 * 23.5] - 2.5
= 59.515 m^3

Energy consumption	=	138.74/59.515
	=	2.33 kWh/m^3

5.6.4. Energy requirements for XF without precoat

Energy during filtration	=	(200 000 * 0.0295 * 5.5)/1000
	=	32.485 kWh
Total energy per cycle	=	32.485 + 0.035
	=	32.485 kWh
Production per cycle	=	[(3.14 * 0.025 * 8 * 30) * 35 * 5.5] - 2.5
	=	1.13 m^3
Energy consumption	=	32.485/3.63
	=	28.75 kWh/m^3

5.6.5. Energy requirements for DE without precoat

Average flowrate	=	(3.14 * 0.025 * 8 * 30) * 80 / 3600
	=	0.00042 m^3/s
Energy during filtration	=	(350 000 * 0.00042 * 5.5)/1000
	=	0.809 kWh
Total energy per cycle	=	0.809 + 0.035
	=	0.844 kWh
Production per cycle	=	[(3.14 * 0.025 * 8 * 30) * 80 * 5.5] - 2.5
	=	5.79 m^3
Energy utilisation	=	0.809/5.79
	=	0.14 kWh/m^3

5.6.6. Summary

Crossflow with precoat	=	2.33 kWh/m^3
Crossflow without precoat	=	28.75 kWh/m^3
Dead-end without precoat	=	0.14 kWh/m^3

As noted above, the calculations here are based on the actual configuration used in this study, which is probably far from optimal in terms of energy usage. For example, in this study curtains were not operated in series, as would be expected in a commercial production unit. Operating curtains in series will decrease energy requirements by a factor of two.

However, as expected, it emerges clearly that the dead-end mode of operation requires the lowest energy, about two orders of magnitude lower than crossflow with a precoat. The energy requirement for crossflow without a precoat is ridiculously high. This is due to the very low fluxes in that mode - over 60 % of the permeate produced is used in cleaning !

6 Conclusion

This project is a follow up to WRC Project No 386, *The Development of a Cross Microfilter for Rural Water* Supply, and concerns the further development of the woven fibre microfiltration system for potable water production in rural and peri-urban areas. The specfic objectives were :

(i) To evaluate the performance of the WFMF unit operated in the dead-end mode (DEMF).

(ii) To improve and optimise the cleaning system on the WFMF unit.

(iii) To establish a reliable, easily operable and fully automated demonstration unit for the process.

6.1. Improvements to the cleaning system

The unit was initially constructed with a spray cleaning system, consisting of a high pressure pump, spray bars, a motorised carriage, and associated piping and control valves. As noted in Project 386, the spray cleaning system adds considerably to the complexity of the rig and control circuitry. Also, major problems were experienced with frequent blockage of the spray nozzles. Thus, in Project 386, the cleaning system was identified as being the part of the rig that is most prone to failure.

In this project a new **pulse cleaning** technique was investigated. In initial investigations the curtains were pulsed by starting and stopping the feed pump, and subsequently allowed to dry for 24 hours. The pulsing causes the curtains to alternately inflate and deflate, presumably destroying the fouling layer which is then swept out by subsequent pulses. The drying phase was expected to cause the remaining foulants to dry and fall off the tube wall. It was found that the daily average fluxes so obtained were 10 % to 20 % lower than that obtained with the spray cleaning system. However, there was no long term decline in the daily average flux, indicating that the pulse cleaning technique was indeed effective.

In subsequent improvements to the pulsing technique, it was found that the drying phase was not necessary. The curtains could be pulsed and a new filtration cycle started immediately thereafter, with no obvious detriment to permeate production. Following further investigations the final pulsing strategy adopted was to pulse the curtains three times for 30 s each.

The implications for the process as a whole are tremendous. If redesigned from scratch, the rig would consist essentially of a feed pump and curtains, with the associated valves, piping and a control system of greatly reduced complexity. The exclusion of the spray system would reduce the capital cost of the rig significantly. In additional the general robustness and reliability of the rig would also improve significantly. The maintenance requirement would decrease and the level of skill required by the operator would also be reduced dramatically.

6.2. Improvements to Reliability and Operability

In Project 386, the following areas were identified as requiring improvement :

(i) The method of fixing the manifolds to the endbocks

(ii) The precoating system

6.2.1. Manifold System

In Project 386, a significant down-time was caused by mechanical problems experienced with the module endblocks and manifolds. It was proposed that this could be alleviated if the method of fastening the endblock to the manifold was improved.

The original fastening system entailed inserting bolts through holes in the manifold and into threaded brass inserts in the endblocks. The brass inserts were removed from the endblocks, and holes corresponding to those on the manifold were drilled all the way through the endblock. Bolts were then welded to a single backing plate which was to have been inserted from the rear of the endblock all the way through the gasket and the manifold. However, it was found that it was extremely difficult to align all twenty bolts with the drilled holes. One unsucessful attempt resulted in an endblock cracking. The singl backing plate was then cut into smaller backing plates, each with five bolts, which could be inserted individually. This proved sucessful. The soft gaskets that were previously used were replaced by a firmer gasket made of inertion rubber, and hat had cross-threads to improve its lateral strength.

The combination of the new fastening method and the new gasket proved extremely sucessful, and problems with leaking gaskets were not experienced during the project. It is confidently stated that the problems with the manifolds have now been solved.

6.2.2. Precoating System

In Project 386, it was shown that operating in the crossflow mode with a precoat yielded a vastly superior performance than operating on raw water only, or with a filter aid. However, it was also identified that the precoating stage was laborious, time consuming, and resulted in a significant waste of precoat suspension.

To improve the operability of the unit, as well as facilitate the reuse of unspent precoat suspension, a separate precoating system was installed. This entailed installation of a precoat tank with a mixer, and modifications to the feed, reject and permeate lines.

The installation of a separate precoating system has greatly simplified the precoating sequence, as well as facilitated the reuse of the precoat suspension.

6.3. Investigations into the Dead-end Mode of Operation

The unit's performance in the crossflow mode on raw water only, with a filter aid, and with a precoat had been established in Project 386, for operation on 12 mm curtains. The workplan for this project entailed evaluating the unit's performance in the dead-end mode, and comparing this to the crossflow performance obtained previously.

However, just prior to commencement of dead-end investigations, the project team decided that dead-end operation on 12 mm curtains would not be viable, and that the system should be changed to 25 mm curtains. It was also realised that dead-end results from 25 mm curtains could not be compared with crossflow results from 12 mm curtains, since the relationship between performance and tube diameter was not known. Hence, it was decided that baseline studies would be performed on the 25 mm curtains in the crossflow mode, prior to commencing dead-end investigations.

Three modes of operation were investigated in this project : crossflow with a precoat; crossflow without a precoat on high turbidity waters; and dead-end without a precoat.

Operation in crossflow with a precoat continues to yield the best performance, with high daily average fluxes, low permeate turbidities and long filtration cycles. Filtration cycles of 24 hours were performed. Daily average fluxes were very dependant on the operating conditions, and ranged from 60 LMH (2 bar, 1.3 m/s) to 140 LMH (2 bar, 2 m/s). The permeate turbidities were < 0.3 NTU for raw water turbidities ranging from 10 NTU to over 100 NTU. The bacteriological rejection was also very good, with > 99 % of indicator microorganisms being rejected. The crossflow mode with a precoat is thus the most suitable for potable water production.

Operating in crossflow without a precoat on high turbidity waters yields average run fluxes of 38 LMH to 110 LMH (2 bar, 2 m/s), and permeate turbidities ranging from about 3 NTU at the start of the filtration cycle to 0.2 NTU at the end of the cycle. The filtration cycles were limited to between 5 and 6 hours, due to very low fluxes at the end of this period.

Operating in the dead-end mode without a precoat yields a very poor permeate turbidity, ranging from 10 NTU to about 2 NTU, and relatively low fluxes. The filtration cycles in this mode were also restricted to 6 hours, and average run fluxes of approximately 80 LMH were obtained.

The differences between the turbidities obtained in the dead-end and crossflow modes without a precoat could probably be ascribed to the nature of the cake. In the crossflow mode the arrangement of the particles in the cake is determined by two velocity components - radial and axial [Pillay (1992)]. In the dead-end mode the particles are subjected mainly to a radial velocity component. Under the action of two perpendicular velocity components, a "tighter" cake is expected to form. This may explain the discrepancy obtained in the crossflow and dead-end modes. This explanation is supported by the higher fluxes obtained in the dead-end mode without a precoat when compared to the cross-flow mode without a precoat.

The energy requirements for each operating mode were calculated, based on the operating conditions and configurations used in this study. Operating in the crossflow mode with a precoat required 2.33 kWh/m^3. The crossflow mode without a precoat draws 28.75 kWh/m^3, while the dead-end mode requires 0.14 kWh/m^3. The extremely high energy requirement for crossflow without a precoat is due to the very low production in that mode - over 60 % of the permeate produced is used in each clean, giving a very low net permeate production.

In overview, operating in the crossflow mode with a precoat produces an excellent quality of permeate at high production rates, while the dead-end mode of operation produces a very poor quality of permeate at reduced production rates. However, the energy requirement for the dead-end mode is about two orders of magnitude less than that required for crossflow with precoat. Operating in crossflow without a precoat produces an intermediate quality of permeate, but at an energy requirement ten times greater than crossflow with a precoat. Accordingly, the crossflow with a precoat mode would be the most appropriate in applications where a high quality of permeate is required, whereas the dead-end mode would probably be the most suitable for pretreatment applications where energy is a major consideration.

7 Recommendations

(i) Improvements to the woven fabric to reduce the permeability.
This could be achieved by a tighter weave or impregnating the fabric with a resin. A tighter fabric could improve the performance in the dead-end mode without a precoat, resulting in an inexpensive pretreatment process.

(ii) Investigate starting up in the crossflow mode and switching over to dead-end (high turbidities feeds only). This may result in a tighter cake forming during the crossflow startup, which would give a better separation and better product qualities during the dead-end filtration period. Whilst this would not reduce the capital costs, it could result in a significant saving in energy requirements.

(iii) Identify possible niche markets for each operating mode.
The product qualities and energy requirements are significantly different for each operating mode, and in general the energy requirement increases with product quality. An analysis of market needs should be performed to match product qualities in each operating mode with specific applications.

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VL Pillay & CA Buckley

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The project was divided into three stages:

- Economic Evaluation of the coupled CFMF/Digestor system
- Microbiological Evaluation of the Coupled CFMF/Digestor system
- Evaluation of the Full-Scale Coupled CFMF/Digestor system

The implication of these pilot plant trials is that existing digesters could be operated at volumetric flowrates which would exceed their current maximum values, while still obtaining the same extent of volatile solids destruction. This would enable Waste Water Treatment Works to cope with increases with inflows and delay the necessity to construct new digesters. Further development of the coupled membrane process will entail establishing and demonstrating its performance on a larger scale, as well as assessing its long term reliability and operability.

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