The Evaluation and Design of Sludge Dewatering and Water Filtration Systems using Tubular Woven Fabric Technology

Final Report to the Water Research Commission
by
Umgeni Water

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Executive Summary

The Pollution Research Group of the School of Chemical Engineering, University of Natal, in collaboration with the Water Research Commission of South Africa and Umgeni Water pioneered research in South Africa in the application of tubular woven-fabric technology in South Africa. A tubular configured sludge dewatering process was developed by Treffry-Goatley et al of the Pollution Research Group in 1987, under a Water Research Commission funded project. Fundamental research in tubular woven application intensified during this period in sludge dewatering (Rencken, 1992) and water filtration (Pillay, 1992).

This report covers research on sludge dewatering (Tubular Filter Press) and water filtration (Cross-flow Microfiltration) under a Water Research Commission funded project. The research on Tubular Filter Press was conducted by Umgeni Water at its Wiggins Process Evaluation Facility and at the Hazelmere Waterworks. The research on Cross-flow Microfiltration was conducted by the Research Unit of the Chemical Engineering Department of the Durban Institute of Technology at their chemical engineering laboratory.

Work on sludge dewatering by Tubular Filter Press contributed to about 80% of the project. The balance of the project involved work on the cross-flow microfiltration system. For dewatering trials by Tubular Filter Press, real waterworks and industrial sludges were used. For filtration studies, by Cross-flow microfiltration, synthetic suspensions were used.

Findings of Previous Work - Sludge Dewatering

Initial pilot-plant studies, undertaken on lime kaolinite and underground mine water slurries, indicated that the process had a wide application in industry (Rencken, 1988).

Horizontal Tubular Filter Press

Work on the innovative sludge dewatering process culminated in the installation of a prototype of a new and locally designed sludge dewatering process at Umgeni Water's HD Hill Waterworks in Pietermaritzburg. A patent was granted to the WRC (Patent Number 87/0553). The (horizontal) Tubular Filter Press Unit at H.D. Hill waterworks was in operation for about 4 years from 1987 until it was shut down in 1991, due to operational strategic reasons and the imminent closure of the Waterworks.

During the operation of the plant various problems were identified that required some fundamental changes to the design. The manifold design, tube size and the horizontal orientation of the array of tubes were found to be the main causes for down time and poor plant performance.

Vertical Tubular Filter Press

There was sufficient confidence in the Tubular Filter Press technology to motivate for further investigative work including pilot and full-scale plant work, especially in those topics mentioned previously. It was envisaged that in addition to its application for the dewatering of waterworks sludge, the tubular filter process can provide good quality potable water. The main objectives of the project, initiated by Umgeni Water in 1994 and funded by the Water Research Council, were to improve the design of the Tubular Filter and develop a commercially operational unit for waterworks sludges, assess the applicability of the new design for potable water production and to develop techniques for determining design parameters for the Tubular Filter Press by extending the filtration model proposed by Dr. Rencken.

The deficiencies in the previous prototype at HD Hill were corrected in the new design. A single tube Vertical Tubular Filter Press pilot-plant with a larger tube diameter was constructed and tested.

Following favourable results from the single tube pilot-plant, a demonstration model, PLC controlled Vertical Tubular Filter Press with two curtains (13 tubes each) was constructed at Wiggins Waterworks in Durban in 1995.

The performance of the filter was satisfactory with cake concentrations between 20 and 32 percent solids (m/m), and solids recoveries up to 75 percent. Filter performance was found to be dependent on sludge characteristics, which in turn were largely influenced by raw water turbidities and treatment chemicals. It was found that the inclusion of bentonite as a coagulant aid in the water treatment process during times of low raw water turbidity resulted in poor sludge filter performance. The addition of lime to a waterworks sludge improved sludge filterability but had a negative impact on the woven tube .

A new generalised *Area Contact* model has been proposed for the constant pressure compressible cake filtration. A predictive model has been developed for design and troubleshooting purposes.

The vertical tubular filter press trials for the production of potable water, indicated that the process was unsatisfactory for potable water in comparison with cross-flow microfiltration. The use of the new vertical configuration operating in *dead end* mode was therefore not recommended for potable water treatment.

Rationale for further work on Vertical Tubular Filter Press

The development of the Tubular Filter Press for the dewatering of waterworks solids (WRC report 568/1/98) concluded that the process was capable of dewatering waterworks solids although the efficiency of the process depended on a number of factors (mainly the nature of the solids). There were however some limitations in the marketing of the process for full-scale application. These revolved mainly around the long-term operability of the process including operational and maintenance costs and filter response to changing sludge characteristics.

Furthermore, a standard design protocol had not yet been established. There was therefore a need for experience in the practical aspects of the technology including development of appropriate laboratory-scale tests for the assessment of sludge suitability to dewatering by Tubular Filter Press, establishment of some correlation between laboratory-scale results and pilot-scale results, filter material fouling and durability and identification of mechanical weaknesses in the Tubular Filter Press process.

The design procedures needed to be assessed and compiled in a form that can be used to efficiently assess the application of the Tubular Filter Press for a particular application. These procedures would then be tested on a number of sludges from different potential applications and the design methods optimised. A comparison of the operating costs of the Tubular Filter Press and other dewatering equipment was needed to provide valuable information to assess the competitiveness of the new technology.

Following the completion of WRC project K5/568, the assets from the project were transferred to Umgeni Water. These included a large-scale vertical Tubular Filter Press for waterworks solids dewatering with its associated equipment. A number of design changes had been implemented since the initial vertical curtain Tubular Filter Press was constructed. Other areas in the operation of the Tubular Filter Press also required attention for continuous operation. These needed to be assessed and a final design protocol documented.

The input from operations and maintenance personnel is invaluable in the final assessment and design of a new process. The relocation of the demonstration Tubular Filter Press to a waterworks where the sludge produced was amenable to dewatering by the Tubular Filter Press process, was considered vital for the development of the Tubular Filter Press technology.

For a wider market, the applicability of Tubular Filter Press to other sludges other than waterworks sludges required to be investigated. Industrial sludges especially textile and mining sludges may be suitable for dewatering by Tubular Filter Press. The comparison of Tubular Filter Press performance to other dewatering processes used in the water industry also needed to be investigated.

Findings of Previous Work – Filtration

Cross-flow microfiltration systems are mainly used for water filtration and other applications where the feed solids are relatively low in comparison with tubular filter press applications in sludge dewatering. Cross-flow microfiltration processes operate at relatively low compressive pressures (typically about 150 kPa and require a suitable pre-coat layer inside the tubes at the start of the filtration cycle.

Microfiltration had been shown to produce excellent quality potable water and had been recommended as a pretreatment process for reverse osmosis and nanofiltration (Jacangelo and Buckley, 1996). Crossflow microfiltration is widely used in the concentration of particulate suspensions and the separation of solids. Due to the economic advantage of this process compared to conventional processes such as centrifugation and clarification, etc, the market for this technology has shown a progressively increasing demand in recent years. The process has produced promising results in recovering valuable material from effluents in a number of industries (Govender, 2003).

However despite the considerable amount of industrial work on microfiltration very little information is available in the literature on design of full-scale plants using data obtained from laboratory tests.

Rationale for Further Work on Cross-flow Microfiltration

Unlike other models developed for reverse osmosis and nanofiltration, etc, no predictive models have been developed to date for microfiltration that enables the design of a full-scale system. For a real system, designers generally rely on performing laboratory experiments to generate data required for design. This is often a time consuming and tedious task as there is a scarcity of relevant information on the experimental protocol and procedure for data processing and application to design.

The need for a suitable design procedure is therefore essential and forms the rationale for this study.

Usually in design, the primary variable is the membrane area required to treat the desired capacity of the full-scale system. This may be calculated using data from the more rigorous and time consuming constant concentration experiments or data from average flux experiments that take the least time and effort.

The overall objective of this study was to evaluate these approaches for the design of full-scale microfiltration systems and recommend a cost-effective procedure that will assist in the prediction of the performance of a full-scale unit for estimation of the filtration area requirement.

Main Findings of Work on Sludge Dewatering By Tubular Filter Press

The work includes development of laboratory sludge characterisation tests, results from single tube pilot- plant trials of different waterworks sludges and industrial sludges. Operating experience of the full-scale demonstration tubular filter press plant including comparison of the tubular filter press process with a centrifuge is also presented.

Development of Laboratory-scale Tests for Sludge Characterisation

A number of laboratory-scale sludge tests were evaluated and modified for application to waterworks and effluent sludges. These included viscosity, volatile solids, capillary suction time (CST) and planar filtration tests.

Comparison of the laboratory test results of the feed sludge with Tubular Filter Press performance data indicated that there was often an insignificant difference in a laboratory determinand (viz viscosity, volatile solids) for a significant difference in Tubular Filter Press performance. Hazelmere sludge dewatered better than Wiggins sludge, however, the relative difference in the respective laboratory tests were not significant and reproducible.

The accuracy and reproducibility of the tests excluding volatile solids were also affected by concentration and the settling nature of the sludge.

The results of the tests are meaningful when interpreted collectively, and relative changes are considered (as opposed to absolute results). Analysis of the results indicate that the laboratory tests especially planar filtration tests, may be useful as an initial screening tool, to establish whether a sludge is amenable to dewatering by Tubular Filter Press.

Single Tube Pilot-Plant Trials

Single tube pilot-plant studies on three waterworks sludges, indicated that dewaterability by Tubular Filter Press can vary significantly amongst the sludges. It was concluded that dewaterability performance is primarily dependant on raw water characteristics and the type and quantity of treatment chemicals added (to the raw water) during the water treatment process.

Work on three industrial sludges, indicated that the Tubular Filter Press technology has potential in some applications such as electroplating sludge. However it is very important that exhaustive preliminary tests are conducted on the sludge over a reasonable period of time to cover sludge variability and upstream process variation and their impact on Tubular Filter Press performance. As mentioned earlier, the Tubular Filter Press process is very sensitive to relatively small changes in measurable sludge characteristics such as viscosity and volatile solids.

Investigation of the performance of a Tubular Filter Press in a textile application

A full-scale Tubular Filter Press, for a textile application, performed poorly over a period of time. The Tubular Filter Press was subsequently removed and replaced with a centrifuge. An investigation into the poor performance of the full-scale Tubular Filter Press in the textile application and subsequent pilot-plant studies, concluded that:

- The *real* thickened feed sludge to the Tubular Filter Press (as opposed to *synthetic* sludge) should be used to generate flux curves and predictions with respect to cake recoveries and cake production so that a more accurate estimation of the required filtration capacity can be made. This means that the thickening process including chemicals should be verified and accurately simulated for the success of the Tubular Filter Press process. The impact of pre-treatment process changes on the Tubular Filter Press process should be considered prior to the implementation of any changes.
- Sludge feed variability with respect to concentration and composition adversely affected Tubular Filter Press performance. A buffering facility should be included in the design to smooth out large variations.

Removal Of Giardia and Cryptosporidium Cysts by Tubular Filter Press

Trials, conducted on the Tubular Filter Press by spiking the sludge feed to the Tubular Filter Press with giardia cysts, indicated that the Tubular Filter Press process can form a barrier that prevents the passage of giardia cysts into the permeate. While there was excellent reduction in giardia cycts in the permeate, detection of the giardia cysts was unsatisfactory due to limitations in the analytical procedure at the time of the experiments. More process control was deemed necessary to ensure that the relatively poor quality permeate produced at the start of the run, during the cake formation and consolidation stage, is re-cycled into the feed tank until the permeate turbidity has improved and the operating pressure has stabilised.

Design procedure for The Tubular Filter Press

A design procedure for the Tubular Filter Press has been compiled. The suggested procedure incorporates preliminary laboratory characterisation of the sludge, generation of single tube pilot-plant data, field experiences on the demonstration Tubular Filter Press plant and improvements on weaknesses of previous full-scale Tubular Filter Press plant designs. Inadequacies of previous mechanical specifications have been highlighted and possible corrections recommended.

Comparison of the Tubular Filter Press with a Centrifuge

Comparison of the Tubular Filter Press with other mechanical dewatering processes, indicated that the most feasible methods for sludge dewatering in a waterworks environment are the vertical Tubular Filter Press and the centrifuge. While both processes, require intermediate thickening of the waterworks sludge, the major difference is that the Tubular Filter Press requires no further chemical conditioning, while the centrifuge requires a high molecular mass polymeric flocculant to pre-condition the centrifuge feed sludge. Comparison of the cost implications of the Tubular Filter Press including estimated capital and operating costs, indicated that there was no significant cost difference between the two options.

The Tubular Filter Press is modular in design and the dewatering capacity could be phased in as the treatment requirement increased whereas a centrifuge may be oversized for current and short term needs. Operating the centrifuge considerably below design capacity may have a significant effect on operating costs. The modular nature of the Tubular Filter Press process also means that 60 to 80% of its capacity should always be available in comparison to the centrifuge process where the inclusion of standby capacity would push the capital costs in favour of the Tubular Filter Press process. However, the cost impact of a standby capacity would be buffered by a significant reduction in the centrifuge maintenance cost component of the operating costs.

The Tubular Filter Press modular process will also be less disruptive during breakdowns relative to the centrifuge process especially when major centrifuge repairs need to be done off site.

The excellent quality of the permeate produced by the tubular filter press makes re-cycling of the permeate more attractive than (re-cycling) of the supernatant from the centrifuge operation.

While the modular design of the Tubular Filter Press presented a clear cost benefit advantage over the centrifuge, especially when the waterworks is operating significantly less than its design capacity, the high curtain replacement costs, coupled with the unproven life expectancy of the curtain weighs heavily against the Tubular Filter Press technology in favour of the more robust and proven centrifuge.

The Tubular Filter Press also suffers from the disadvantage of mechanical complexity for large-scale applications compared to the centrifuge.

The Vertical Tubular Filter Press is therefore recommended for small batch-scale operations, where other mechanical dewatering systems are uneconomical.

Tubular Filter Press For Industrial Sludges

Tubular Filter Press technology can be applied after careful investigations, to industrial applications where the sludge feed composition is uniform. Favourable results were obtained using an electroplating sludge.

Tubular Filter Press - Recommendations

It is recommended that efforts be made to improve the operation of the single tube pilot plant to make it more versatile in the production of accurate design data.
The Vertical Tubular Filter Press at the Umgeni Water Hazelmere Waterworks should be upgraded to operate as a full-scale plant with two curtain modules. The unit will easily

handle present dewatering requirements where sludge production is very much lower than the design capacity of the centrifuge. Important operating data and experience pertaining to the Tubular Filter Press performance during 24-hour operation and curtain life, may be obtained. Only through continuous operation, under plant operating conditions, can the curtain life be assessed.

It was further recommended that a variety of different woven fabric material suitable for filtration should be tested on a laboratory-scale before any follow up research is considered.

Design Procedure for Cross-flow Microfiltration

Investigations into design protocols for cross-flow microfiltration systems produced a cost-effective procedure for the accurate estimation of the required filtration area for the sizing of a cross-flow microfiltration unit. It was concluded that:

1. For the design of a microfiltration system, where the final conditions are exactly known, the average flux method may be used because of its simplicity and accuracy.
2. Where the final conditions are unknown, the rigorous method is appropriate, since more reliable concentration-time and flux-time profiles are obtained with the rigorous method.

Further Work on Design of Cross-flow Microfiltration systems

The design procedure for cross-flow microfiltration should be tested more rigorously using real suspensions. Trials need to be performed on a range of non-newtonian slurry types including biological and gelatinous suspensions.

Closure

This work, including others that are referenced in this report, has shown that tubular woven fabric technology has potential for application as alternate processes for solids liquid separation especially in the water industry.

For sludge dewatering, the tubular filter press has produced favourable results with certain waterworks sludges, where the type of upstream treatment chemicals used and the raw water profile produced a sludge that was more amenable to dewatering by woven fabric technology. Similarly, it has been shown that Tubular Filter Press worked well on some industrial sludges (electroplating) and poorly on others (textile sludges).

For water filtration, cross-flow microfiltration have been shown to produce high quality potable water in water treatment applications and good separation and concentration of valuable material in certain niche industrial applications.

Finally, it is important to note that tubular woven fabric technology requires individual consideration for each application. As environmental issues become more serious and the momentum to delivery of potable water to per-urban and rural areas increases, tubular woven fabric technology will become more and more relevant to the water industry, especially small system applications.

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The Evaluation and Design of Sludge Dewatering and Water Filtration Systems Using Tubular Woven Fabric Technology.

The Steering Committee responsible for this project consisted of the following persons:

Dr G Offringa............................... Water Research Commission (Chairman)

Mr GN Steenveld......................... Water Research Commission

Mr GH du Plessis......................... Sasol

Mr SA Pieterse............................. City of Cape Town

Mr J Linde................................... Rand Water

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Prof CA Buckley.......................... University of Natal, Durban

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Dr GE Rencken............................ Vivendi Water

Mr EJA Coopmans....................... Explochem

Mr G Gericke............................... Eskom Technology Research & Investigation

Prof WA Pretorius........................ University of Pretoria

Ms S Chetty................................. Water Research Commission (Committee Secretary)

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Nomenclature

A	area of plane perpendicular to the direction of filtrate flow, (m^2)
$\overline{A}$	plant membrane area, (m^2)
C_{2b}	final concentration of the batch, (g/l)
CF_F	final concentration factor
C_{2i}	initial concentration, (g/l)
C_b	particle concentration in the bulk suspension, (g/l)
C_w	particle concentration at the wall, (g/l)
C_1	constant, (-)
C_2	solute concentration at time, t, (g/l)
$\tilde{J}$	average flux, (l/m^2h)
J_F	final flux, (l/m^2h)
J_O	initial flux, (l/m^2h)
$J(x)$	local permeate flux, (l/m^2h)
J_n	normalised flux, (l/m^2h)
J_r	permeate flux at reference temperature = 25 ^oC, (l/m^2h)
J_T	permeate flux at arbitrary temperature, T, (l/m^2h)
J	permeate flux, (l/m^2h) or (LMH)
K	permeability, (m^2)
L	length of tube, (m)
P_l	liquid pressure, (Pa)
ΔP	pressure drop, (Pa)
Q	volumetric flowrate, (m^3/h)
Q_{in}	flowrate of stream entering the module, (m^3/h)
Q_F	flowrate of feed stream, (m^3/h)
Q_P	permeate flowrate, (m^3/h)
$R_c(t)$	cake resistance, (1/m)

$R_m(t)$	membrane resistance, (1/m)
R	radius of tube, (m)
s	empirical constant, (-)
T	temperature, (^oC)
t	batch processing time, (s)
t_c	cake thickness, (m)
t_{perm}	the time taken to collect a quantity of permeate, (s)
U_s	crossflow velocity, (m/s)
V_F	final volume, (m^3)
V_o	initial batch volume, (m^3)
V_p	volume of permeate, (m^3)
WR	water recovery, (-)
X	distance from medium, (m)

Greek Symbols

α	specific cake resistance, m/kg
μ	fluid viscosity, (Pa.s)
ρ	liquid density, (kg/m^3)
ν	kinematic viscosity, (m^2/s)
μ_f	liquid viscosity, (Pa.s)
ρ_s	particle density, (kg/m^3)
μ_T	viscosity of permeate at measured temperature, (Pa.s)
μ_{ref}	viscosity of permeate at reference temperature, (Pa.s)

Abbreviation

BSA	bovine serum albumen
CFMF	cross-flow microfiltration
CSA	capillary suction apparatus
CST	capillary suction time
DIMDAAC	dimethyl-diallyl-ammonium chloride
PLC	programmable logic control
TFP	tubular filter press
WRC	water research council

Terminology

Cake Production Rate	dry solids in the dewatered cake expressed as a function of dewatering cycle or run time.
Cake Recovery	dry mass of the filter cake collected during a dewatering cycle or run expressed as a percentage of the total feed solids.
Cake Resistance, α	measure of the ability of the cake layer in the filter tube, to resist the flow of liquid through the cake, at a constant pressure.
Cake Solids	dry solids mass of the filter cake determined by drying in an oven maintained at 130°C.
Curtain	an array of filter tubes. There are 13 tubes per curtain.
Dewatering cycle	time measured from the start to the filtration cycle to the end of the tube cleaning or flushing cycle.
Filter Cake	dewatered sludge that collects in the filter tube during filtration.
Final Permeate Flux	also called end flux, this is the flow rate of the permeate per m^2 of filtration area (m^3/m^2h).
Volatile Solids	the organic component of the cake solids normally determined by volatilising a dried cake solids sample in a furnace maintained at 600^0C.

1. Introduction

The Pollution Research Group of the School of Chemical Engineering, University of Natal, in collaboration with the Water Research Commission of South Africa and Umgeni Water pioneered research in South Africa in the application of tubular woven-fabric technology in South Africa. A tubular configured sludge dewatering process was developed by Treffry-Goatley *et al* of the pollution research group in 1987, under a Water Research Commission funded project. Fundamental research in tubular woven application intensified during this period in sludge dewatering (Rencken, 1992) and water filtration (Pillay, 1992).

1.1 Findings of Previous Work – Sludge Dewatering

Initial pilot-plant studies, undertaken on lime kaolinite and underground mine water slurries, indicated that the process had a wide application in industry (Rencken, 1988).

1.1.1 Horizontal Tubular Filter Press

Work on the innovative sludge dewatering process culminated in the installation of a prototype of a new and locally designed sludge dewatering process at Umgeni Water’s HD Hill Waterworks in Pietermaritzburg. A patent was granted to the WRC (Patent Number 87/0553). The (horizontal) Tubular Filter Press Unit at H.D. Hill waterworks was in operation for about 4 years from 1987 until it was shut down in 1991, due to operational strategic reasons and the imminent closure of the Waterworks.

During the operation of the plant various problems were identified that required some fundamental changes to the design. The manifold design, tube size and the horizontal orientation of the array of tubes were found to be the main causes for down time and poor plant performance.

1.1.2 Vertical Tubular Filter Press

There was sufficient confidence in the Tubular Filter Press technology to motivate for further investigative work including pilot and full-scale plant work, especially in those topics mentioned previously. It was envisaged that in addition to its application for the dewatering of waterworks sludge, the tubular filter process can provide good quality potable water. A proposal made to the Water Research Commission (WRC), for a project to pursue further experimental work at Umgeni Water's Process Evaluation Facility, was accepted by the WRC. The main objectives of the project initiated in 1994 were:

1. To improve the design of the Tubular Filter
2. To develop a commercially operational unit for waterworks sludges
3. To assess the performance of the new design by extended operation during the project.
4. To assess the use of the new design for potable water production.
5. To develop techniques for determining design parameters for the Tubular Filter Press by extending the filtration model proposed by Dr. Rencken and incorporate this into a design procedure.

The deficiencies in the previous prototype at HD Hill were corrected in the new design. A single tube Vertical Tubular Filter Press pilot-plant with a larger tube diameter was constructed and tested.

Following favourable results from the single tube pilot-plant, a demonstration model, PLC controlled Vertical Tubular Filter Press with two curtains (13 tubes each) was constructed at Wiggins Waterworks in Durban in 1995.

The performance of the filter was satisfactory with cake concentrations between 20 and 32 percent solids (m/m), and solids recoveries up to 75 percent. Filter performance was found to be dependent on sludge characteristics, which in turn were largely influenced by raw water turbidities and treatment chemicals. It was found that the inclusion of bentonite as a coagulant aid in the water treatment process during times of low raw water turbidity resulted in poor sludge filter performance. The addition of lime to a waterworks sludge improved sludge filterability but had a negative impact on the woven tube .

A new generalised *Area Contact* model has been proposed for the constant pressure compressible cake filtration. A predictive model has been developed for design and troubleshooting purposes.

The vertical tubular filter press trials for the production of potable water, indicated that the process was unsatisfactory for potable water in comparison with cross-flow microfiltration. The use of the new vertical configuration operating in *dead end* mode was therefore not recommended for potable water treatment.

Some of the more important recommendations of the report covering this work were the testing of this technology on different waterworks sludges and operation of the filter on a more continuous basis at another site to get operators and maintenance personnel more intimately involved with the day-to-day running of the Tubular Filter Press. It was considered important to solicit their input for future designs. It was also recommended that the applicability of Tubular Filter Press to the dewatering of industrial sludges be further investigated, especially textile sludges.

1.1.3 Rationale for further work

The development of the Tubular Filter Press for the dewatering of waterworks solids (WRC report 568/1/98) concluded that the process was capable of dewatering waterworks solids although the efficiency of the process depended on a number of factors (mainly the nature of the solids). There were however some limitations in the marketing of the process for full-scale application. These revolved mainly around the long-term operability of the process including operational and maintenance costs and filter response to changing sludge characteristics.

Furthermore, a standard design protocol had not yet been established. There was therefore a need for experience in the practical aspects of the technology including development of appropriate laboratory-scale tests for the assessment of sludge suitability to dewatering by Tubular Filter Press, establishment of some correlation between laboratory-scale results and pilot-scale results, filter material fouling and durability and identification of mechanical weaknesses in the Tubular Filter Press process.

A number of techniques have been developed over the past 10 years to establish characteristics of sludges and assess the suitability of the Tubular Filter Press technology for solids dewatering. The design procedures needed to be assessed and compiled in a form that can be used to efficiently assess the application of the Tubular Filter Press for a particular application. These procedures would then be tested on a number of sludges from different potential applications and the design methods optimised. A comparison of the operating costs of the Tubular Filter Press and other dewatering equipment was needed to provide valuable information to assess the competitiveness of the new technology.

From a marketing perspective the application of the Tubular Filter Press is not limited to waterworks solids. Prior to this project a plant was installed at the effluent plant of a textile manufacturer. Its cost effective operation was not sustainable, and it was therefore critical to the success of further applications that the reasons for the poor performance be identified. Future applications therefore require careful selection criteria and investigation prior to design and installation of a full-scale plant. Different potential applications need to be identified and carefully investigated.

Following the completion of WRC project K5/568, the assets from the project were transferred to Umgeni Water. These included a large-scale vertical Tubular Filter Press for waterworks solids dewatering with its associated equipment. A number of design changes had been implemented since the initial vertical curtain Tubular Filter Press was constructed. Other areas in the operation of the Tubular Filter Press also required attention for continuous operation. These needed to be assessed and a final design documented.

The input from operations and maintenance personnel is invaluable in the final assessment and design of a new process. The relocation of the demonstration Tubular Filter Press to a waterworks where the sludge produced was amenable to dewatering by the Tubular Filter Press process, was considered vital for the development of the Tubular Filter Press technology.

For a wider market, the applicability of Tubular Filter Press to other sludges other than waterworks sludges required to be investigated. Industrial sludges especially textile and mining sludges may be suitable for dewatering by Tubular Filter Press. The comparison of Tubular Filter Press performance to other dewatering processes used in the water industry also needed to be investigated.

1.2 Findings of Previous Work - Filtration

Microfiltration had been shown to produce excellent quality potable water and had been recommended as a pretreatment process for reverse osmosis and nanofiltration (Jacangelo and Buckley, 1996). Crossflow microfiltration is widely used in the concentration of particulate suspensions and the separation of solids. Due to the economic advantage of this process compared to conventional processes such as centrifugation and clarification, etc, the market for this technology has shown a progressively increasing demand in recent years. The process has produced promising results in recovering valuable material from effluents in a number of industries (Govender, 2003).

However despite the considerable amount of industrial work on microfiltration very little information is available in the literature on design of full-scale plants using data obtained from laboratory tests.

1.2.1 Rationale for Further Work

Unlike other models developed for reverse osmosis and nanofiltration, etc, no predictive models have been developed to date for microfiltration that enables the design of a full-scale system. For a real system, designers generally rely on performing laboratory experiments to generate data required for design. This is often a time consuming and tedious task as there is a scarcity of relevant information on the experimental protocol and procedure for data processing and application to design.

The need for a suitable design procedure is therefore essential and forms the rationale for this study.

Usually in design, the primary variable is the membrane area required to treat the desired capacity of the full-scale system. This is usually obtained from laboratory experiments in the following ways:

In the first approach, experiments are performed at constant concentration over a range of concentrations. Constant concentration occurs when both the permeate and retentate are returned to the feed tank, or simply when the concentration in the feed tank remains constant during the run. The laboratory tests are conducted to determine the degree of separation that can be achieved and also to evaluate the influence of operating variables such as pressure, crossflow velocity and feed composition on performance. From this, the relationships between permeate flux and concentration can be determined. This is then used to infer a flux from the constant concentration experiments which is subsequently used to determine the membrane area required for larger scale operations.

In the second approach, the average flux approach is used whereby a laboratory-scale batch concentration is performed. This involves concentrating a suspension from a specific initial concentration to a specific final concentration. From this, the average flux can be determined and used to predict the membrane area required for the full-scale unit.

The overall objective of this study was to evaluate these approaches for the design of full-scale microfiltration systems and recommend a cost-effective procedure that will assist in the prediction of the performance of a full-scale unit for estimation of the filtration area requirement.

1.3 Aims of the Project

The aims of this study were to:

1. Review all the laboratory techniques used in previous projects for obtaining design parameters for the Tubular Filter Press process. Document a specific design procedure for the effective design of plants for specific applications.
2. Investigate other potential applications for the use of the Tubular Filter Press. Adopt the design procedure to perform laboratory-scale investigation using existing pilot-plant equipment to investigate these applications.
3. Install and operate a Tubular Filter Press at one of the Umgeni Water waterworks to compare the operation to that of other waterworks solids dewatering equipment (centrifuge).
4. Critically examine the application of the Tubular Filter Press in the treatment of textile effluent, and investigate the reasons for problematic operation.
5. Compile the results of the pilot plant testing for the application of the Tubular Filter Press to waterworks sludges. Compare these results to the installed design. Monitor the process performance and document aspects of the operation useful for future applications in this field. This would include (if possible) an assessment of the long-term curtain replacement and maintenance requirements.

6. Study the mechanical design of the Tubular Filter Press technology, review the modifications made to the design, address perceived weaknesses in the design.
7. To establish the applicability of the “constant concentration approach” and “average flux approach” to predict the performance of a microfiltration system.
8. To develop a protocol to design full-scale microfiltration units from pilot plant experiments.

2. Laboratory-Scale Sludge Characterisation Tests

Before a particular process is considered for an application, some initial screening tests are generally performed, either on a laboratory batch-scale or continuous pilot plant-scale. The outcome of these tests are used for decision making on the suitability of the process with respect to a number of factors including cost, sustainability and environmental impact. The results of these preliminary tests may also be used for the sizing of the proposed equipment.

The rheological characterisation of non-newtonian sludges (viz. waterworks, industrial and wastewater sludges) pose a challenge due to its variability and inconsistency. The development of this discipline is on-going (Slatter, 2001). Data on shear stress versus shear rate were generated, for the two waterworks sludges (Wiggins and Hazelmere Waterworks) using sophisticated equipment at the Cape Technikon, department of Civil Engineering. The results showed some differences between the two sludges but were inconclusive with respect to dewatering performance by tubular filter press. Due to the huge costs attached to the shear stress versus shear rates measuring equipment, further work was discontinued.

The use of particle analysis for sludge characterization was considered impractical due to the limitations with respect to available particle counting equipment handling of high concentration sludge samples. Dilution of the sludge samples will alter the characteristics of the sludge particles.

Due to the variable and settling characteristics of the sludge, conventional laboratory physical testing equipment were ineffective in producing reliable, reproducible results. Therefore much effort was invested in the development of simple laboratory tests.

2.1 Development of Suitable Tests

In order to adequately determine the sludge characteristics for modelling and plant design, laboratory experiments were set up to measure the filterability of the sludge. Experience has shown that the measurement of filterability is not entirely adequate to determine whether the Tubular Filter Press process is suitable for dewatering of a particular sludge. The identification and development of suitable laboratory tests for sludges was challenging due to the variable nature of the sludge both physically and chemically.

2.1.1 Viscosity

Various methods of measuring the viscosity of sludge were considered and although not the most appropriate, it was decided to use the Saybolt viscometer. The recommended method for sludges is a capillary tube viscometer to determine the true shear – stress relationship for non-newtonian slurries (Holman,1989). The viscosity as a single value (assuming Newtonian behavior) may be adequate to differentiate sludges at the same solids concentration.. Methods considered include:

1. **Rotating Concentric Cylinder** - This type of apparatus consists of two cylinders. An inner stationary cylinder which is attached to a torque measuring device and an outer cylinder which is driven at a constant angular velocity. The liquid is placed in between the two cylinders. The annular space must be sufficiently smaller than the radius of the inner cylinder for the movement of the fluid in the annulus to be compared to that of fluid moving between two parallel plates. This apparatus was considered unsuitable due to the fact that the sludge may settle between the two rotating cylinders.
2. **Falling Sphere Method** - This method involves dropping a sphere in a fluid and measuring the time taken for the sphere to pass a set distance and hence obtain the velocity of the falling sphere. This type of measuring device would not be suitable because sludges with low concentrations could settle in this long cylinder and it would be difficult to observe a falling sphere in a sludge.
3. **Capillary Tube Viscometer -** The capillary tube viscometer is the most commonly used method of measuring viscosity. It consists of a long thin tube and the rate of flow and pressure drop across this tube is measured.

This measurement is done for laminar flow of the fluid in the tube. Tube lengths of up to 8 m were used when measuring the viscosity of sludges. The height of the tube posed a problem hence it was decided not to use this type of measuring device.

4. **Saybolt Viscometer** - This type of viscometer is used in industries and uses the capillary-tube principle of measuring viscosities of liquids. The cylinder is filled to the top with the liquid to be measured and this cylinder is enclosed in a constant temperature bath. This is to ensure constant uniformity of temperature when recording the viscosity of the fluid.

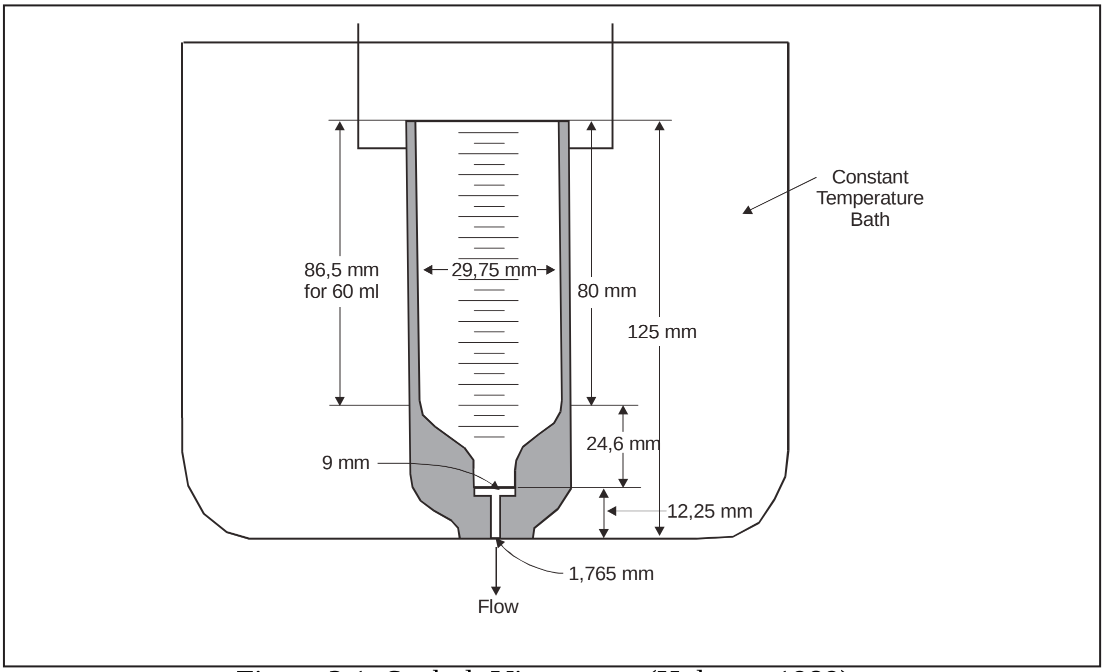

Figure 2.1: Saybolt Viscometer (Holman, 1989)

A cylinder is filled to the top with the fluid and enclosed in a constant temperature bath to ensure uniformity of temperature during measurements. The fluid is then allowed to drain from the bottom through the short capillary tube. The time take to drain 60 ml of the fluid is recorded and this time is taken as indicative of the viscosity of the fluid.

Since the capillary tube is short, a fully developed laminar-viscosity profile is not established. If the velocity profile were fully developed, kinematic viscosity would vary directly with the time of drainage.

$$\upsilon = \frac{\mu}{\rho} = c_1 * t \qquad \text{.......................................2.1}$$

where ν – kinematic viscosity

μ = absolute viscosity

t = time of drainage

c_1 = constant

To correct for the non-uniform velocity profile, another term is added to the above equation and the following equation is obtained:

$$\upsilon = c_1 * t + \frac{c_2}{t} \qquad \text{...2.2}$$

After inserting the constants, the final equation for kinematic viscosity is obtained:

$$\upsilon = \left[0.00273 * t - \frac{1.93}{t}\right] \times 9{,}2903 \times 10^{-5}\ m^2/s \qquad \text{..........................2.3}$$

$$\upsilon = \frac{\mu}{\rho} \qquad \text{...2.4}$$

And the absolute viscosity is obtained from equation 2.1.

Due to the compact nature of this device and ease of operation, it was decided to use the Saybolt viscometer to measure the viscosity of sludge.

2.1.1.1 Laboratory Experiments using the Saybolt Viscometer

The Saybolt viscometer was not readily available locally. A glassblower was commissioned to manufacture the equipment, complete with a temperature control vessel into which the viscometer was immersed for maintenance of a constant temperature environment for the test sample. The capillary dimensions were specified to match dimensions in Figure 2.1 (Holman, 1989).

Due to the dependence of viscosity on sample concentration (Figure 2.2) a narrow sludge concentration range was selected for comparison purposes. The concentration range for viscosity measurement corresponded with the acceptable feed solids range (25-30 g/l) for the tubular filter press (TFP).

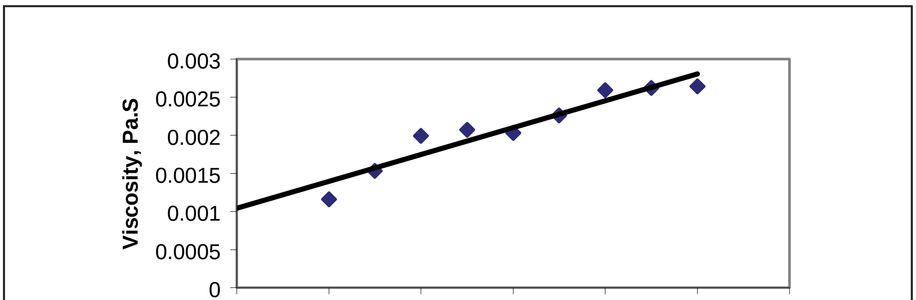

Figure 2.2: Effect of Waterworks Sludge Concentration on Viscosity at 25^{o}C

2.1.2 Planar Filtration

The planar filtration apparatus is essentially a laboratory pressure filtration unit where a fixed volume of sludge is filtered under a constant pressure. The filter media is similar to the polyester cloth used for the Tubular Filter Press tubes. The volumetric filtrate flowrate is monitored for the duration of the filtration time. For planar filtration the expression describing the liquid pressure gradient for a fluid flowing through a porous medium is given by:

$$\frac{dp_l}{dx} = \frac{\mu_f Q_f}{Ak} \qquad \text{..3.2}$$

Where:
μ_f = liquid viscosity, (Pa.s)
Q_f = volumetric flowrate of filtrate, (m^3/s)
χ = distance from medium, (m)
P_l = liquid pressure(Pa)
A = area of plane perpendicular to the direction of filtrate flow, (m^2)
k = permeability, (m^2)

An important parameter derived from this experiment is the specific cake resistance, also called specific resistance to filtration (SRF). The specific cake resistance describes the filterability of the sludge under a constant compressive pressure.

The planar filtration apparatus (Figure 2.3) is a simple cylindrical pressure filter with an air inlet on one end and the polyester cloth filter media mounted on the other end. A pressure regulator controls the desired pressure.

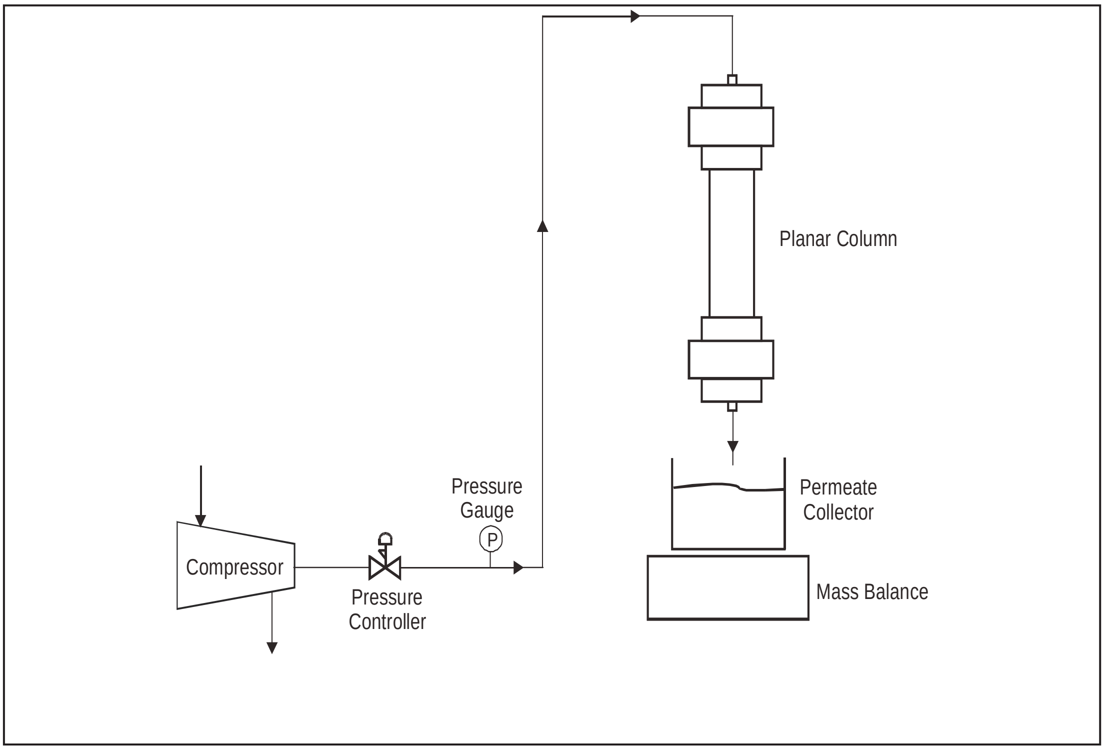

Figure 2.3: Planar Filtration Apparatus

2.1.2.1 Sludge Planar Filtration Rate Profile

Planar filtration experiments were initially conducted on two different waterworks sludges. These included sludges from Wiggins Waterworks and Hazelmere Waterworks. These sludges are produced by the addition of synthetic blended polymeric coagulants (poly DIMDAAC's blended with polyamines and poly aluminium chloride) to the raw water for turbidity removal. Single tube pilot plant filtration tests indicated that Hazelmere sludge dewaters better than Wiggins sludge. Cake solids recovery and production rates were higher for Hazelmere sludge in comparison with Wiggins sludge. However planar filtration profiles (Figure 2.4) showed no significant differences between the two waterworks sludges, indicating that planar filtration profiles were not good indicators of Tubular Filter Press performance.

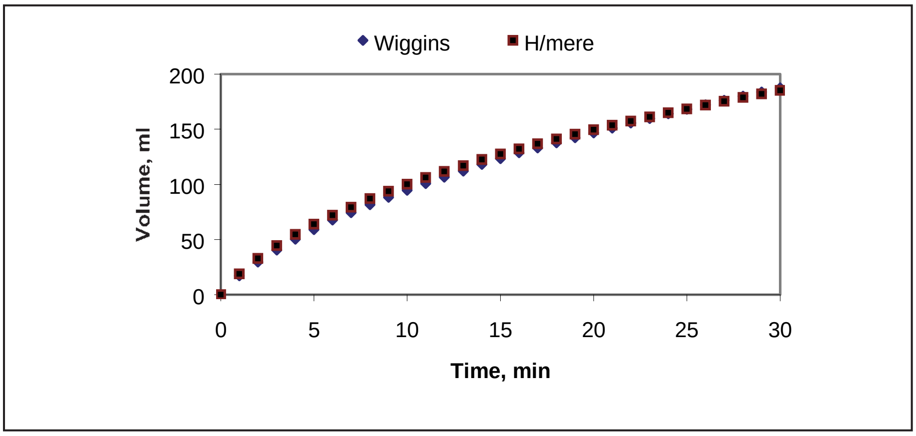

Figure 2.4: Comparison of Waterworks Sludge Filtration Rate Profile for Planar Filtration at 250 kPa Constant Compressive Pressure

2.1.2.2 Effect of Bentonite on Waterworks Sludge Filterability

Previous experience (WRC report No 568/1/98) has shown that the addition of bentonite in the water treatment process had a negative effect on sludge dewaterability by Tubular Filter Press. The addition of bentonite in Wiggins raw water due to low turbidities resulted in poor cake recoveries and production rates. No bentonite was added to the Hazelmere raw water. Planar filtration tests were run on Hazelmere waterworks sludge samples both before and after the addition of bentonite .

Figure 2.5 shows that the planar filtration profile of Hazelmere sludge is not significantly affected by the addition of bentonite.

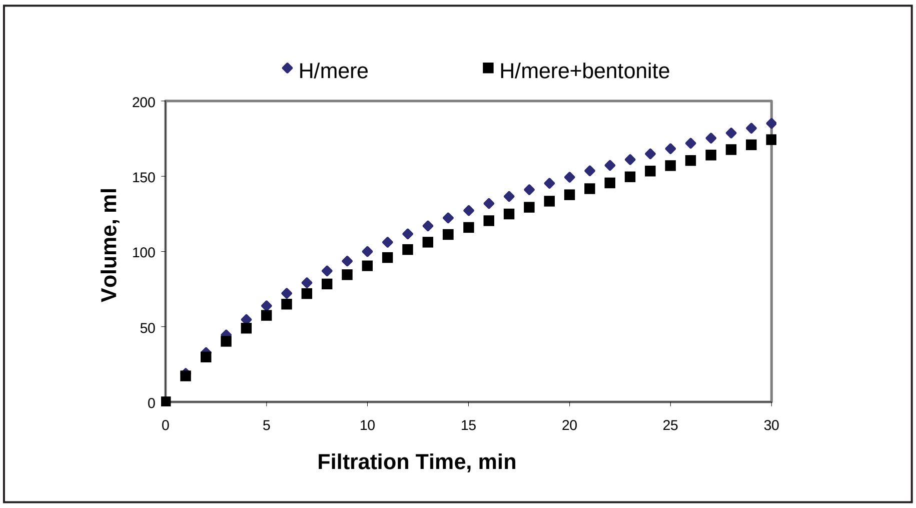

Figure 2.5: Effect of Bentonite on the Planar Filtration Profile of Hazelmere Waterworks Sludge

2.1.3 Capillary Suction Time

The capillary suction (Triton WPRL Type 92/1) apparatus (Figure 2.6) is a simple means of determining the ease with which a sludge releases free unbound moisture i.e filterability. Bound moisture is the residual moisture in the sludge (cake) after the dewatering process. The capillary suction apparatus measures the capillary suction time taken for the free moisture in a constant volume of sludge to move an annular fixed distance, between two concentric rings, on a special chromatographic paper. The higher the capillary suction time, the slower is the release of unbound moisture.

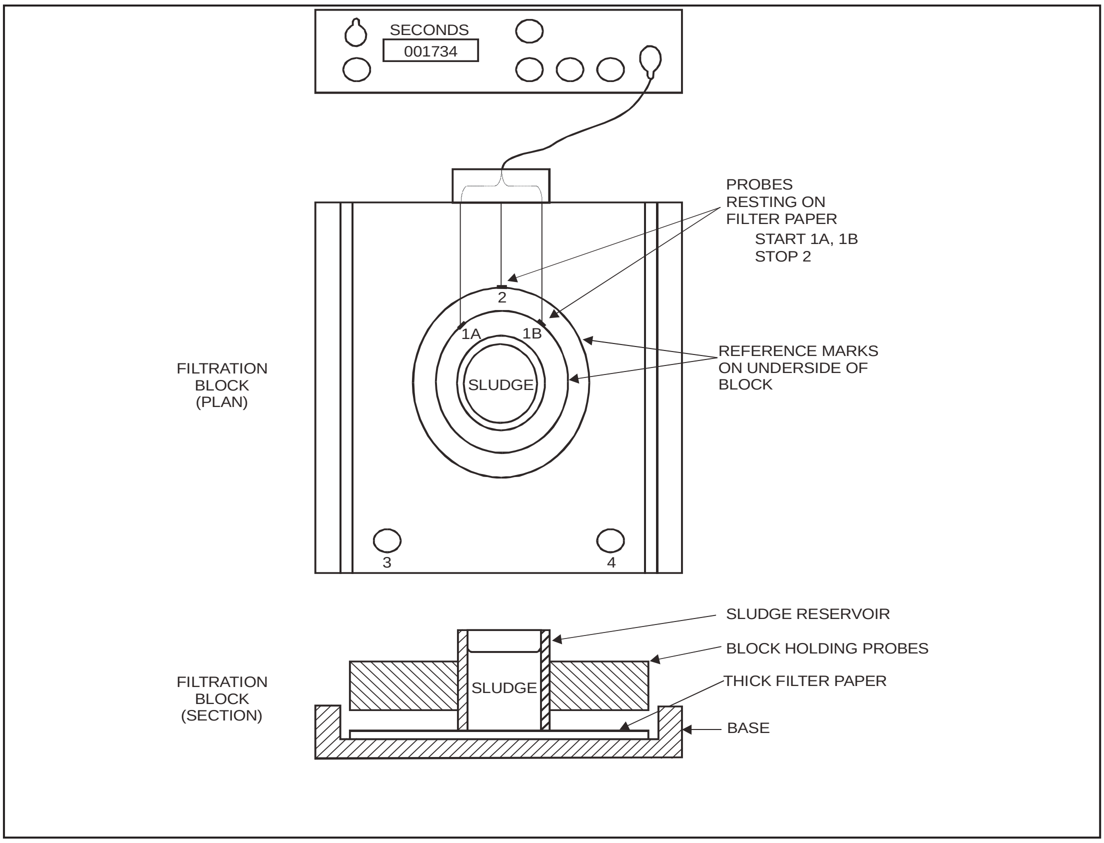

Figure 2.6: Capillary Suction Time Apparatus

Investigations were conducted with sludge samples to determine how CST measurements relate to sludge dewaterability.

Previous work (WRC Report No 568/1/98) had shown that the presence of bentonite in waterworks sludge adversely affected dewatering by Tubular Filter Press. It is also known that the addition of lime significantly improved the dewaterability of sludge containing bentonite. Therefore, CST and viscosity measurements were made after incremental additions of bentonite to waterworks sludge. The results are shown in Figure 2.7.

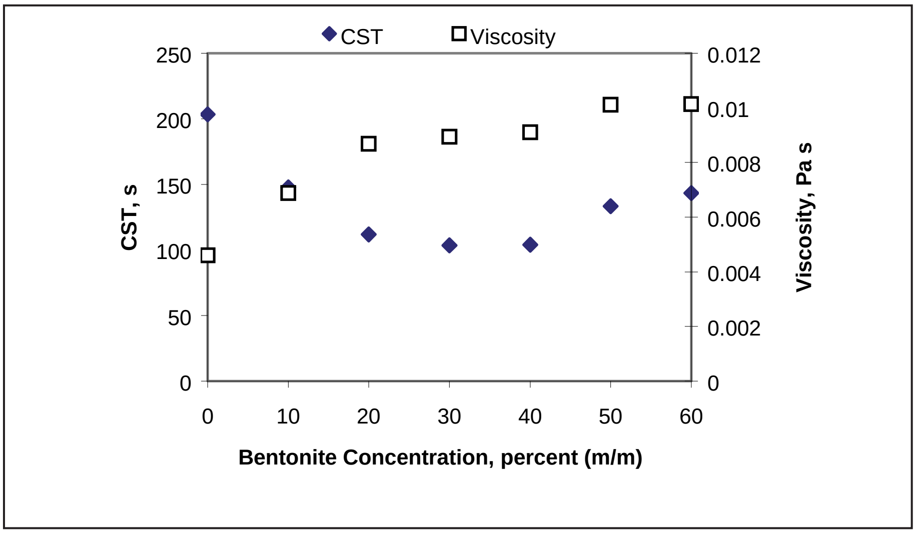

Figure 2.7: Effect of Incremental Addition of Bentonite to Waterworks Sludge on CST and Viscosity

As expected bentonite addition increased the viscosity of the sludge up to the 20% bentonite concentration level. Thereafter, the rate of viscosity increase with bentonite addition was relatively slow. In a waterworks sludge, the concentration of bentonite does not exceed 20% (m/m).

Single-tube pilot plant and Tubular Filter Press demonstration plant trials have shown that the presence of bentonite in the feed sludge adversely affects dewatering performance by Tubular Filter Press. However, CST measurements appear to show the opposite effect i.e that bentonite initially increases water release by the sludge, implying an apparent improvement in filtration.

Figure 2.8 shows the effects of incremental lime addition to a waterworks sludge. From the results presented it was concluded that the addition of lime into the sludge had no significant effect on either CST measurements, or the viscosity.

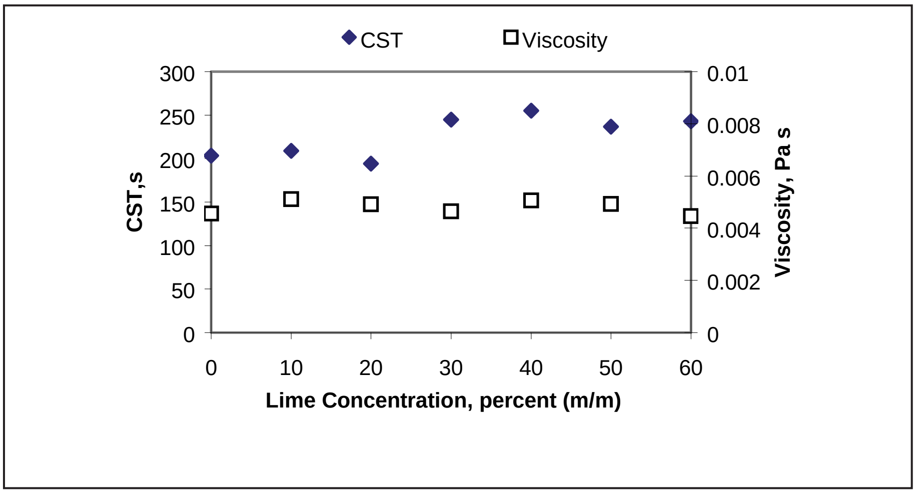

Figure 2.8: Effect of Incremental Addition of Lime in Waterworks Sludge on CST and Viscosity @ 25°C

The experiments were useful in showing that CST results should be interpreted and used cautiously, especially in the presence of bentonite. The use of absolute CST values has severe limitations especially when the sludge being characterised contains a relatively large amount of bound water, bentonite or lime. In general CST readings should be used to indicate relative trends rather than absolute values.

2.1.4 Volatile Solids

Sludges with high organic content have been found to produce poor cake recoveries. For sludges with high organics (due to its stickiness), cake removal from the tubes becomes progressively more difficult and inefficient until the cake formation stage becomes so short that virtually no cake forms.

Volatile solids are the organic component of the total solids in the sludge. It was anticipated that a correlation would be obtained between the volatile solids of the sludge and the parameters that define the dewatering efficiency of the Tubular Filter Press. Volatile solids are determined by volatising a known mass of the dried sludge cake solids in a furnace maintained at 600^0C. The resultant weight loss is the volatile solids expressed as a percentage of the dry solids. The error in volatile solids measurements, determined experimentally, was 10% (relative).

Figure 2.9, shows a typical relationship between cake recovery and volatile solids for a waterworks sludge. The graph indicates that the range within which volatile solids vary in a waterworks sludge does not appear to have a significant impact on cake recovery.

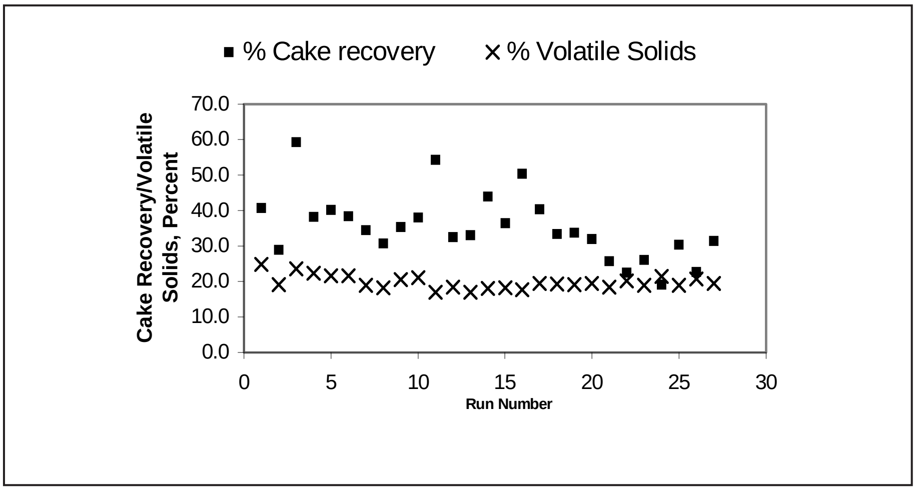

Figure 2.9: Relationship Between Cake Recovery and Volatile Solids

2.1.4.1 Viscosity and Volatile Solids

A relationship between the volatile solids, being the organic component of the total cake solids, and the sludge viscosity within a suitable concentration range and at a temperature of 25^0C, was investigated. Figure 2.10 shows the variation in viscosity and volatile contents for various sludge samples. The relatively wider spread of viscosity data contributed to the poor correlation between viscosity and volatile solids (Regression coefficient, R^2 = 0,05). The fact that viscosity measurements are dependant on sludge concentration and volatile solids are independent of sludge solids concentration also contributed to the poor correlation.

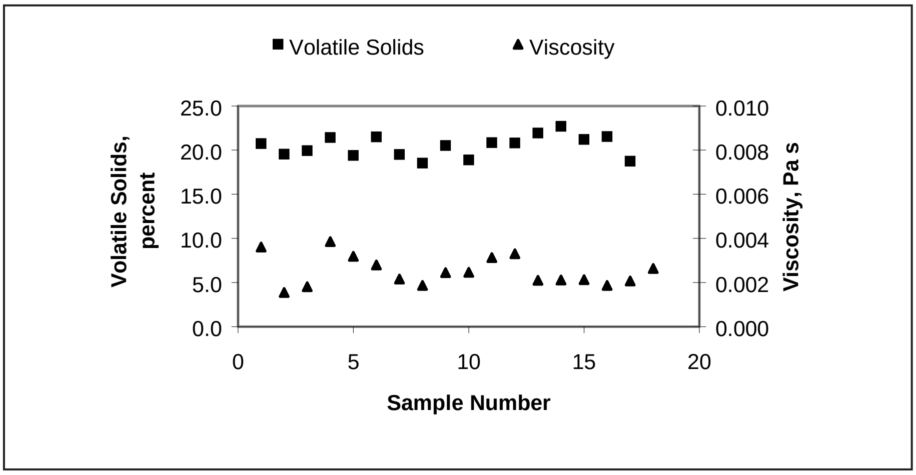

Figure 2.10: Variation of Waterworks Sludge Viscosity @ 25°C with Volatile Solids

2.2 Summary of Laboratory-scale Tests

A number of laboratory-scale sludge characterisation tests were evaluated and modified for application to waterworks and effluent sludges. These included viscosity, volatile solids, capillary suction time (CST) and planar filtration tests.

Comparison of the laboratory results with Tubular Filter Press performance data indicated that there was often an insignificant difference in a laboratory determinand (viz viscosity, volatile solids) for a significant difference in Tubular Filter Press performance. Hazelmere sludge dewatered better than Wiggins sludge, however, the relative difference in the respective laboratory tests were not significant and reproducible.

The accuracy of the tests excluding volatile solids were also affected by concentration and the settling nature of the sludge.

The results of the tests are meaningful when interpreted collectively, and relative changes are considered (as opposed to absolute results). Analysis of the results indicate that the laboratory tests especially planar filtration tests, may be useful as an initial screening tool, to establish whether a sludge is amenable to dewatering by Tubular Filter Press.

3. Tubular Filter Press Plant Operation

Previous work (WRC Report No 568/1/98) showed that sludge dewatering by Tubular Filter Press produced promising results in terms of cake solids and production rates.

Further experiments and trials on the single tube pilot-plant and the larger demonstration plant, as part of the current project, shed light on the operating limits of these variables. The raw water quality, especially turbidity at the two waterworks from which the test samples were drawn, viz. Wiggins Waterworks and Hazelmere Waterworks, had changed significantly compared to the period when the previous work (WRC Report No (568/1/98) was done. The raw water chemical and biological attributes (during the present study) are presented in the appendices. Turbidity measurements are indications of the suspended solids concentration in the water and these were significantly lower during this study.

Waterworks sludge characteristics are strongly influenced by the concentration and type of chemicals added in the treatment process chain. The chemicals used in the treatment process are lime (for pH correction) and polymeric organic coagulants. The coagulants used in the waterworks when test sludge samples were taken for tubular filter press trials, were organic polymerised DIMDAAC's blended with polyamines and polyaluminium chloride. Bentonite, a coagulant aid, is also used during times of low turbidity.

The dewatering capability of the tubular filter on three different waterworks sludges and industrial sludges was evaluated using the single tube pilot-plant. An assessment of the correlation between results obtained from the continuous operation demonstration tubular filter press plant and the batch-scale single tube pilot-plant was also made.

3.1 Operating Parameters

The effects of the main variables on dewatering performance were investigated. These variables included operating pressure, feed concentration, final permeate flux (before inception of tube cleaning). The efficiency of the cleaning sequence was also investigated and optimised.

3.1.1 Feed Concentration

Low feed solids concentrations were experienced (under 15g/l) which produced uneconomically low cake recoveries and long filter runtimes. Cake removal by flushing was also inefficient at the low feed solids concentrations. Very high feed concentrations (greater than 40 g/l) on the other hand also resulted in poor dewatering performance. Short filter run times, due to inefficient cleaning, resulted in poor cake consolidation on the inside of the tube. Operating experience indicated that a feed concentration range between 20 and 30 g/l, was suitable for dewatering by Tubular Filter Press. The procedure has therefore been to either dilute or concentrate the feed sludge so that its concentration is between the working concentration range (20 to 30 g/l).

3.1.2 Operating Pressure

The operating pressure affects the process in a number of ways. Higher compressive pressures (greater than 300 kPa) result in relatively shorter filter run times and lower mass of solids in the tubes for the same end flux and consequently lower cake recoveries. Higher pressures are also not recommended from a safety point of view. One needs to operate well below the bursting pressure of the tubes which has been roughly found to be between 500 and 600 kPa. Lower operating pressures (less than 250 kPa) also resulted in poor cake deposition in the tube because the compressive pressure was too low to form a compact cake that will withstand the erosive effect of the feed and flushing fluid velocities. The end result is a mushy cake that passes through the pores of the conveyor belt during the cake removal stage. A number of tests carried out at different pressures indicated that operating pressures between 250 and 300 kPa gave the best results.

3.1.3 Cake Removal

In the operation of the Tubular Filter Press process, at the end of the ‘dead-end’ filtration or cake formation stage, pressure in the system was relieved by opening the outlet valve at the bottom tube manifold. This action caused the tube to collapse and facilitate the separation of the filter cake from the tube. It was noted that most of the cake was removed during the flushing action.

Cake removal in the single tube pilot-plant was achieved by pulsing the dirty tubes with feed sludge at high flush flow rates for short durations. It was noted that over 99% cleaning efficiency was achieved by flushing. The larger demonstration Tubular Filter Press had an auxiliary cleaning facility in the form of a roller mechanism. The roller action squeezed the tubes as it moved down the tubes at the last flushing cycle. Tests indicated that the roller mechanism was not necessary especially if the filtration cycle was optimised to allow for a longer pressurisation time resulting in greater consolidation of the cake in the tubes. The flushing duration was 5 seconds at a flow rate of approximately 6 m^3/h per tube (velocity 0,24 m/h). The removal of the roller mechanism was beneficial to the Tubular Filter Press system by reducing the complexity of the Tubular Filter Press operation and capital costs. It further added to the safe operation of the unit.

3.1.4 Final Permeate Flowrate or End Flux

The filtration rate at constant pressure is momentarily at its maximum at the start of the run, and then rapidly declines as cake formed in the tube increases the resistance to filtration. The final permeate or end flux is the flowrate of the permeate per square metre of filtration area, at the end of the cake formation stage and onset of the cleaning (flushing) stage. The end flux is an important operating parameter because it controls the cake formation run time and contributes directly to the cost-effectiveness of the Tubular Filter Press dewatering process. Setting a high end flux results in a short cake formation time that may be insufficient for proper cake consolidation in the tubes. The result of a high end flux may be a thin mushy cake that is easily re-slurried and transported back into the feed tank by the flushing fluid. On the other hand, low end fluxes lead to excessively long filtration times that may be detrimental to the process in two important ways. Firstly, the cake production rates are poor due to the long filter run length at the low filtration rates towards the end of the cake formation stage. Secondly, excessive solids loading in the tubes may lead to tube blockages and tube damage. Generally for a 20 to 30 g/l waterworks sludge, an end flux between 40 and 60 ℓ/m^2h. that provides a filtration run time between 20 and 30 minutes, produced acceptable cake recoveries and dewatering performance for compressive pressures in the range 250 to 300 kPa.

3.2 Single Tube Pilot-Plant Trials

The single tube pilot-plant (Figure 3.1) is an important tool for characterising the sludge and determining whether or not the Tubular Filter Press process can dewater the given sludge cost-effectively. The pilot plant is manually operated but simulates the cake formation and cake removal stages in the dewatering process. There are obvious differences between the single tube and the demonstration full-scale plant, in that the demonstration plant has an array of 13 tubes (curtain) connected to an inlet and outlet manifold. The demonstration tubular filter press is PLC controlled and is a continuous operation system. The single tube pilot-plant is a manually operated plant.

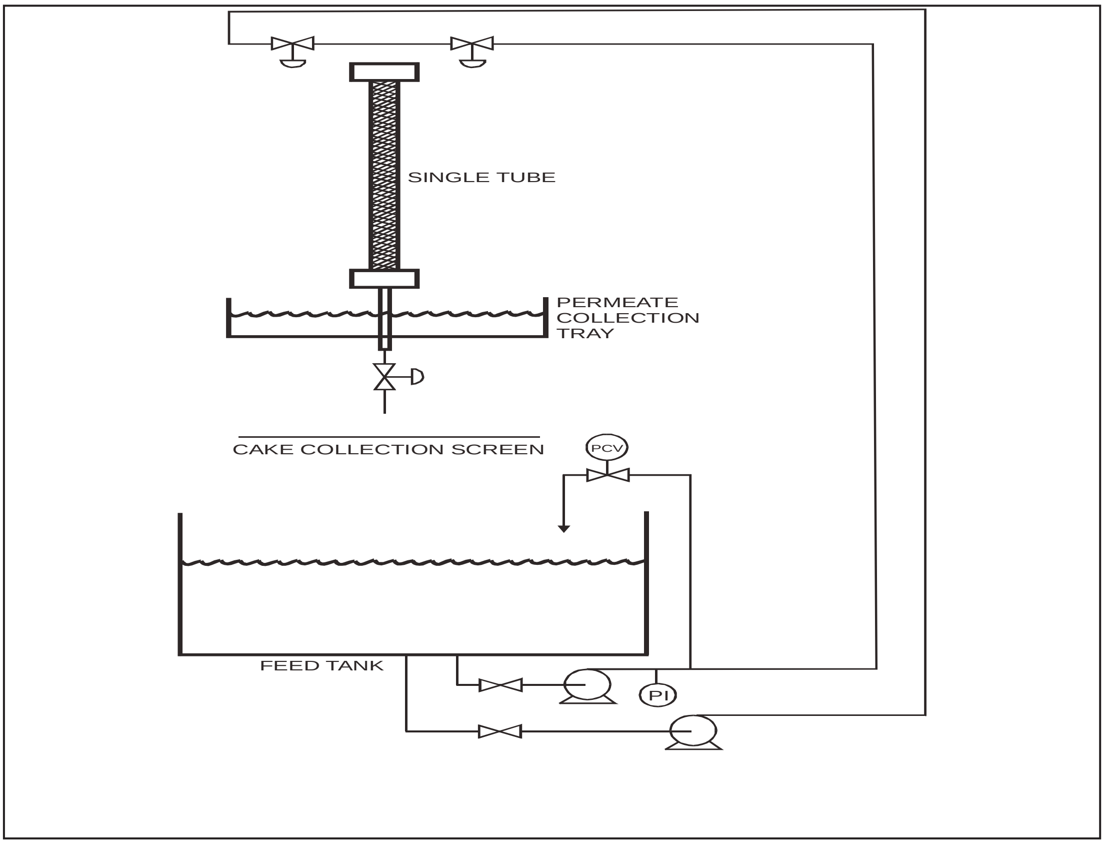

Figure 3.1: Process Flow Diagram of The Single Tube Pilot Plant

Figure 3.2: The Single Tube Pilot Plant

3.2.1 Comparison of Waterworks Sludges

A number of experiments with three different waterworks sludges (all polymer based) were conducted using the single tube pilot-plant. Laboratory sludge characterisation tests were conducted on the same samples to establish a possible correlation between the results obtained from the single tube pilot-plant trials with those obtained from laboratory characterisation tests. The average results for the different waterworks sludges are presented in Table 3.1.

Table 3.1: Comparison of Waterworks Sludges

Determinand	Units	Midmar Waterworks	Hazelmere waterworks	Wiggins Waterworks
Laboratory Tests				
Concentration	g/l	26	27	25
Viscosity	Pa.s	0.004119	0.00458	0.00467
Volatile Solids	Percent (m/m)	16 - 19	20 - 21	24 - 32
Filterability (CST)	S	47	203	168
Specific Cake Resistance (Planar Filtration)	m/kg x 10^{11}	2.6 - 2.8	2.6 - 2.8	3.4 - 3.5
Single Tube Tests				
Cake Recovery	Percent	61	55	45
Cake Production	kg/h	5.8	4.1	2.8
Dry Solids	Percent	23	20	13
Dry Solids Production	kg/h	1.3	0.81	0.37
Specific Cake Resistance	m/kg x 10^{13}	3.1 - 3.4	3.8 - 4.4	4.0 - 4.3
Waterworks Treatment Chemicals				
Raw Water Turbidity	NTU	3 -5	3 - 4	0.5 -2
Coagulant Dose	mg/l	3 - 4	1 - 2	2 - 3
Bentonite	mg/l	0	0	1-2
Lime	mg/l	6 - 8	2 - 3	1 - 2
Thickener				
Flocculant dose	mg/l	1	1	0
No of Runs		50	100	165

Table 3.1, indicates some correlation between the dewatering performance of the sludges from the different waterworks and the respective laboratory tests. The single tube results indicate that the Midmar sludge and the Hazelmere sludge dewaters better by Tubular Filter Press than the sludge from Wiggins. This is deduced from the relatively higher cake recovery for Midmar (61%) and Hazelmere (55%) compared to Wiggins (45%). The cake production rate also follows the same trend i.e Midmar (1.3 kg/h dry solids) and Hazelmere

(0.81 kg/h dry solids) have higher cake production rates than Wiggins (0.37 kg/h dry solids).

The specific cake resistance results obtained from the planar filtration tests also indicated that the Midmar sludge and the Hazelmere sludge dewater better than the Wiggins sludge because the Wiggins sludge had the lowest cake resistance. However, the specific cake resistance obtained from the single tube data, appears to contradict the planar filtration trend.

Comparison of the volatile solids indicates that the Midmar sludge has the lowest volatile solids with Wiggins sludge showing the highest organic content.

Viscosity measurements further indicated that Midmar sludge was the least viscous with Wiggins sludge being the most viscous. As concentration and temperature was found to be an important variable affecting viscosity, they were kept constant for the sludges tested. Since there was no significant difference in the concentrations of the sludge samples, it may be deduced that the viscosity measurements were related to the organic content of the sludge. The specific cake resistance calculated from planar filtration data showed a trend of increasing cake resistance with increasing volatile solids and viscosity.

The capillary suction time (CST) test that measures the filterability of a sludge sample produced inconclusive results.

3.2.2 Comparison of Single Tube Pilot Plant Results With Tubular Filter Press Full-scale Plant

The main purpose for single tube pilot-plant trials was to investigate the possibility of comparing and correlating the results obtained from the single tube pilot-plant to the results obtained from the full-scale demonstration Tubular Filter Press plant. It was envisaged that a good correlation between the pilot plant and the full-scale plant will greatly improve prediction of full-scale performance from small scale pilot-plant trials resulting in more cost-effective design and specification of full-scale Tubular Filter Press plants.

For purposes of comparison, parallel tests were run on the full-scale demonstration continuous operation Tubular Filter Press and the single tube batch scale Tubular Filter

Press. Sludge feed concentrations ranged between 24 and 28 g/l and the operating pressure was constant at 250 kPa for both the units.

3.2.3 Cake Recovery

Figure 3.3 shows a wide spread of data points for the cake recoveries, with the full-scale plant yielding greater variances compared to the single tube pilot-plant. Inconsistencies in the demonstration plant results may be attributed to a combination of reasons. The more significant reasons were the relatively poor control of the operating pressure, blinding of the cake conveyor when more cake is deposited and the errors associated with taking a representative sample for cake solid determination and cake mass.

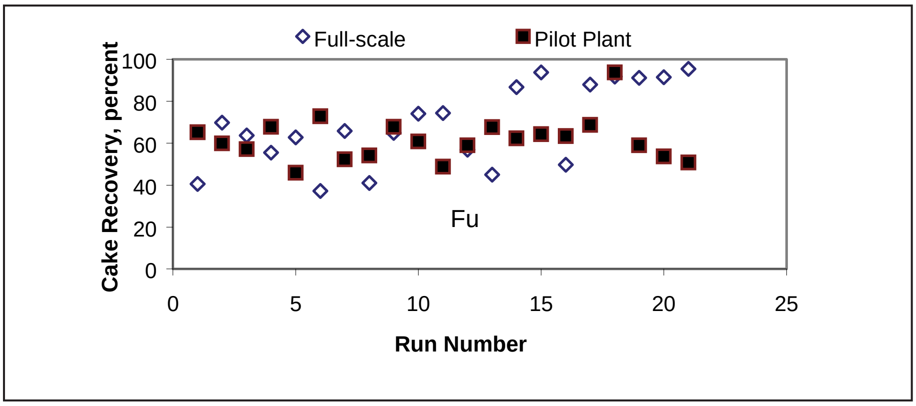

Figure 3.3: Comparison of Cake Recovery Between the Full-scale Tubular Filter Press and the Single Tube Pilot Plant

3.2.4 Cake Production Rate

Figure 3.4 shows that there was an acceptable correlation in cake production between the demonstration tubular filter press plant and the single tube pilot. Under carefully planned experimental conditions and controlled operating parameters, single tube data may be used for full-scale design with reasonable confidence. The cake production rate may be optimised by careful selection of the terminal flux so that a suitable filtration run time is obtained.

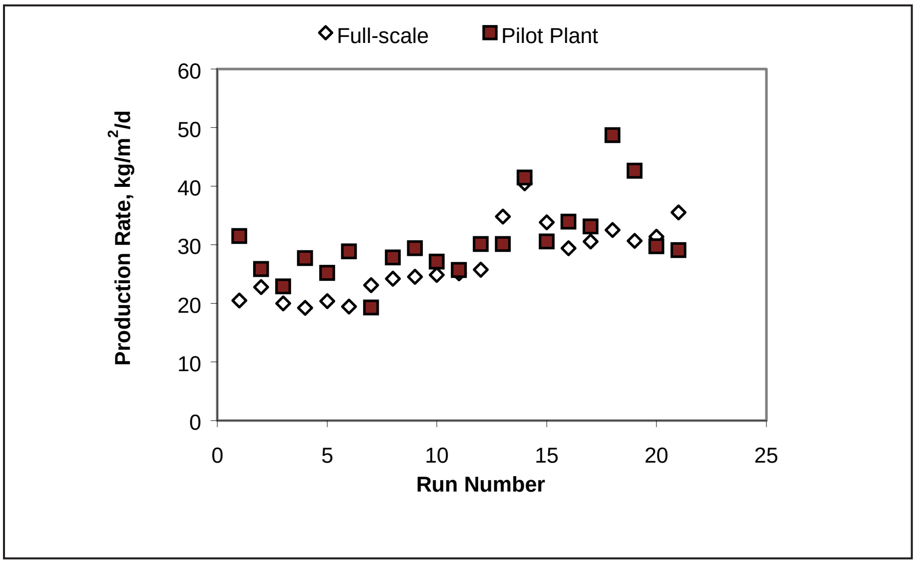

Figure 3.4: Comparison of Cake Production Rates Between the Full-scale Tubular Filter Press and the Single Tube Pilot Plant

3.3 Application of Tubular Filter Press to Industrial Sludges

The applicability of Tubular Filter Press to the dewatering of industrial sludges was further investigated. Based on developmental work from previous projects, Tubular Filter Press technology was used in the dewatering of a textile sludge and a mining sludge, both with limited success. The reasons for the poor dewatering performances in both these cases related to Tubular Filter Press process issues as well as other issues relating more to the consistency and composition of the feed sludge that were outside the control and specifications of the Tubular Filter Press process.

3.3.1 Mining Sludge Containing Hexavalent Chromium

A large chromium smelting operation in South Africa produced an effluent with fine particles which was collected and pumped into slime dams. Problems were experienced with the handling of the effluent and its disposal in a cost-effective and environmentally friendly way.

The project team was involved in the initial testing of the effluent on a pilot plant scale. The main objectives of the investigation were to obtain reliable data for the design of a full-scale Tubular Filter Press.

A number of single tube pilot-plant experiments were performed and some good correlations were obtained. Results indicated that the final cake concentration was between 50 and 55%. Modelling of the single tube operation, indicated that there was an acceptable correlation between the experimentally determined *volume filtered versus filtration time profile* and the model predictions.

Cake thickness is an important operating parameter because if it is not controlled, tube blockages and premature tube damage can occur. It was proposed that the cake thickness should not exceed 10 mm (one-third the tube radius) to allow sufficient tube volume for effective cleaning and removal of the cake after filtration. A filtration time between 10 and 15 minutes was recommended.

On the basis of data from the single tube pilot-plant, a full-scale Tubular Filter Press plant was designed and commissioned for dewatering the chromium (VI) sludge. As mentioned previously, a chemical process that converted Cr(VI) to Cr(III) was the pre-treatment step for the Tubular Filter Press. The efficiency of the pre-treatment process was very important as the Cr(VI), a strong oxidising agent, was known to attack the tube material and cause premature material wear and tear.

The performance of the Tubular Filter Press on the chromium (VI) sludge was characterised by high cake recoveries and cake solids (50 – 55%). Because the sludge filtered easily, the feed solids and the end flux was carefully controlled to reduce incidences of tube blockages. The feed solids concentration was controlled by continuous monitoring of the feed sludge density. Dilution water was introduced to maintain the feed density between suitable limits.

The 20 curtain Tubular Filter Press system, was fitted with larger manifold blocks. Each tube was fitted with a suitably sized orifice plate, on the feed side to ensure even velocity distribution especially during the cleaning cycle. ‘O’ ring inserts were groove moulded into the resin block for better sealing. More space was allowed between the curtains for ergonomic and practical reasons. Each module was made up of one curtain as opposed to three curtains per module in the textile application. The adjustable bottom manifold made it easier to tension the curtain and allowed for greater tolerance in the length of the tube.

The dewatering process worked very well initially but problems were experienced later. There were two main problems.

- The sludge pre-treatment process was not efficient enough to completely reduce Cr(VI) in the effluent to Cr(III). The accumulation of unreacted Cr(VI) attacked the curtain material and reduced the curtain life drastically. Curtains were reported to fail within a week.
- Plant personnel added a polymeric coagulant to the sludge in the gravity thickeners. The underflow from the gravity thickener was then fed into the Tubular Filter Press. This resulted in poor cleaning of the tubes with consequent tube blockages and tube failures.

Plant management obtained a permit to discharge the sludge into sludge lagoons. The tubular filter press operation was discontinued, pending the efficient conversion of Cr(vi) in the effluent to Cr(iii).

3.3.2 Other Potential Applications for the Tubular Filter Press

Following the limitations in sustainable performance of full-scale application of Tubular Filter Press technology to a textile and a mining sludge, laboratory tests and single tube tests were carried out on a textile and electroplating sludge. The main purpose of this exercise was to establish whether the laboratory test results that characterise the sludge, can be used to predict the amenability of the sludge to dewatering by Tubular Filter Press.

3.3.2.1 Electroplating Sludge

A comparison of the single tube results (Table 3.2) for the waterworks sludge and the electroplating sludge indicated that the electroplating sludge dewaters as easily as the waterworks sludge. This is evident from the similarity in the cake recovery and cake production rate for the two sludges. However, laboratory tests for the two sludges indicated a relatively wider difference in their characteristics. The electroplating company uses a *plate and frame* dewatering unit that appears to produce a drier cake.

3.3.2.2 Textile Sludge

Sludge characteristics had changed from the time a fullscale Tubular Filter Press was operated at the textile plant to when the present trials were conducted.. A critical examination of the performance of the full-scale Tubular Filter Press in the treatment of textile effluent and possible reasons for its poor performance, is included later in this section. At the time of sampling (for the present study) and for the duration thereof, sludge pre-treatment included flocculation with alum, sludge thickening by dissolved air flotation (DAF) and further conditioning with a cationic polyacrylimide before dewatering by centrifuge. Samples for the single tube tests were taken before the thickened sludge entered the centrifuge. Plant personnel at the textile company reported that the centrifuge produced a relatively dry cake (33%).

The textile sludge sample taken for the single tube pilot-plant tests was viscous and organic in appearance. As the results in Table 3.2 indicate, the textile sludge dewatering by Tubular Filter Press was very poor, with cake recoveries as low as 13%. Comparison of sludge characteristics between the electroplating sludge that dewaters satisfactorily and the textile sludge indicates that poor dewaterability may be due to the high organic content in the textile sludge (85%).

Table 3.2: Laboratory and Single Tube Tests for Industrial Sludges

	Units	**Waterworks Sludge**	**Electroplating sludge**	**Textile Sludge**
Laboratory Tests				
Concentration	g/l	27	27	27
Viscosity	Pa.s	4.6×10^{-3}	4.7×10^{-3}	5.2×10^{-3}
Volatile Solids	Percent	20	28.1	84.5
Filterability, CST	s	203	93	275
Specific Cake Resistance (Planar Filtration)	$\times 10^{11}$ m/kg	2.6 – 2.8	1.0 – 1.2	5.4 - 5.6
Single Tube Results				
Cake Recovery	Percent	55	55	11
Cake Production Rate	kg/m^2h	1.81	1.61	0.36
Cake Solids	percent	20.0	18.3	21.3
Specific Cake Resistance	$\times 10^{13}$ m/kg	3.8 – 4.4	1.4 – 1.7	13.5 - 20

3.3.3 The Removal of Giardia by Tubular Filter Press

The contamination of recycle water in a waterworks with cryptosporidium and giardia cysts is a concern, especially where the raw water source is known to contain significant numbers of these cysts. The occurrence of Cryptosporidium and Giardia in the impounded surface water in South Africa is low. In order to assess the performance of the filter for Giardia removal 50 l of wastewater works sludge which contained Giardia cysts was homogenised with a batch of waterworks sludge in the feed tank. During filtration, 10 l samples of the filtrate were collected at 3 minute intervals. During the initial investigation (Run 1 and Run 2 in Table 1) only samples of the sludges and the permeate were analysed.

Table 3.3: Initial Operation to Quantify the Removal of Giardia cysts

	Spiked Waterworks Sludge			**Permeate Collected**		
	Vol. (l)	**Solids Conc. (g/l)**	**Giardia Conc. (Cysts/l)**		**Turb. (NTU)**	**Giardia Conc. (Cysts/l)**
RUN 1						
Feed Tank before filtration	1900	17,2	2.1×10^5	sample 1	0,38	nd
Feed Tank after filtration	1500	19,5	$2.1 \text{ X } 10^4$	sample 2	0,20	nd
				sample 3	0,14	na
Filter Cake	24 kg	Na		sample 4	0,18	na
RUN 2						
Feed Tank before filtration	1900	18,7	1.6×10^4	sample 1	0,83	nd
Feed Tank after filtration	1622	20,2	1.1×10^4	sample 2	0,46	nd
				sample 3	0,22	na
Filter Cake	36,6 kg	Na		sample 4	0,19	na

nd - Giardia cysts not detected in sample na - sample not analysed for Giardia

The initial experiments in Run 1 and Run 2 showed that Giardia cysts were not detected in the initial and second “clear” water samples and an average permeate turbidity of 0,7 NTU was achieved. During the first two minutes of operation before sufficient solids have been deposited on the inside of the filter tubes, the turbidity of the permeate exceeds 1 NTU. Following these encouraging results a second set of experiments were performed to confirm that Giardia is significantly removed during filtration using the vertical tubular filter. Table 2 presents the results of Runs 3 - 5, including a solids mass balance to verify the performance of the filter. A sample of 50 l of wastewater works sludge containing Giardia was added to waterworks sludge in the feed tank of the filter before the experiments.

Table 3.4: Second Experiment to Establish the Removal of Giardia from Waterworks Sludges

	Spiked Waterworks Sludge			Permeate Collected		
	Vol. (l)	**Solids Conc. (g/l)**	**Giardia Conc. (Cysts/l)**		**Turb. (NTU)**	**Giardia Conc. (Cysts/l)**
RUN 3						
Feed Tank before filtration	1870	25,4	1.5×10^5	sample 1	0,92	nd
Feed Tank after filtration	1580	27,3	0.5×10^5	sample 2	0,28	nd
				sample 3	0,21	nd
Filter Cake	21,71 kg	22,6 %	0.5×10^5			
Solids Recovery	101,5 %					
RUN 4						
Feed Tank before filtration	1950	24,8	1×10^5	sample 1	0,48	nd
Feed Tank after filtration	1600	27,1	0.5×10^5	sample 2	0,24	nd
				sample 3	0,20	nd
Filter Cake	36,6 kg	22,5 %	0.5×10^5	sample 4	0,20	nd
Solids Recovery	101,5 %					
RUN 5						
Feed Tank before filtration	1850	24,5	1×10^5	sample 1	0,96	nd
Feed Tank after filtration	1420	27,7	0.2×10^5	sample 2	0,51	nd
				sample 3	0,40	nd
Filter Cake	36,6 kg	21,6 %	1×10^5	sample 4	0,31	nd
Solids Recovery	98,8 %			sample 5	0,21	nd
				sample 6	0,23	nd
nd - Giardia cysts not detected in sample				na - sample not analysed for Giardia		

Table 3.5: Analysis of Particle Trapped in the Visser Helminth Filter

	Run 3	**Run 4**	**Run 5**
100 mm filter	0	0	Na
80 mm filter	0	0	Na
30 mm filter	55	45	Na
na - sample not analysed for Giardia cysts			

The results from the second set of experiments confirmed the initial findings that the vertical tubular filter is capable of removing protozoan cysts from waterworks sludges. All the samples of permeate analysed resulted in zero detection of Giardia cysts. It should be noted that although only 20 μl of sample was exposed to the IFA determination, the reported results are an average of three determinations per sample.

The results are significant in that during the five experiments a total of 51 analyses were performed resulting in no occurrence of Giardia cysts in the permeate. The samples of waterworks sludge before and after each run were analysed to contain greater than 1×10^5 Giardia cysts per litre. The vertical tubular filter is therefore capable of achieving a 5 log reduction of cysts in a single filtration pass.

During the analysis of the filter cake samples, 50 g of wet filter cake was resuspended in tap water and made up to a volume of 1 litre. The analyses of the resulting sample show significant numbers of cells in the filter cake which verifies that the filter can effectively remove Giardia cysts form waterworks sludge during the solids dewatering. The permeate turbidity is also an indication of the quality of the filtered water resulting in an excellent removal of particles.

The vertical tubular filter shows significant advantage over other dewatering equipment with regard to the separation of protozoan particles and is therefore worth considering as an appropriate process, especially where the occurrence of Cryptosporidium and Giardia has been identified. In being able to remove these organisms from the water treatment process, settled solids and filter backwash waters can be dewatered and the permeate can be recycled back to the process. This will significantly improve the water recovery of a waterworks and result in a water saving.

3.3.4 Comments on the Poor Performance of the Full-scale Tubular Filter Press Plant for the Dewatering of Textile Sludge

The full-scale Tubular Filter Press dewatering plant in the textile application performed poorly over a period of time because the cake formed was mushy and tube cleaning became increasingly problematic. This resulted in shorter run times, poor cake recoveries and a general deterioration in the dewatering process. The client has replaced the Tubular Filter Press with a centrifuge and appeared to be satisfied with the dewatering performance. In hindsight, a number of lessons were learnt from the textile sludge dewatering experience.

- The sludge from the textile process was not available for pilot plant trials as the sludge pre-treatment process which included colour removal by iron precipitation and sludge thickening by dissolved air flotation (DAF) were not in place during the pre-design testing period. A laboratory simulated sludge was used and predictions with respect to cake recovery, cake production rate and cake solids concentration were made based on this synthetic sludge. The plant was undersized because the flux curves generated from the synthetic sludge, were not true representations of the real textile sludge.
- Effluent concentration variability impacted negatively on sludge pre-treatment control. The consequent change in feed sludge composition and concentration adversely affected Tubular Filter Press performance.
- The use of polymer to increase flux had a detrimental effect on the cleaning cycle. The sludge formed was sticky and re-slurried easily. The reslurried sludge returned to the feed tank and increased the feed concentration, resulting in shorter run times.
- Sealing of the tubes was unsatisfactory especially at higher compressive pressures (between 300 and 400 kPa). High effluent alkalinity had a detrimental effect on the polyester cloth of the filtration tube and drastically reduced tube life.

3.4 Summary of Single Tube Pilot-Plant and Full-scale Tubular Filter Press Plant Trials

1. Single tube pilot-plant studies on three waterworks sludges, indicated that dewaterability by Tubular Filter Press can vary significantly amongst the sludges and that dewaterability performance is primarily dependant on type and quantity of treatment chemicals added during the water treatment process and the raw water characteristics.
2. Results from pilot plant work on three industrial sludges, showed that the Tubular Filter Press technology has potential in some applications such as electroplating sludges. It is very important that exhaustive preliminary tests are conducted on the sludge over a reasonable period of time to cover sludge variability and upstream process worst case scenarios and their impact on Tubular Filter Press performance. As mentioned earlier, the Tubular Filter Press process is very sensitive to relatively small changes in measurable sludge characteristics like viscosity and volatile solids.
3. Investigation of poor performance of a full-scale Tubular Filter Press in a textile application and subsequent pilot plant studies, found that upstream pre-treatment process has a significant impact on tubular filter press dewatering performance and therefore exhaustive tests are required to understand the effects of variable feed chemical characteristics and concentration on dewatering efficiency by tubular filter press.
4. Trials, conducted on the Tubular Filter Press that involved spiking of the sludge feed to the Tubular Filter Press with giardia cysts, indicated that the Tubular Filter Press process can form a barrier that prevents the passage of giardia and cryptosporidium cysts into the permeate. Due to difficulties in the analysis and quantification of the cysts at the time of the experiments, detection of the giardia cysts was unsatisfactory. While the results looked promising, more process control was deemed necessary to ensure that the permeate produced at the start of the run, during the cake formation and consolidation stage, is re-cycled into the feed tank until the permeate quality has improved and the operating pressure has stabilised.

4. Protocol for Design of Tubular Filter Press

The use of inexpensive and rapid laboratory tests is invaluable when assessing the potential of a sludge for dewaterability by Tubular Filter Press. While the application of the test results has severe limitations when interpreted individually and when absolute measurements are considered, useful information may be obtained when the results are interpreted in combination with other tests and sludge characteristics.

4.1 Sludge Characterisation

Knowledge of the process that generates the effluent will provide vital information that may disqualify the Tubular Filter Press dewatering process for the application before further tests are undertaken. Effluent with high concentrations of high molecular mass organic polyelectrolytes should be avoided. Highly alkaline sludges and powerful oxidising agents are known to attack the polyester filter cloth and reduce tube life. Other useful information includes:

- Current cost of sludge disposal and environmental impact
- Sludge flowrates and volumes – average and peak flows
- Sludge concentrations, variability, chemical analysis reports.

4.1.1 Laboratory Sludge Characterization Tests

Historically, all off-spec products, chemical spillages and chemical tank washings were dumped into the waste drain. This mixture, which may vary considerably in strength and composition, now finds its way into the effluent and sludge plant. The sludge may collect in a sump or tank before treatment and disposal. Some chemical plants have adopted a waste minimisation strategy that makes sludge treatment simpler or even unnecessary.

Ideally about 50 litres of the thickened sludge should be taken for laboratory and single tube tests. Otherwise a larger sample may be taken at the sludge sump and thickened to the desired concentration in the laboratory. Preliminary tests include.

- Solids concentration and pH
- Viscosity

▪ Volatile Solids
▪ Planar Filtration at constant pressure (300 kPa)

Typical filtration rate decline curve that may be plotted from planar filtration data are presented in Figure 4.1.

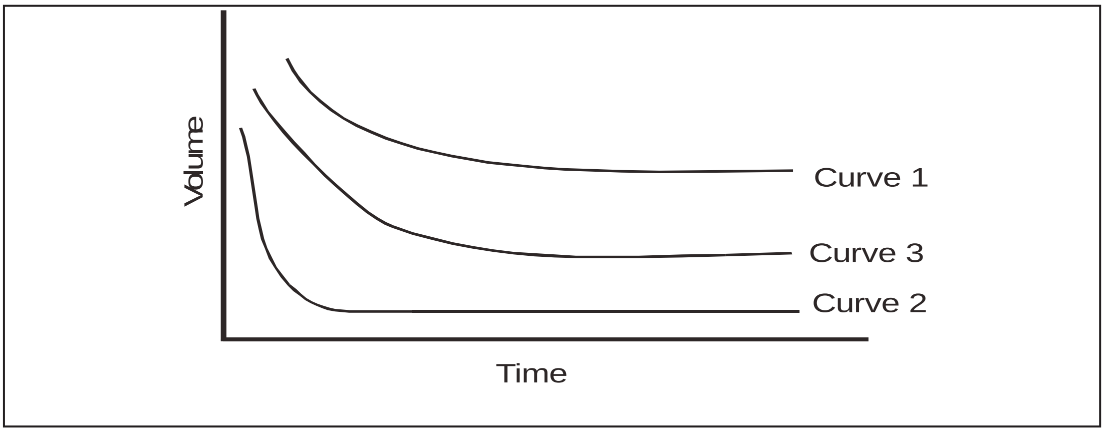

Figure 4.1: Typical Sludge Filtration Rate Decline Curves Generated from Planar Filtration or Single Tube Pilot-Plant Data

Curve (1) in Figure 4.1 tends to indicate that the sludge is largely inorganic in character and filters rapidly. This type of sludge would be unsuitable for Tubular Filter Press because it has a greater tendency to settle and cause tube blockages. Curve (2) on the other hand is probably for a highly organic sludge and would rapidly blind the filter media, resulting in poor cake consolidation and recoveries. Curve (3) presents a more favourable filtration profile for Tubular Filter Press. Viscosity and volatile solids measurements, when interpreted with the planar filtration results, will give more insight into the dewaterability of the sludge by Tubular Filter Press.

If the preliminary laboratory-scale tests indicate a potential for the test sludge to be dewatered by Tubular Filter Press, single tube pilot-plant tests may then be conducted.. The following information can be obtained from batch scale single tube tests.

▪ **Operating pressure :** The sustainability of the Tubular Filter Press process is dependant on a safe and cost-effective operating pressure. While the optimum pressure may differ slightly for different applications, operating pressures between 250 and 300kPa have generally been shown to be adequate for waterworks and industrial sludges.

- **Filtration time:** The thickness of the cake formed in the tubes is a function of filtration time and is critical to the success of the process. A large cake thickness is likely to cause tube blockages, while a thin cake layer results in poor cake consolidation in the tubes and poor cake recoveries. As a rule of thumb, the cake thickness should not exceed 10 mm (one third the radius of the tube) to allow sufficient tube volume for effective cleaning and cake removal. Actual measurements of the cake thickness can be made with a vernier slide calipers or a micrometer screw gauge.

- **Average flux:** An important design parameter for the sizing of the Tubular Filter Press plant, the average flux determines the filtration area required to dewater the proposed sludge load. The average flux must be determined fairly accurately so the sizing of Tubular Filter Press plant is both commercially competitive and the process is able to dewater the design load.

- **Terminal flux:** The filter run time is controlled by the terminal flux which is derived from the lowest filtration rate reached before initiation of the cleaning stage (section 4.1.4).

- **Cake solids:** Single tube pilot-plant experiments give a reasonably accurate estimation of the expected cake solids from a full-scale plant. Cake solids are influenced to some extent by the operating pressure and run time. In a full-scale plant, cake solids are more significantly affected by the drainage of the entrained flush fluid during cleaning as the cake is transported to the porous conveyor by the flush fluid.

- **Cake recovery:** Expressed as a percentage of the feed solids, cake recovery determines whether the dewatering process will be cost-effective and sustainable. A poor cake recovery implies that most of the solids entering the filter is recycled into the feed tank. This is wasteful from an energy point of view but also impacts negatively on the dewatering process.
- **Cake production rate:** Generally a function of the operating parameters and the sludge characteristics, cake production rate (expressed as dry cake mass/filtration area/time, kg/m^2d may be used for comparison purposes with other dewatering processes.

4.2 Operational Experience for Future Design

The design of the tubular filter press has evolved over a period of time. Solutions to operational problems were constantly incorporated into the design. The relocation of the Tubular Filter Press demonstration unit to a Waterworks site has resulted in valuable input regarding operational, maintenance and safety issues. Front view of a curtain module is shown in Figure 4.2.

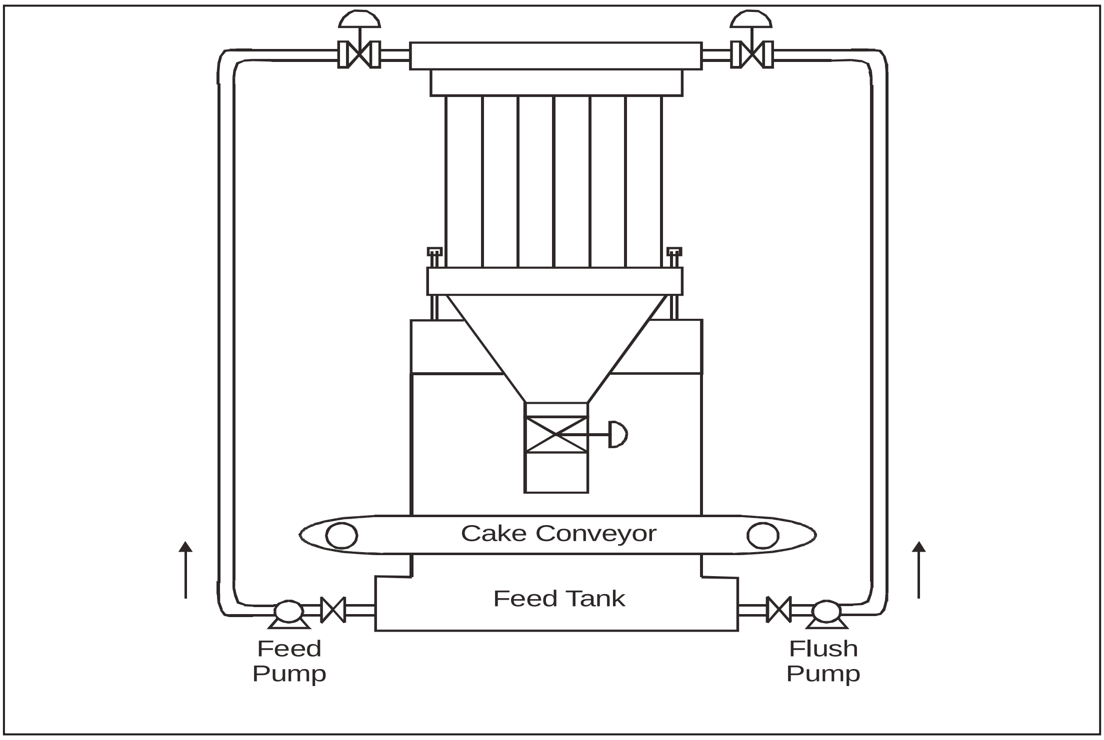

Figure 4.2: Front View of Tubular Filter Press Module

4.2.1 Modifications to Mechanical Design

The Tubular Filter Press is essentially a dewatering equipment with a large mechanical component to the design. The process has been improved to make the mechanical operation as simple and cost-effective as possible.

4.2.1.1 Roller Cleaning Mechanism

The roller cleaning mechanism in the previous design was completely eliminated. Pulse flushings at 6 m^3/h per curtain (velocity 0,54 m/s) was sufficient for efficient cleaning. Removal of the roller system drastically reduced the Tubular Filter Press capital costs and further increased the life of the curtain. Rollers were found to damage the curtain material due to the abrasive action of the metal rollers on the curtain under pressure.

4.2.1.2 Module Mould Design

The resin moulded inlet and outlet block that housed the curtain tubes were modified to correct problems associated with, sealing and tube weakness at the tube/resin block interface. A recess to fit a 5 mm diameter rubber ‘O’ ring (as shown in Figure 4.3) was incorporated in the resin block. This arrangement solved the sealing problems and eliminated the use of gaskets. Tube weakness and a poor bond between the resin block and the tubes was resolved by the use of carefully machined tube inserts at the tube ends. The polypropylene inserts prevent chafing of the tubes and block weakness. The inserts also prevented tube failures at the end of the curtains.

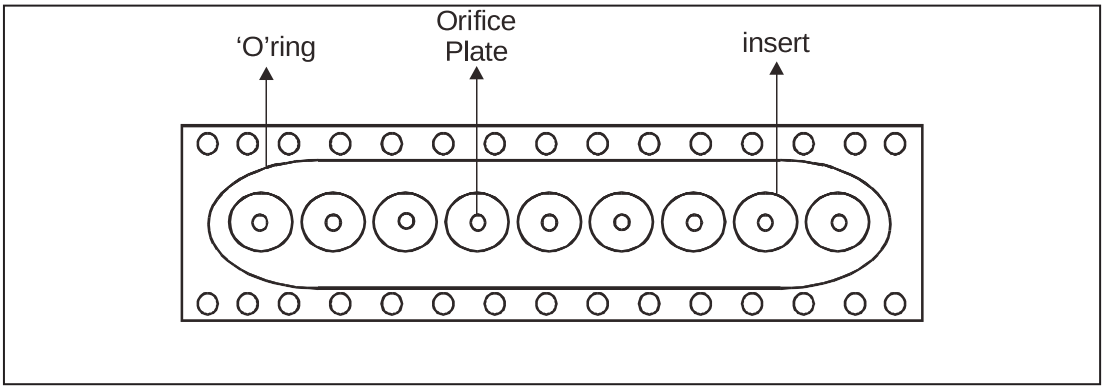

Figure 4.3: Top View of End Block Mould

4.2.1.3 Inlet and Outlet Manifold Design

Uneven flow velocities through the tubes during the flushing cycle resulted in inefficient cake removal in some tubes and ultimately lead to solids accumulation and tube blockages. Even flow distribution was achieved by installing suitably sized orifice plates on the inlet distribution manifold. The attachment of the curtain module to the mild steel manifold was also problematic due to uneven torque applied to the bolts and resin. A stainless steel plate on the module side distributed the torque evenly and prevented any leaks.

4.2.1.4 Bottom Manifold Curtain Tensioning Mechanism

After installation of the curtain module to the manifold, the curtain tension may be easily adjusted by jacking bolts attached to the bottom manifold. The previous arrangement made it necessary for the curtain lengths to be exactly the same length. This was both time consuming and difficult to achieve.

Figure 4.4: The Full-Scale Demonstration Tubular Filter Press Plant

4.2.1.5 Filter Tubes/Curtains

The polyester fabric filter curtain consists of 14 X 63 mm diameter tubes joined by a single seam. Triple seams at the ends of the curtain provide greater strength. The curtain length is 2.7 m. The curtain is sealed at the seams using a genkem fast setting adhesive (VAW 595). The sole local supplier for the curtain is Gelvenor Textiles situated in Hammasdale between Durban and Pietermaritzburg.

4.2.1.6 Feed Pump Specification and Filtration Pressure Control

The feed pump should be a positive displacement pump, capable of delivering relatively high flow rates at the beginning of the filter run and also operating safely at the low flow rates as the cake thickness in the tubes increases. Two options may be considered for the control of the filtration pressure. For a pump with no variable speed control, a bypass on the feed line with flow back to the feed tank was satisfactory for maintaining constant pressure. A pneumatic diaphragm valve on the bypass line controlled the feed flowrate to maintain a constant preset feed pressure to the curtains. The diaphragm valve required regular maintenance due to solids entrainment in the mechanism. The other option for feed pressure control was the installation of a variable speed drive mechanism. This also entailed reducing the motor drive ratio so that the motor can slow down to deliver the low flowrates. A mechanical fan was also installed to cool the motor. A variable speed controller, acting on a signal from a pressure transducer on the feed line, controlled the motor speed to keep the operating pressure constant. Problems with the variable speed option were the relatively long time the system required to reach the required pressure, and the relatively high cost of the variable speed control system. For this reason the variable speed option is not recommended.

4.2.1.7 Flush Pump and Cleaning strategy

The flush pump is a high rate centrifugal pump, specified to deliver a flush rate per tube of $6m^3h^{-1}$ (0.54 m/s). For a multiple module system, more than one flush and feed pump may be required. For operation and control purposes, a ten module system should have its own feed and flush facility. Flushing is achieved by opening and closing the flush discharge valve at 6 second intervals. About 4 to 6 flushes (pulses) are sufficient to achieve proper tube cleaning.

4.2.1.8 Control of Feed Solids Concentration

One of the disadvantages of returning the flush fluid to the feed tank, is the increasing concentration of the feed solids which in turn impacts negatively on dewatering performance. The feed concentration may be maintained within suitable limits by returning a potion of the filtrate to the feed tanks at controlled rates. A solids meter with a 4 – 20 mA signal may be used for control purposes.

4.2.1.9 Cake Collection Conveyor

The conveyor material is a highly porous and durable swiss silk type material, that allows adequate drainage of the entrained liquid back into the feed tank. The conveyor should be wide enough (1 m) to contain the fluid. Ideally the conveyor bearings should be non corrosive and sealed. To reduce the movement of fluid to the conveyor pulleys, a plate is mounted under the curtain, to distribute the flush water to the sides of the conveyor rather than the opposite ends (where the pulleys are located). A high pressure spray cleaning mechanism helps to keep the conveyor pores open. The conveyor transports the cake directly to a skip that can be removed from site for sludge disposal.

4.2.1.10 Filtration Run Time Control

As mentioned previously, filtration time (cake formation stage) is an important control aspect of the Tubular Filter Press process. The filtration time control signals the end of the filtration cycle and onset of the curtain cleaning cycle. The most effective and direct method is the use of a magnetic flowmeter installed on the discharge of the feed pump. The flowmwter signal (4 – 20 mA) is relayed to a PLC, which can stop the filtration cycle and initiate the cleaning sequence.

4.2.1.11 Automatic Control

The Tubular Filter Press is remotely controlled by programme logic control (PLC). Operator intervention is through a supervision, control and data acquisition (SCADA) system. The operating sequence is easily written into a commercial control software from a PLC supplier. The process flow diagram for the demonstration Tubular Filter Press is shown in Figure 4.5.

The Tubular Filter Press system still requires some field monitoring and operation. The cake collection skips need to be removed when full and replaced with clean skips.

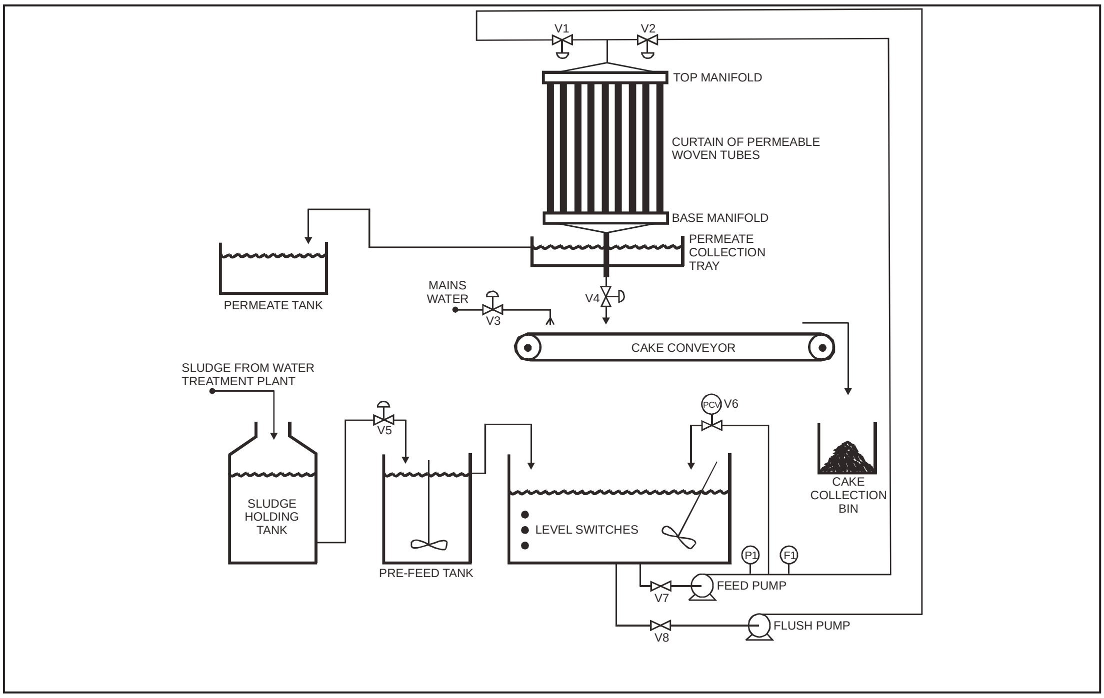

Figure 4.5 Process Flow Diagram - Vertical Tubular Filter Press

4.2.1.12 Safety and Ergonomic Considerations

During the development of the Tubular Filter Press and its operation in a full-scale waterworks environment important safety and ergonomic issues were considered to be necessary.

- Detailed HAZOP studies, incorporating all role players in the HAZOP team, should be conducted from the inception of the design to plant handover (to the Operating staff).
- Due consideration should be given to the ‘high pressure’ nature of the operation. Fittings, piping material and supports should be specified accordingly.
- Suitable ladders and walkways should be specified for maintenance access to overhead equipment and process pipework.
- Space between modules must be adequate for easy and safe access for maintenance personnel.
- Suitable screens should be provided for the curtains to prevent sludge splashing.
- Bundwalling and drainage should be included in the civil design to contain sludge spillages.

5. Comparison of the Tubular Filter Press with the Centrifuge

There are other dewatering processes that fall into the category of mechanical systems and natural dewatering systems that are available on the market. The mechanical systems include plate and frame presses, belt presses and vacuum filters. Suppliers of these mechanical equipment have not marketed them in the water industry because the characteristics of the waterworks sludge generally render them unsuitable. However, belt presses and plate and frame presses are used for the dewatering of some industrial and wastewater sludges. Natural dewatering processes like sand drying beds and lagoons are not popular in the urban and peri-urban areas due to the large surface area requirement, dependence on climatic factors and negative environmental impact.

The two most feasible alternative methods of sludge dewatering appear to be the vertical tubular filter press and the centrifuge processes. Both processes require intermediate thickening of the waterworks sludge. The major difference is that the Tubular Filter Press requires no further chemical conditioning whereas the centrifuge requires a high molecular mass polymeric flocculant to pre-condition the centrifuge feed sludge. This is especially true where polyelectrolytes are used as coagulants in the water treatment chain.

5.1 Rationale for Comparison

The basis of comparison for the two dewatering options was the Hazelmere Waterworks scenario. Valuable full-scale operating and maintenance experience was gained by relocating the demonstration Tubular Filter Press plant to the Hazelmere Waterworks. While it was hoped that the Tubular Filter Press and centrifuge could operate in parallel to obtain reliable operating data, circumstances on the plant had a negative impact on the quality and quantity of data generated. Problems were experienced with the centrifuge operation resulting in the removal of the centrifuge for repairs. The protracted delay in the repair and re-commissioning of the centrifuge resulted in a significant interruption to the plant trial. In addition to mechanical problems, sludge availability in the Hazelmere plant was low due to unusually low raw water turbidities experienced during the plant trial. As a result, the centrifuge plant was only operated for about 3 hours per a week. For a more realistic comparison between the centrifuge and the Tubular Filter Press, estimated costs are therefore based on historical data over a 10 year period.

The current sludge treatment plant at Hazelmere incorporates a gravity thickener, centrifuge and ancillary facilities. The design basis was that the turbidity of the raw water entering the plant can increase from 30 NTU to over 800 NTU in a few hours (Voortman, 1998). After consideration of the hydraulic load, at the design capacity of the Waterworks raw water flow of 45 Ml/d, the maximum design solids capacity of the sludge plant was 10.8 tons dry solids per day.

Capital costs and operating costs for the tubular filter press and the centrifuge are detailed separately. The comparison between the two dewatering systems is presented as a table incorporating both the estimated capital and operating costs.

5.2 Estimated Cost for Vertical Tubular Filter Press

The estimated cost of the vertical tubular filter press included both capital and operating costs. The filtration area required for design and cost purposes was based on the operating data obtained from the single tube pilot-plant and the demonstration Tubular Filter Press that was moved to the Hazelmere site.

5.2.1 Capital Cost

The estimate of capital costs, presented in Table 5.1, is based on the provision of a vertical Tubular Filter Press to dewater 10.8 t/d (as dry solids).

Table 5.1: Breakdown of Tubular Filter Press Capital Costs

Components	Cost in (R) Jan 2004
Mechanical (piping, mixer, compressor)	161 000
Electrical (PLC, wiring and panels)	322 000
Instrumentation (meters for monitoring plant)	161 000
Vertical Tubular Filter Press (5 modules)	1 305 000
Sub Total	**1 949 000**
Contingencies @ 20%	390 000
Estimated Total Cost (excluding fees and escalation allowance)	**2 339 000**

5.2.2 Operating Cost

The operating cost of the vertical Tubular Filter Press comprises operator intervention and supervision, process chemicals used in the gravity thickener, maintenance, power consumption, and replacement curtains. The basis of the estimate is the continuous dewatering of solids at the design capacity of 10.8 t/d dry solids. Table 5.2 shows the estimated operating costs.

Table 5.2: Estimated Operating Costs for Tubular Filter Press

Operating Cost Components	Specific Cost R/t (dry solids) Jan 2004
Labour	16
Energy	35
Maintenance and Repairs	4
Replacement of Curtains	56
Total	**111**

5.2.2.1 Labour Costs

The average daily workload of an operator is estimated to vary depending on the solids loading through the plant. During continuous operation, an operator will have to inspect the plant once every 4 hours and take samples to assess performance. Some general maintenance of the plant may be performed by the operator. During these times an operator or trained assistance may be required for up to 3 hours per day. The general worker/attendant will be required to check the sludge levels in the waste skip and move the waste skips when they are full. This work may amount to 4 hours/day when operating at design capacity. The workload is roughly proportional to 1 hour/day for the operator and 1.5 hour/day for the shift attendant.

5.2.2.2 Electricity Costs

During the operation of the vertical Tubular Filter Press at Wiggins and Hazelmere, the energy consumption was determined to be about 80 kWh/ton dry solids. There are a number of factors that influence power consumption (viz. operating pressure, feed solids concentration, etc.), each of which will influence the filtration time and the number of flush sequences per day. Data has shown that, provided that the plant is optimised, the energy consumption will be less than 100 kWh/ton dry solids. The feed pumps, supernatant return pumps, gravity thickener and other ancillary equipment are estimated to consume an additional 50 kWh of power per ton of dry solids. The cost of producing a ton of dry solids was estimated, based on the power cost of R0.23/kWh (Durban Metro’s current Business and General Tariff).

5.2.2.3 Maintenance

During operation, the curtains should be regularly checked for pin-holing and leaks. When these occur, the faulty units must be isolated and allowed to dry before the holes can be repaired with an epoxy glue. Other maintenance will include the regular servicing of the mono feed pump, centrifugal flush pump, conveyor belts and automatic valves. The gravity thickener mechanism and associated equipment will also require regular attention. It is estimated that regular maintenance may be as high as 12 hours per month. The cost of maintenance was based on the cost of a skilled artisan and an assistant.

The expected life of the curtain fabric is estimated to be two years. On this assumption 22 curtains will have to be replaced each year, at a cost of R10 000 per curtain. The total cost for the replacement of 22 curtains is therefore R220 000 per annum. This relates to R56 / ton dry solids.

5.3 Estimated Cost of Centrifuge

The capital cost of the centrifuge was based on budget prices obtained from suppliers and current operating experience of the centrifuge.

5.3.1 Capital Cost

The estimate of capital costs is based on a centrifuge dewatering plant with a dry solid capacity of 10.8 t/d. Table 5.3 shows the estimated capital cost of the centrifuge dewatering plant.

Table 5.3: Capital Cost for the Centrifuge

Component	**Cost in (R) Jan 2004**
Centrifuge	1 289 000
PLC and Instrumentation	242 000
Centrifuge Feed Pump and pipework	43 000
Poly dosing system	81 000
Subtotal	**1 655 000**
Contingencies @ 20%	331 000
Total (excluding consulting fees and escalation)	**1 986 000**

5.3.2 Operating Cost

The operating costs presented in Table 5.4 include labour, chemical, electricity and maintenance. The cost of removing dewatered sludge off site and immobilising them are not included.

Table 5.4: Operating Costs for the Centrifuge

Component	**Specific Costs R/t Dry Solids Jan 2004**
Labour	13
Chemicals	53
Energy	25
Maintenance	69
Totals	**160**

Variable costs such as electricity and chemicals depend on the amount of solids being processed. The lower the quantity of solids processed, the higher is the operating cost per ton of dry solids.

5.3.2.1 Labour

If appropriate automation is installed, it will be unnecessary for the plant to be attended on a full-time basis. Routine tasks which must be carried out include: preparation of polymer solutions, visual inspections and adjustment, sampling of solids concentration, record-keeping, start-up and shut-down of the centrifuge. Most of the tasks can be handled at shift attendant level although the operator should be responsible for inspections, adjustments, sampling and record-keeping.

5.3.2.2 Chemicals

A high molecular mass polymeric flocculant is generally added to the sludge feed to the centrifuge. Polymer consumption has been estimated at 1.5 kg/t dry solids. The current cost of polymer is R35/kg.

5.3.2.3 Energy Consumption

Power consumption, including all drives, instrumentation and lighting is calculated at 110 kWh/ton dry solids. Durban Metro’s current business and General electricity tariff is R0.23 / kWh and translates to R25/ton dry solids.

5.3.2.4 Maintenance

For chemical plants an annual maintenance cost between 2 and 6% of the capital cost is usually assumed. The centrifuge at Hazelmere was more problematic than normal therefore the maximum of 6% of capital cost was used in the maintenance calculation.

5.3.3 Comparison between the Tubular Filter Press and the Centrifuge

Allowing for a margin of error in the cost estimates it can be concluded that there is no significant difference in the combined costs between the Tubular Filter Press and centrifuge option. Table 5.5 indicates that the Tubular Filter Press is slightly more capital intensive while the centrifuge carries a higher operating cost.

Table 5.5: Cost Comparison Between Tubular Filter Press and Centrifuge

Cost Element	**T F P (R) Jan 2004**	**Centrifuge (R) Jan 2004**
Capital Cost	2 377 000	1 986 000
Operating Cost Components	**Specific Costs**	**(R/t) Dry Solids)**
Labour	16	13
Chemicals	-	53
Energy	35	25
Maintenance and Repairs	4	69
Replacement of Curtains	56	-
Total operating cost	111	160

5.3.3.1 Advantages of the Vertical Tubular Filter Press Process

The Tubular Filter Press is modular in design and the dewatering capacity could be phased in as the treatment requirement increased whereas a centrifuge may be oversized for current and short term needs. Operating the centrifuge considerably below design capacity may have a significant effect on operating costs. The modular nature of the Tubular Filter Press process also means that 60 to 80% of its capacity should always be available in comparison to the centrifuge process where the inclusion of standby capacity would push the capital costs in favour of the Tubular Filter Press process. However, the cost impact of a standby capacity would be buffered by a significant reduction in the centrifuge maintenance cost component of the operating costs.

The Tubular Filter Press modular process will also be less disruptive during breakdowns relative to the centrifuge process especially when major centrifuge repairs need to be done off site.

The excellent quality of the permeate produced by the tubular filter press makes re-cycling of the permeate more attractive than (re-cycling) of the supernatant from the centrifuge operation.

Trials, conducted on the Tubular Filter Press involved spiking of the sludge feed to the Tubular Filter Press with giardia cysts. Indications were that the Tubular Filter Press process can form a barrier that prevents the passage of giardia and cryptosporidium cysts into the permeate.

5.3.3.2 Disadvantages of the Tubular Filter Press Process

The supply of curtain material for the filter is currently negotiated through a single supplier. Since the material has to be specially woven and stitched for the Tubular Filter Press process, the minimum supply length of the fabric is in excess of 1 000 m which would require a large initial investment. The fabric then has to be manufactured into curtain elements using resin moulding blocks. The production of the finished curtain including the resin blocks on either ends of the curtain is time consuming and also requires careful quality control because the curtain represents the weakest link in the Tubular Filter Press system.

The life expectancy of the curtain fabric and the expected replacement costs, weighs heavily against the implementation of this technology, especially as a cost-effective and reliable fabric supply has not been established. While there is no guaranteed source of spare curtains for the Tubular Filter Press although local manufacture is possible, mechanical spares for the centrifuge are available in South Africa.

Data on prolonged continuous operation of the Tubular Filter Press, has indicated that cake recovery and filtration time is reduced with operation time. During these times normal cleaning strategies become progressively inefficient. It has been observed that the curtain is effectively cleaned by stopping the process after the flushing sequence and allowing the curtain to dry over night. The Tubular Filter Press process is not recommended to run (on the same module) continuously for 24 hours. A 12 hour operation time per module is recommended.

6. Design Protocol for Cross-flow Microfiltration Systems

Cross-flow microfiltration systems are mainly used for water filtration and other applications where the feed solids are relatively low in comparison with tubular filter press applications in sludge dewatering. Cross-flow microfiltration processes operate at relatively low compressive pressures (typically about 150 kPa and require a suitable pre-coat layer inside the tubes at the start of the filtration cycle.

The basis of this chapter is a Masters thesis (Govender 2003), *The Development and Evaluation of Design Approaches for cross-flow microfiltration.*

6.1 Introduction

Fundemental research on cross-flow microfiltration (WRC Project No. 238), initiated in 1987, looked at the mechanisms that govern the behaviour and performance of high-velocity cross-flow microfiltration. Other work (Pillay, 1992B) studied the behaviour of the filter cake and in particular, effects associated with the compression of the cake.

Cross-flow Microfiltration is widely used in the concentration of particulate suspensions and the separation of solids. Due to the economic advantage of this process compared to conventional processes such as centrifugation and clarification, etc, the market for this technology has shown a progressively increasing demand in recent years. However despite the considerable amount of industrial work on microfiltration very little information is available in the literature on design of full-scale plants from data obtained on laboratory tests.

6.2 Basic Principle of Operation

The cross-flow microfiltration process operates on a principle similar to that of ultrafiltration systems, where a suspension containing particles is pumped through a tube, having porous membrane walls, under pressure (Figure 6.1). Due to the higher pressure within the tube, a crossflow of permeate through the membrane wall occurs. The flow of permeate carries particles to the membrane surface where they are retained and hence a buildup of cake layer gradually occurs over the entire surface.

If this build-up of cake layer continued indefinitely, it would result in blockage of the tube. However, this generally does not occur in practical Cross-flow Microfiltration processes. The cake layer accumulates only until the hydrodynamic shear exerted by the flow of suspension causes the cake to flow tangentially along the membrane surface at a rate that balances the deposition of particles. As a result the thickness of the cake layer is minimised due to the high shear and hence the cake layer remains relatively thin (Blatt *et al*., 1970; Kraus, 1974 and Schneider and Klein, 1982).

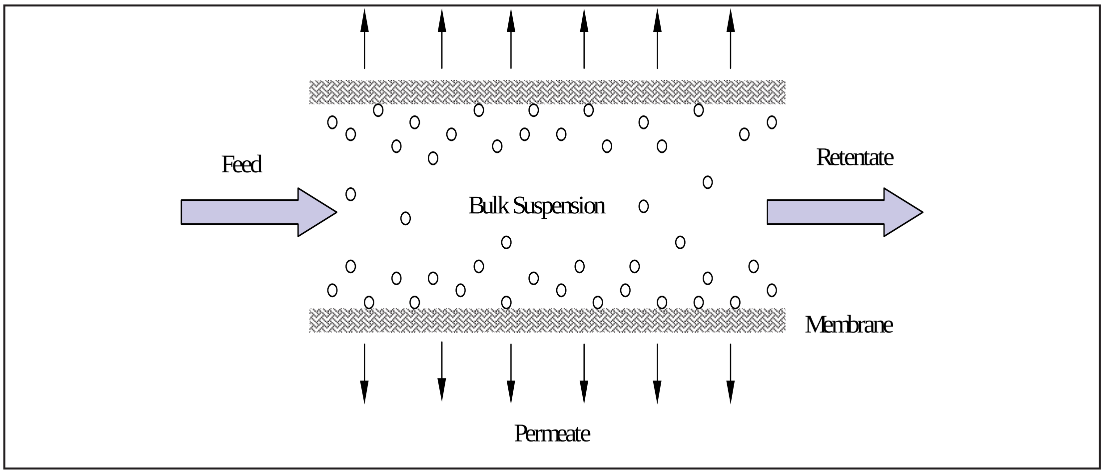

Figure 6.1: Schematic of a Cross-flow Microfiltration Process

The crossflow configuration is quite effective in controlling concentration polarisation. Therefore continuous cake buildup and consequent reduction in filtrate flowrate is avoided. Hence relatively high filtrate flux rates can be achieved over prolonged time periods in cross-flow microfiltration. Generally, as the layer of cake thickness increases, there is a corresponding decline in flux until steady state cake thickness is reached. In theory this would result in a steady state flux, as shown in Figure 6.2. However in practice, long-term flux decline is observed even after cake buildup has stopped.

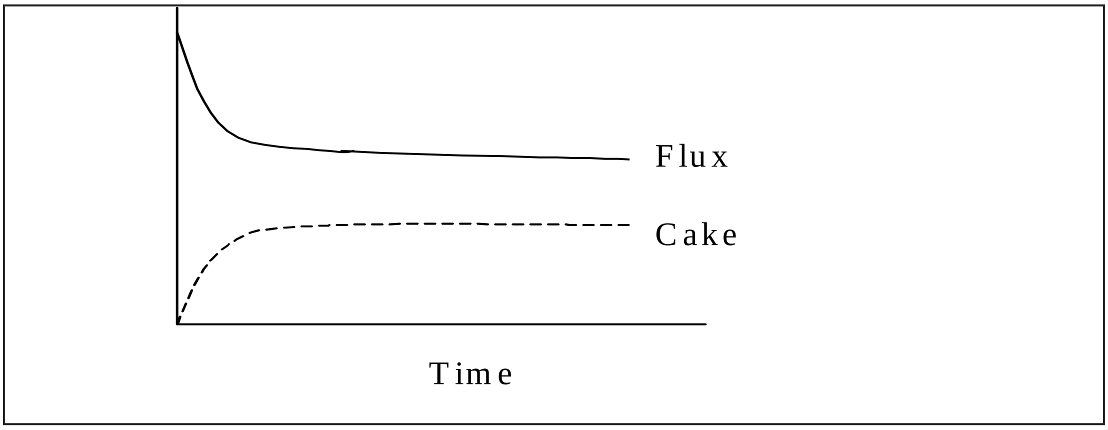

Figure 6.2: Typical Profiles of Cake Thickness and Flux Decline With Time

6.2.1 Rationale for Investigation

Unlike other models developed for reverse osmosis and nanofiltration, etc., no predictive models have been developed to date for microfiltration that enables the design of a full-scale system. For a real system designers generally rely on performing laboratory experiments to generate data required for design. This is often a time consuming and tedious task as there is a scarcity of relevant information on the experimental protocol and procedure for data processing and application to design.

The need for a suitable design procedure is therefore essential and forms the rationale for this study.

Usually in design, the primary variable is the membrane area required to treat the desired capacity of the full-scale system. This is usually obtained from laboratory experiments in the following ways:

In the first approach, experiments are performed at constant concentration over a range of concentrations. Constant concentration occurs when both the permeate and retentate are returned to the feed tank, or simply when the concentration in the feed tank remains constant during the run. The laboratory tests are conducted to determine the degree of separation that can be achieved and also to evaluate the influence of operating variables such as pressure, crossflow velocity and feed composition on performance. From this, the relationships between permeate flux and concentration can be determined. This is then used to infer a flux from the constant concentration experiments which is subsequently used to determine the membrane area required for larger scale operations.

In the second approach the average flux approach is used whereby a laboratory-scale batch concentration is performed. This involves concentrating a suspension from a specific initial concentration to a specific final concentration. From this, the average flux can be determined and used to predict the membrane area required for the full-scale unit.

The overall objective of this study was to evaluate these approaches for the design of full-scale MF systems and recommend a cost-effective procedure that will assist in the prediction of the performance of a full-scale unit for estimation of the filtration area requirement.

6.2.2 Objectives

To establish the applicability of the *constant concentration approach* and *average flux approach* to predict the performance of a MF system.

To develop a protocol to design full-scale MF units from pilot plant experiments.

6.2.3 Approach

This study will evaluate and compare methods by which a cross-flow microfiltration system may be designed when flux data relating to constant concentration and batch concentration experiments are available. The reference curve used in this study will be a batch concentration curve.

The steps involved in this study are as follows:

1. Identification of a suitable synthetic suspension that can be used in all the experiments. The criteria for selection will be that the suspension should yield a flux range similar to that expected from typical MF suspensions (20 to 150 LMH). Therefore various kaolin: bentonite mixtures will be investigated.
2. Determine a batch concentration curve for specified initial and final concentrations. This will be used as a reference curve for comparison purposes.
3. Using the constant concentration approach, perform appropriate small-scale experiments. From the numerical solution procedure that will be developed in this study, predict the batch concentration curve and compare to (2).

4. Using the average flux approach, perform appropriate small-scale experiments. Determine the average flux and use to predict the batch performance. Compare prediction to (2).
5. Finally compare (3) and (4).

The most appropriate method to design a MF system will be established by comparing the constant concentration approach with the average flux approach in terms of the time and effort required and also the level of accuracy associated with each prediction.

6.3 Brief Literature Review

6.3.1 Modes of Operation for Cross-flow Microfiltration

There are several operational modes that can be used to design a microfiltration plant. These include:

- Constant concentration
- Batch concentration
- Feed and Bleed
- Diafiltration

Each operational modes has its own requirements with respect to the design of these systems. The cost determining factors, i.e. membrane area and power consumption, are governed by the mode of operation of the cross-flow microfiltration due to the difference in behaviour of these systems.

6.3.1.1 Analysis of Constant Concentration Mode

In constant concentration experiments (or total recycle), no net concentration of particles occur because both the permeate and retentate are returned to the feed tank. Usually the constant concentration mode of operation is used in research to characterise the system and to measure the permeate flux at different operating conditions.

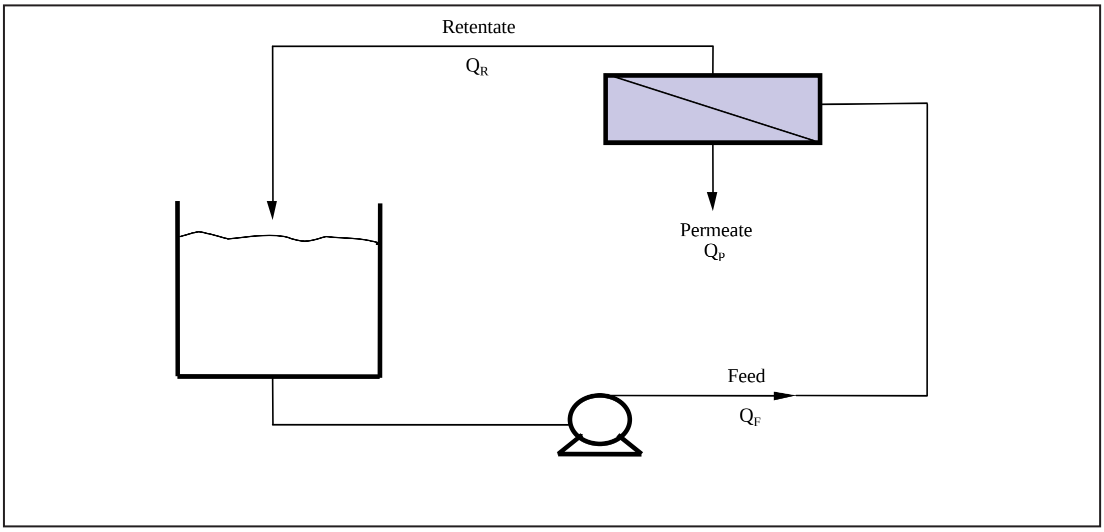

Figure 6.3: Schematic of a Cross-flow Microfiltration Showing Constant Concentration Mode of Operation

6.3.1.2 Analysis of Batch Concentration Mode

The batch recycle configuration (Figure 6.4) is used to concentrate a suspension in a transient, batchwise manner. This is achieved by drawing permeate from the system without replacement and returning the retentate to the feed tank.

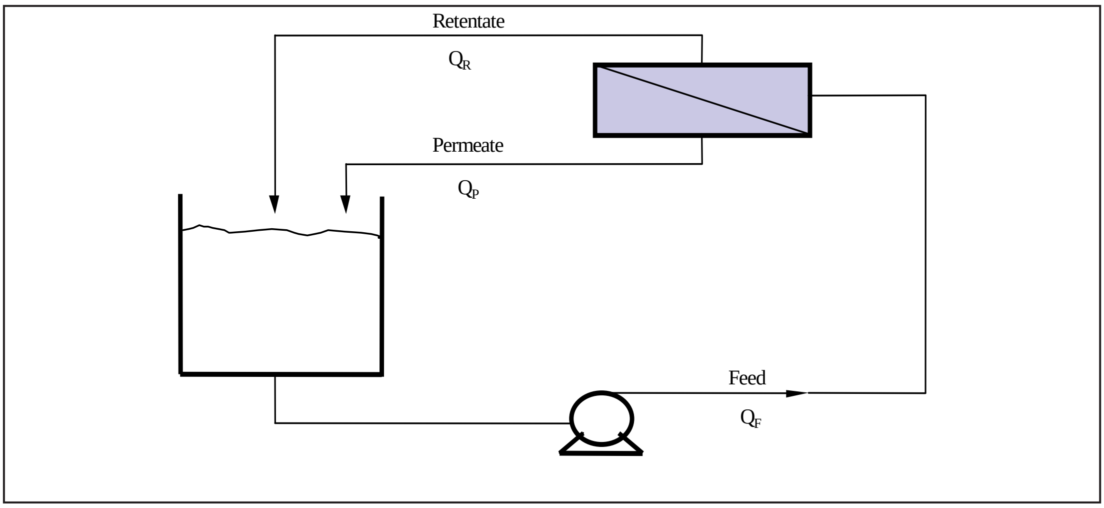

Figure 6.4: A Schematic Cross-flow Microfiltration Process Showing a Batch Concentration Mode

6.3.1.3 Analysis of Feed and Bleed Mode

The feed and bleed configuration is used in almost all large-scale continuous membrane processes. The recommended crossflow rates through the membrane modules are maintained by re-circulating of most of the retentate stream. This type of plant is referred to as a feed and bleed plant, since part of the retentate stream is bled from the system, with the rest being re-circulated, as shown in Figure 6.5.

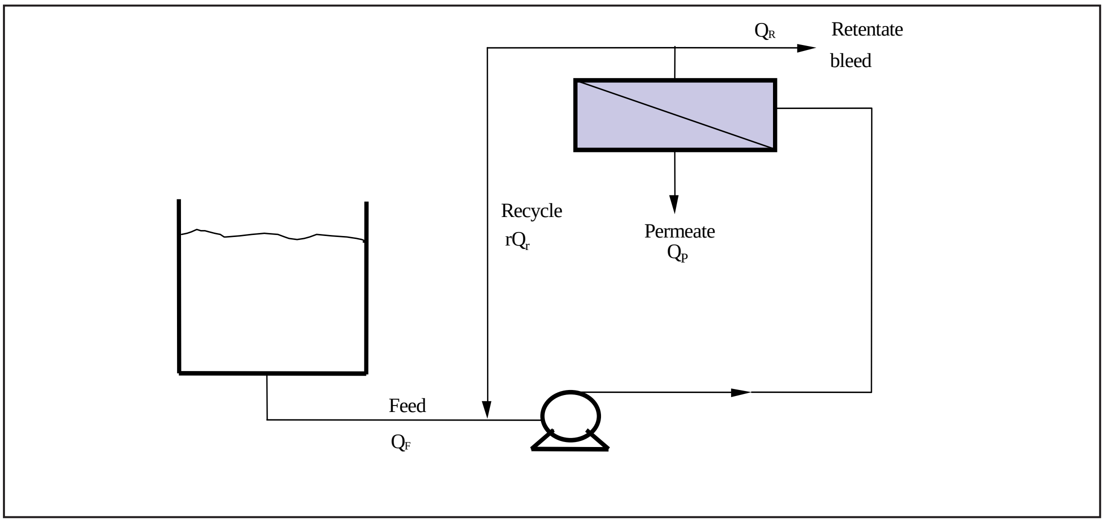

Figure 6.5: A Schematic of a Cross-flow Microfiltration Showing Feed and Bleed Operation

6.4 Review of Standard Design Procedures

The normal practice adopted for the design of reverse osmosis applications to the desalination of brackish water and seawater is to install sufficient feed pretreatment in order to reduce membrane fouling to very low levels - since membrane fouling is the key phenomenon that affects the prediction of membrane performance. Due to this controlled effect of membrane fouling in reverse osmosis, the performance of the membrane is primarily influenced by concentration polarisation which for ionic solutes is sufficiently well understood by using the thin film analyses. The details of this phenomenon is presented elsewhere (Gutman, 1987). Hence for RO, there are reasonable models to predict performance profiles.

Thus the supplier can specify the membrane area required and the optimum operating conditions for the desired processing rate and feed composition. Usually confirmatory experimental studies are only required if there is some uncertainty with regards to the level of pretreatment required or if there is a possibility of scale formation within the plant.

Due to the nature of membrane fouling and/or gel formation in ultrafiltration and microfiltration systems, the performance of these systems differs quite significantly from that of reverse osmosis systems. To date there are no predictive models for UF and cross-flow microfiltration, i.e. where fluxes can be predicted from the characteristics of the suspension alone. In most instances, performance has to be obtained by experiment. As a result the design for UF and MF systems is based upon firstly obtaining the experimental performance data, i.e. flux and solute removal efficiency, for that particular feed. From these tests the necessary information, i.e. the membrane area, operating conditions and configuration for the full-scale plant can be estimated.

6.4.1 Procedure for Design of a UF Batch System

It is assumed that the feed solution of interest is available and the type of membrane element is known.

- Before starting the experiment, the membrane element is thoroughly washed and the pure water flux rate is measured.
- Using the process feed material, measure the flux rate at zero recovery (i.e. return the permeate to the feed tank) as a function of trans-membrane pressure and cross-flow pressure differential.
- Concentrate to 25 % recovery and maintain this condition by returning permeate to the feed tank while measuring flux rate as a function of trans-membrane pressure and cross-flow pressure differential.
- Repeat at 50 %, 75 % and 90 % recovery. If possible run at the maximum concentration factor required by the process.
- Then the membrane element is thoroughly cleaned and the pure water flux is measured again.

A graph of flux rate versus the concentration factor is plotted and used for scaling up a batch process. The method is as follows:

When the relationship between flux rate, J and the log of concentration factor is linear, $\tilde{J}$ can be approximated by the following equation (Cheryan, 1986):

$$\tilde{J} = J_O - 0.33(J_O - J_F) \quad \text{.........(6.1)}$$

where J_O : initial flux, i.e. CF = 1.0, (l/m^2h)

J_F : final flux at CF_F, (l/m^2h)

If the concentration factor is known, i.e.

$$CF_F = \frac{V_O}{V_F} \quad \text{.........(6.2)}$$

where CF_F : concentration factor, final

V_O : initial volume, (m^3)

V_F : final volume, (m^3)

and the run time to process the desired capacity is specified, then the membrane area required to perform the duty can be calculated as follows :

$$A = \frac{V_O - V_F}{\tilde{J} \times t} \quad \text{.........(6.3)}$$

where A : membrane area required, (m^2)

t : processing time, (s)

6.4.2 Classical Approach For the Design of MF Systems

The design procedure for UF systems can be similarly applied to cross-flow microfiltration systems.

6.4.2.1 Constant Concentration Experiments

- Perform various constant concentration experiments over a range of concentrations
- Obtain flux-time curves for these runs
- Infer a pseudo steady state flux from each curve
- Plot a pseudo steady state flux versus in concentration curve

- Determine area required for full-scale operation

6.4.2.2 Average Flux Approach

- Do batch concentration on small-scale unit
- Obtain an average flux
- Apply to full-scale unit

6.5 Cross-flow Microfiltration Experimental Work and Results

6.5.1 Feed Suspension

Studies were conducted using synthetic feed suspensions in order to avoid the effects of changing feed characteristics on the evaluation and performance of these systems. To be able to more accurately deduce any trends from a set of experiments, a consistent feed composition is essential. Due to the variability of real suspensions, a synthetic suspension was used for the experiments.

Various mineral and gelatinous suspensions used by many researchers are shown in Table 6.1.

Table 6.1: Typical Suspensions Used in Microfiltration Studies

Suspension	Reference
Limestone	Hunt (1986), Pillay (1992)
Mixture of polymerised silica particles & Bovine Serum Albumen (BSA)	Gekas & Hallstrom (1990)
Mixture of bentonite and kaolin	Swart (1993)
Bentonite with the presence of macromolecules of BSA, dextran and Polyethylene glycol	Jiraratananon (1998)

6.5.2 Choice of Suspension

The criteria used to choose the most appropriate suspension was that it should allow a flux range between 20 and 150 LMH similar to that expected in typical MF applications. Further, the following factors were considered when choosing the appropriate particles to make up the suspension:

- A small particle size (< 10 μm) was required applicability in a real system
- The particles must be insoluble in water
- The particles must be relatively resistant to abrasion

6.5.3 Suspension Formulation

The exact nature of the suspension for this study was not important and the main requirement was that it should be repeatable and yield a flux similar to real microfiltration systems. Tests indicated that a 0.8 kaolin : 0.2 bentonite ratio was the most suitable ratio to produce the desired flux range.

6.5.4 Suspension Preparation

The objective was to obtain a reproducible and consistent feed suspension for all the experiments. Therefore several factors were taken into account to achieve this.

1. Representative samples of bentonite and kaolin were used throughout the trial.
2. Solid Addition

   Unlike kaolin, bentonite is very difficult to disperse in water and requires a relatively long time (with stirring) for the bentonite suspension to stabilise. A laboratory stirrer was used to mix the concentrated feed suspension overnight for approximately 16 hours.
3. Temperature Control

   The temperature fluctuations affected the repeatability of the experiments. The temperature of the feed was maintained constant by heating the feed suspension to 32°C using a heating element, linked to a temperature controller. As a result, fluxes were normalised to 25°C.

6.5.5 Apparatus

The experimental apparatus consisted of two 200 L stainless steel tanks, a positive displacement pump, a cross-flow microfiltration module and associated piping and instrumentation. A schematic diagram of the crossflow microfiltration system is shown in Figure 6.6.

The feed tank was fitted with a mixer in order to keep the feed suspension well stirred and thereby prevent solids settling out of from the suspension. Baffles were also welded into the feed tank to prevent vortexing of the fluid material during mixing. Good mixing was achieved, as there were no visible solids at the base of the feed tank at the end of each run. A heating element linked to a temperature controller was also fitted to the feed tank in order to prevent temperature fluctuations in the system.

Pressure tappings were positioned at the inlet and exit of the crossflow tube and were connected via a two-way valve to a single pressure gauge. A Saunders diaphragm valve on the reject line was used to control the backpressure in the membrane tube.

The reject stream from the crossflow tube was returned to the feed tank whilst the permeate, accumulated in the permeate tray positioned below the membrane. The permeate flowed to either the permeate tank (for a batch system) or to the feed tank (total recycle system) by gravity.

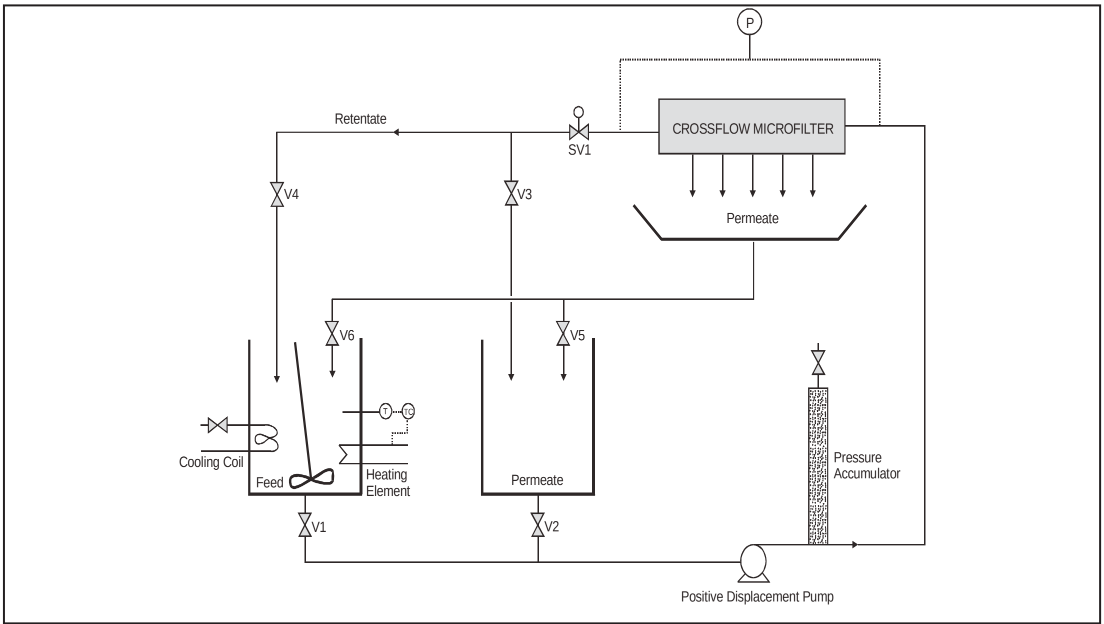

Figure 6.6: Schematic Diagram of the Cross-flow Microfiltration Apparatus

6.5.6 Cross-flow Microfiltration Tubes

The cross-flow microfiltration membrane was a polyester woven fabric obtained from a local supplier, Gelvenor Textiles. However, unlike other filters, the woven fabric MF does not have a definite pore size, as can be seen from Figure 6.7. The performance of the woven fabric microfilter is therefore largely dependent upon the formation of a suitable cake layer that provides the resistance and hence the retention of the contaminants in the feed stream.

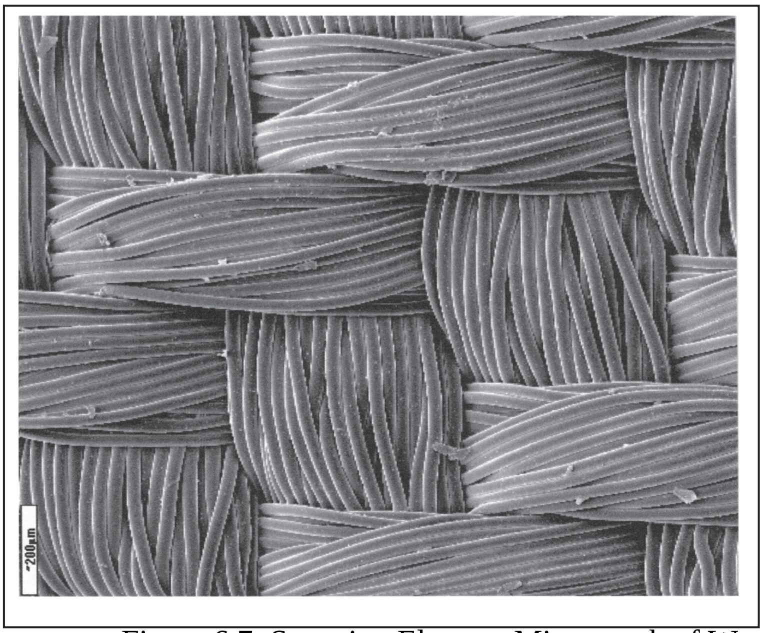

Figure 6.7: Scanning Electron Micrograph of Woven Fibre Fabric

The total path length of the membrane was 7.57 m, yielding a filtration area of 0.599 m^2.

The same experimental filter elements were used to perform all the experiments in this study.

6.5.7 Results

Flux-time curves were characterised at a range of constant concentration experiments and a series of batch concentration experiments. These results were used to predict the performance of the MF system by two design approaches. The following test conditions were set during the experimental work program:

Table 6.2: Operating Conditions for the Cross-flow Microfiltration Experiments

Operating parameter	**Units**	**Value**
Pressure, ΔP	kPa	2 bar
Cross-flow velocity, U	m/s	2
Feed flowrate, Q_f	L/h	3591
Temperature, T	^{o}C	32 ± 2

The applicability of constant concentration and batch concentration experiments to predict the performance of a full-scale microfiltration plant was established by two design approaches:

- Constant concentration approach and
- Average flux approach.

6.5.7.1 Batch Concentration Reference Curves

Batch concentration experiments (i.e. an increase in feed concentration with time, where the permeate is withdrawn and the retentate returned to the feed tank) were performed at different initial feed concentrations. The MF system was operated at a water recovery of approximately 80 % due to the physical limitations of the experimental system. Batch concentration curves were obtained over the range of concentrations considered during the constant concentration experiments.

The flux-time and concentration-time curves for the batch concentration experiments are shown in Figures 6.8 to 6.10 below. These batch curves will be used as the *Reference Curves*.

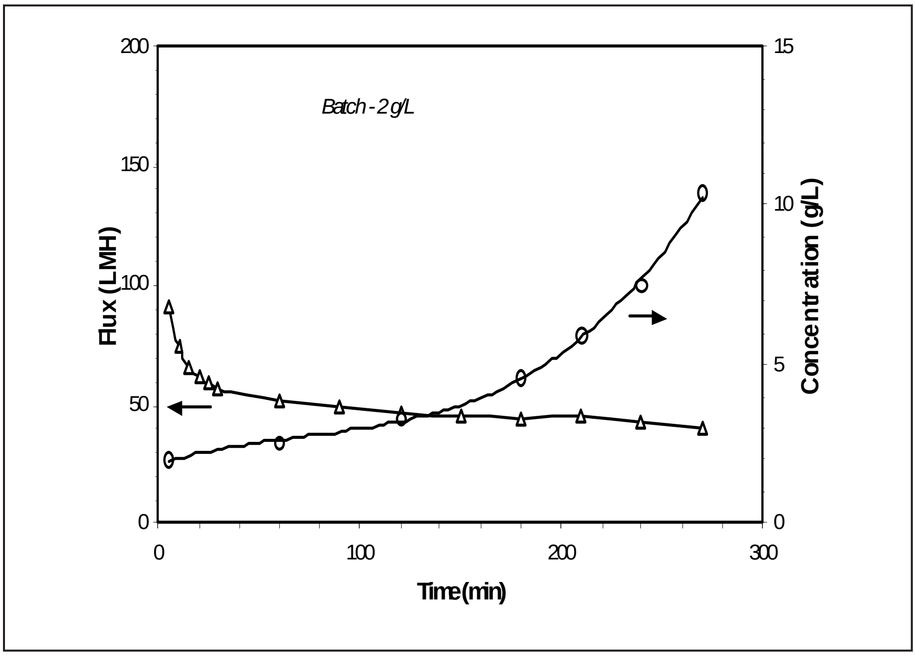

Figure 6.8: Flux and Concentration Profiles for Batch Concentration at 2 g/L

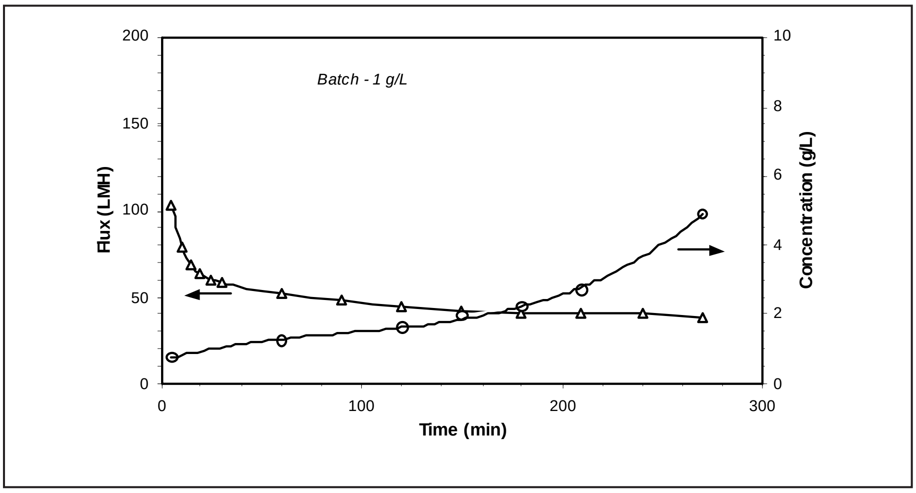

Figure 6.9: Flux and Concentration Profiles for Batch Concentration at 1 g/L

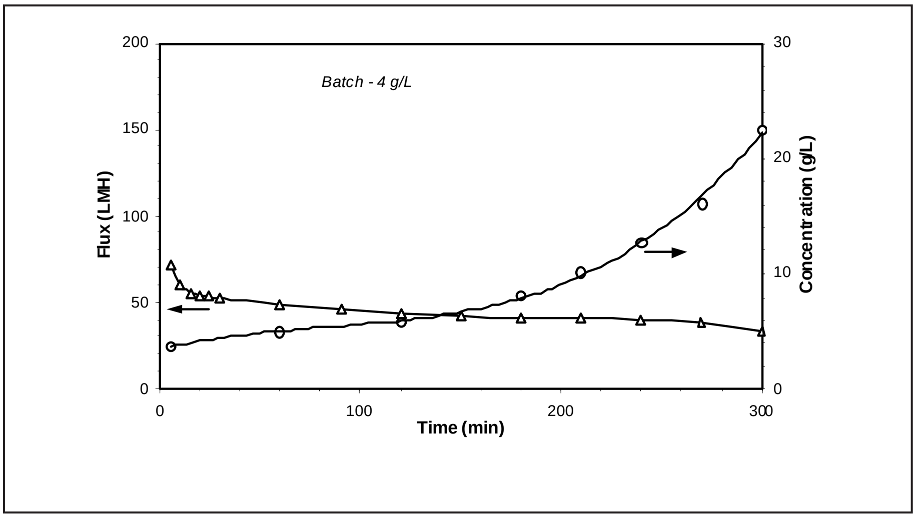

Figure 6.10: Flux and Concentration Profiles for Batch Concentration at 4 g/L

The form of the above curves is in agreement with trends observed in the literature. It can be seen that there is a slight decrease in flux with each increase in concentration.

6.5.7.2 Constant Concentration Approach

6.5.7.2.1 Flux Time Curve Characteristics

Constant concentration experiments (during which the concentration in the feed tank remains constant) were performed at bulk feed concentrations ranging from 0.1 g/L to 20 g/L. The effect of concentration on permeate flux is shown in Figure 6.11.

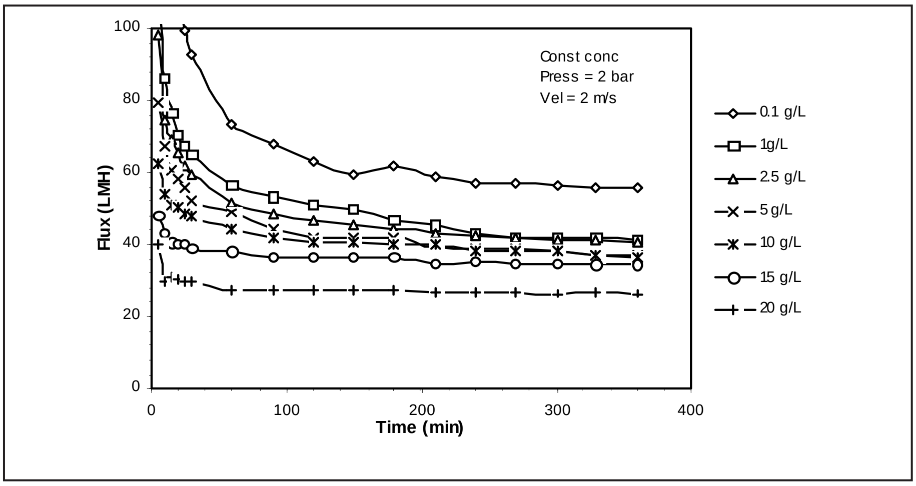

Figure 6.11: The Effect of Concentration on Flux-time Behaviour

It can be seen that permeate flux is dependent on bulk feed concentration and is known to decrease with an increase in feed concentration as reported by other researchers. This trend was shown to hold true, as the reported initial flux was lower for each experiment performed at a higher feed concentration (Figure 6.11). A further observation was that the pseudo steady state flux appeared to be established at a much faster rate at higher concentrations. This trend is consistent with previously reported literature [Tarleton and Wakeman (1991), Pillay (1992a)] and also with the data shown in Figure 6.8 through Figure 6.10.

When a pseudo steady state flux was inferred from each flux curve at a constant time, t, (Figure 6.11), a graph of pseudo steady state flux versus log concentration produced a straight line (Figure 6.12). This experimental finding conformed to the literature (Bertera *et al*., 1984).

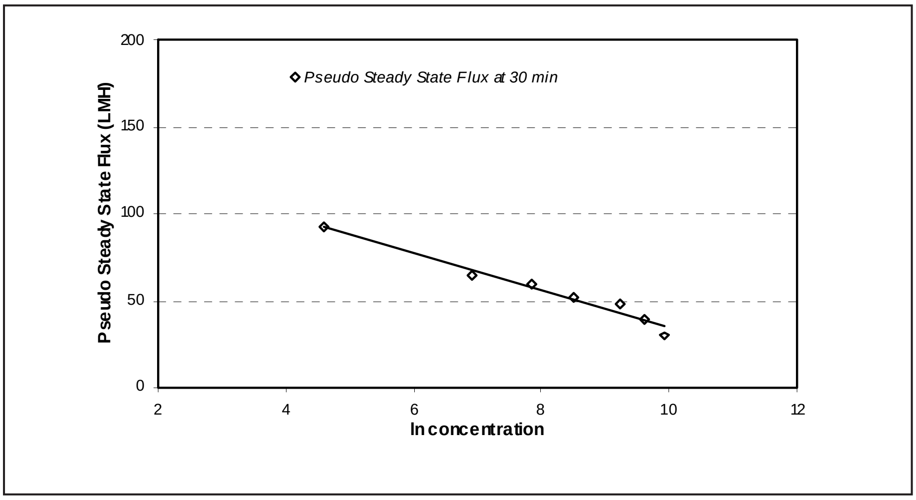

Figure 6.12: Pseudo Steady State Flux vs In Concentration

6.5.7.3 Design Procedure for Constant Concentration Approach

In the constant concentration approach, the flux-time profile was carefully monitored. Two design procedures were developed and were used to predict the performance of the full-scale micro-filtration plant, namely :

a) pseudo steady state flux approach, J = f (c); and

b) rigorous approach, J = f (c,t)

6.5.8 Pesudo Steady State Flux Approach

Several constant concentration experiments were performed over a wide range of feed concentrations. A pseudo steady state flux was obtained for each of these runs and hence a graph of pseudo steady state flux versus log concentration was plotted (Figure 6.12).
A numerical solution procedure was developed and used to predict the batch curve by performing a mass balance on the proposed system. The membrane area required to treat the desired capacity was therefore established by a mathematical approach. (M Tech Thesis, R Govender, Chapter 4)

The pseudo steady state flux approach only considered the effect of concentration on permeate flux, i.e. J = f (concentration). In practice, flux decline from an initial value to a steady state value is also dependent on time.

In practice, long-term flux decline is observed even after cake build-up has stopped. The extent of cake build-up is a function of system dynamics or hydraulics. Here we refer to both linear velocity of the process (shear) and operating pressure (compaction). The hypothesis was tested on one set of conditions, i.e. ΔP and U , and the assumption made that if the hypothesis holds for one condition, it can be extrapolated to other operating conditions.

A true steady state is rarely achieved and hence it is firstly difficult to define a "steady state flux" and secondly to establish when it is reached. Mathematically the term steady state flux refers to when the rate of change of flux with time is constant, or quite simply, when the flux levels off and no further decline in flux is observed with time. However, this phenomenon does not occur in MF systems, and it was also very difficult to define for the runs performed in this study. Thus a the problem arises when choosing a flux to design the full-scale plant as one is not sure when a true steady state has been reached and hence what steady state flux should be used. Generally steady state fluxes from pilot plant experiments are used to design a full-scale system, as this is a more conservative design approach.

As a means to overcome the uncertainty of when a steady state flux is reached, "pseudo steady state fluxes" were taken at different time periods in the run and plotted against the log of concentration (Figure 6.13). These curves were subsequently used to predict the batch curves.

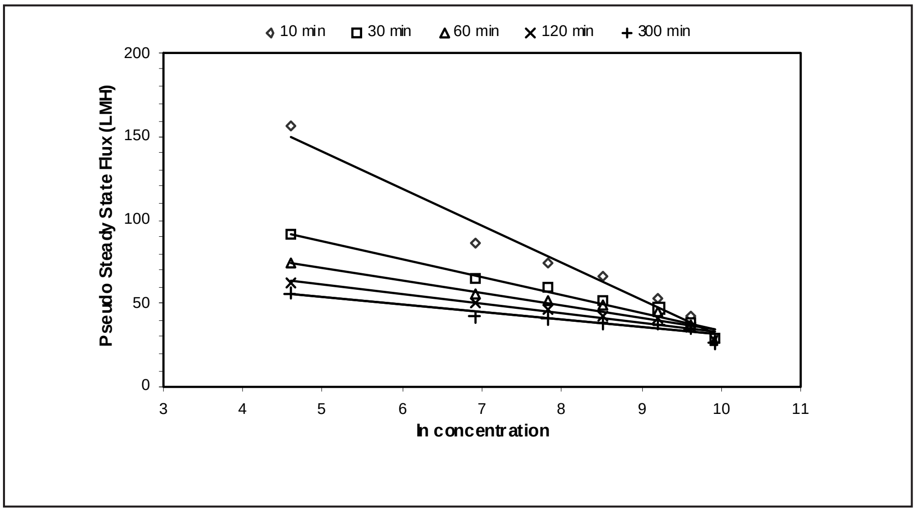

Figure 6.13: Pseudo Steady State Flux vs ln Concentration Curve at Different Times

The numerical procedure to predict the batch curve was repeated by using the various pseudo steady state flux versus log concentration curves at different operating times in Figure 8.8. A spreadsheet of a typical numerical solution procedure for a pseudo steady state flux taken at 60 min is presented in Table 6.3.

Table 6.3: Pseudo Steady State Flux Numerical Solution Procedure

t (min)	Vol (L)	Conc (g/l)	Flux (LMH)	d t (min)	Vol Perm (L)	New Vol (L)	New Conc (g/l)
0	180.00	2.00	52.2	5	2.61	177.39	2.03
5	177.39	2.03	52.1	5	2.60	174.79	2.06
10	174.79	2.06	52.0	5	2.60	172.19	2.09
15	172.19	2.09	51.9	5	2.59	169.60	2.12
20	169.60	2.12	51.8	5	2.59	167.02	2.16
25	167.02	2.16	51.6	5	2.58	164.44	2.19
30	164.44	2.19	51.5	10	5.15	159.29	2.26
40	159.29	2.26	51.3	10	5.12	154.17	2.34
50	154.17	2.34	51.0	10	5.10	149.07	2.41
60	149.07	2.41	50.8	30	15.22	133.85	2.69
90	133.85	2.69	50.0	30	14.98	118.87	3.03
120	118.87	3.03	49.1	30	14.71	104.17	3.46
150	104.17	3.46	48.1	30	14.41	89.76	4.01
180	89.76	4.01	47.0	30	14.07	75.68	4.76
210	75.68	4.76	45.7	30	13.69	62.00	5.81
240	62.00	5.81	44.2	30	13.24	48.76	7.38
270	48.76	7.38	42.4	30	12.69	36.07	9.98

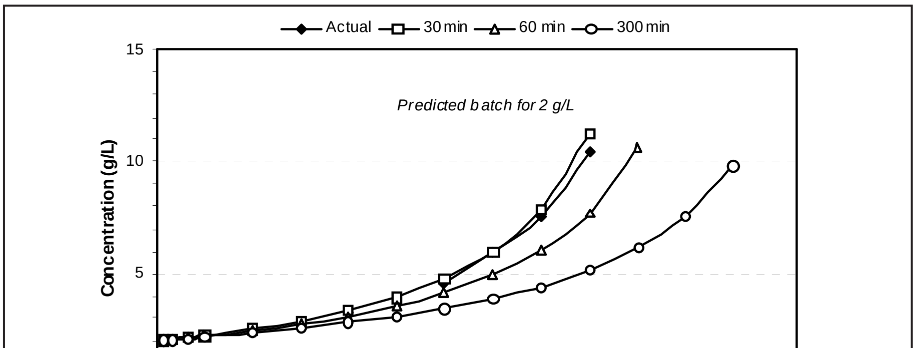

Figure 6.14: Comparison of the Actual vs Predicted Concentration-time Profiles for a Batch Run at 2 g/l Using the Pseudo Steady State Flux Method. (Open Symbols : Predicted Value)

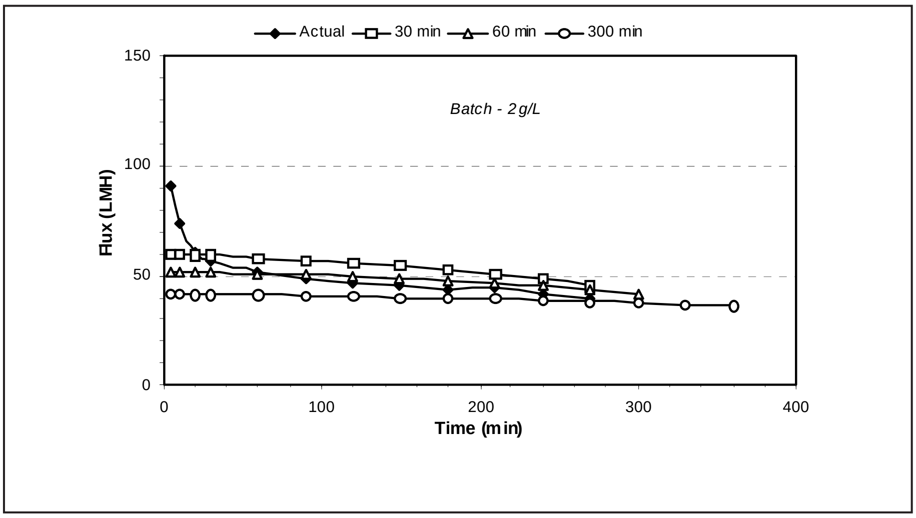

Figure 6.15: Comparison of the Actual vs Predicted Flux-time Profiles for a Batch Run at 2 g/L Using the Pseudo Steady State Flux Method. (Open Symbols : Predicted Value.)

The predictions obtained for the concentration and flux data derived from the pseudo steady state flux approach were plotted against the actual experimental data. These results are shown in Figure 6.14 and Figure 6.15 respectively.

A comparison of the actual versus the predicted profiles for a batch run at 2 g/L indicated that poor correlations are obtained using the pseudo steady state flux method. The flux-time profile correlations did not correspond with the experimental data, and showed a significant difference, as can be seen from Figure 6.15. Figure 6.14 indicates that the predicted curves are time dependent. The predicted curve obtained using a pseudo steady state flux at 30 min yielded a good correlation to the experimental curve. However, fluxes taken at 60 min and 300 min respectively produced poor correlations.

Prediction of the concentration-time profile using the pseudo steady state flux method, over the different concentration ranges were therefore unreliable.

6.5.9 Rigorous Approach

The distinguishing feature of the rigorous approach is that time dependent fluxes are used, i.e. J = f (c, t), whereby the long-term flux decline is incorporated within the prediction. The numerical analysis of the rigorous approach is similar to the pseudo steady state flux method. However, in the rigorous method, instead of merely obtaining a flux at a particular concentration, the flux is taken at a particular concentration and at a specific time. This procedure is illustrated below.

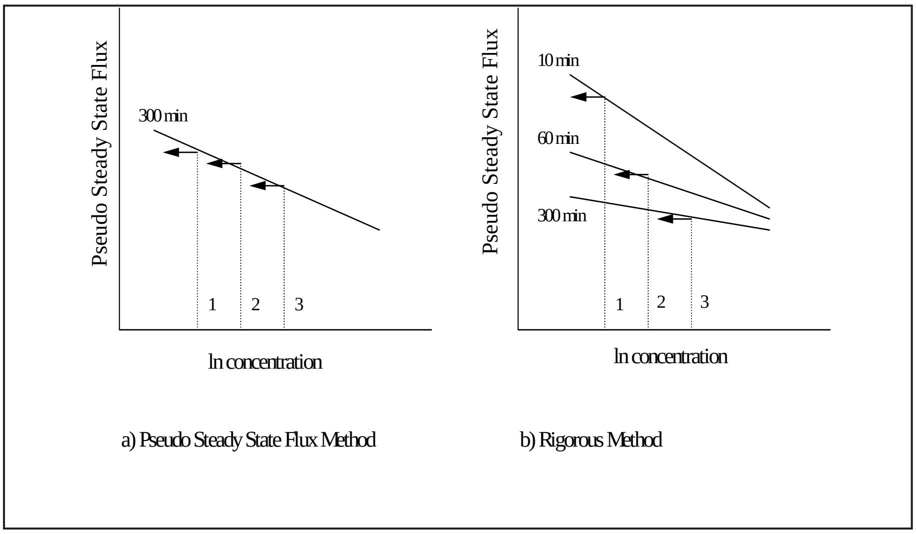

Figure 6.16: Pseudo Steady State Flux vs ln Concentration Curves

In the rigorous method, both the effects of concentration and time are taken into account. Here the pseudo steady state flux vs ln concentration curves at different operating times are used. The mathematical procedure, as outlined in the pseudo steady state flux approach was used, and the predictions as shown in Figures 6.17 to 6.19 were produced.

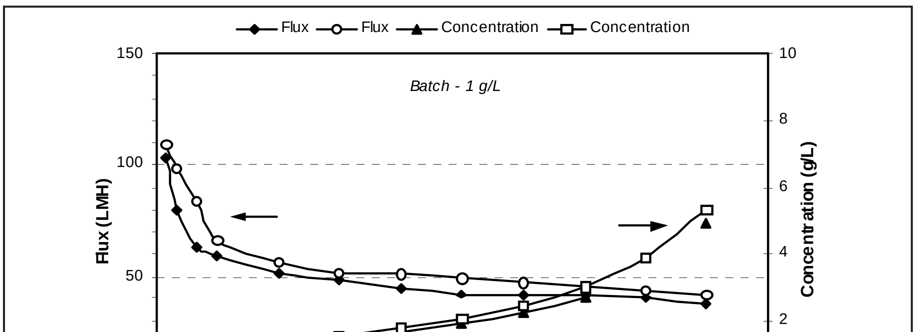

Figure 6.17: Rigorous Prediction of the Concentration-time and Flux-time Profiles at 1 g/L. (Actual : Solid Symbols, Predicted : Open Symbols)

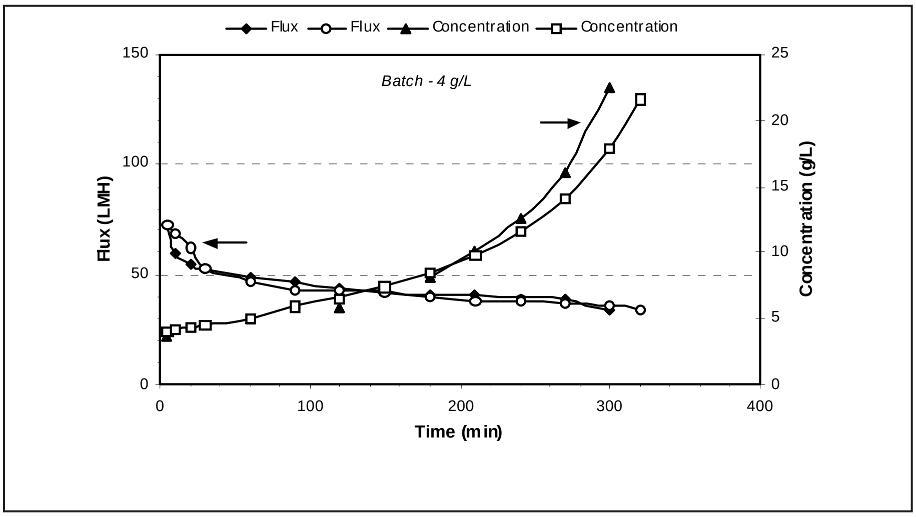

Figure 6.18: Rigorous Prediction of the Concentration-time and Flux-time Profiles at 2 g/L. (Actual : Solid Symbols, Predicted : Open Symbols)

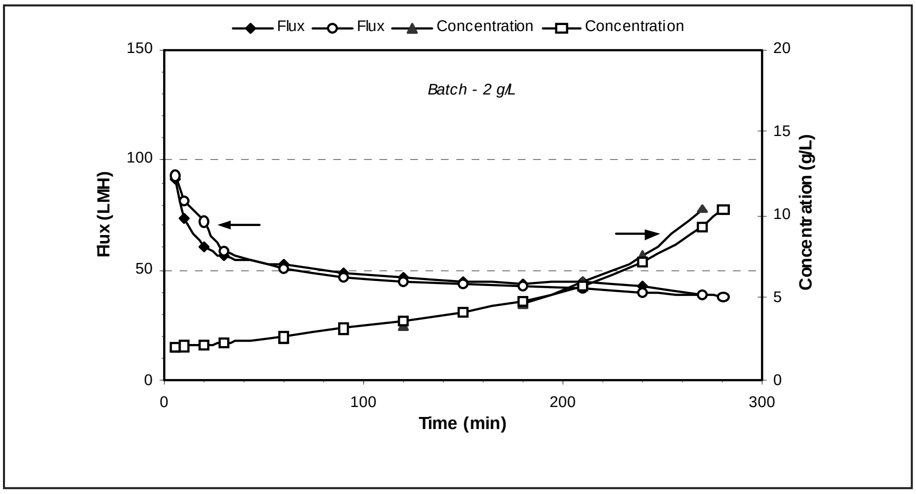

Figure 6.19: Rigorous Prediction of the Concentration-time and Flux-time Profiles at 4 g/L. (Actual : Solid Symbols, Predicted : Open Symbols)

Since the flux dependent variables, i.e. the time and concentration effects were taken into account in the rigorous approach; this method yielded very good predictions of the concentration-time and flux-time profiles.

6.5.10 Average Flux Approach

The strategy adopted in the average flux method is to first perform a batch concentration experiment on a laboratory unit and use the average flux obtained from the laboratory experiment to predict the membrane area required for the full-scale unit. These predictions will then be compared to the reference curves in order to evaluate the accuracy of the predictions.

Usually in the batch concentration experiments, the main criterion is the desired final concentration. Batch concentration experiments were therefore performed on the laboratory unit to the same end-concentration as the full-scale unit. Runs performed at different starting volumes are shown in Table 6.4. It is seen that the average fluxes differ widely, and are strongly dependent on time. Depending on the initial volume of feed chosen on the laboratory unit, the time to get to the desired end-concentration differs.

This results in different average fluxes and hence the prediction of the membrane area required is directly affected.

Table 6.4: Table of Average Flux for Different Run Times

Batch Concentration – 1 g/l		
Run	**Run Time (min)**	**Average Flux (LMH)**
49	270	79.8
50	150	86.1
51	340	70.5

It was observed that the shorter the run time to get to the desired end- concentration, the higher the average flux obtained.

It is proposed that the batch system be designed such that the run time and the final concentration on both the small-scale and full-scale units are fixed.

In order to implement the above proposition, the feed tank on the laboratory unit was modified to allow the feed to be concentrated within the desired time. This was achieved by reducing the bottom third of the feed tank to half the tank diameter. This was done so that the feed volume could occupy a higher height above the suction point to the pump and thereby prevent the introduction of air into the system so the desired water recovery could be achieved. Furthermore, in order to get to the desired end concentration on the laboratory unit within the same time as the full-scale unit the initial feed volume on the laboratory unit requires to be varied in order to reach the final concentration within the specified time. Once this was achieved on the laboratory unit, an average flux was calculated and used to predict the membrane area required for the full-scale unit.

6.5.11 Procedure for the Average Flux Method

In the average flux method, the initial volume, V_o and concentration, C_i for the full-scale unit was specified. The water recovery, WR and the time to process the slurry were also given.

From the design equation of a batch system:

$$A = \frac{V_o - V_F}{\tilde{J} \times t} \quad \ldots\ldots\ldots\ldots 6.4$$

Only $\tilde{J}$ and V_F are unknowns. V_F can be calculated, since, from the definition of water recovery :

$$\text{Water recovery, } WR = \frac{Volume\ of\ permeate}{Volume\ of\ initial\ feed} = \frac{V_p}{V_o} \quad \ldots\ldots\ldots 6.5$$

The total volume of permeate can be calculated, since V_o and WR are known. The final volume of feed, V_F can therefore be calculated:

$$V_F = V_o - V_p \quad \ldots\ldots\ldots\ldots 6.6$$

Therefore the only unknown variable for any given application is on what average flux, $\tilde{J}$ should one base the system design. This can be obtained by performing a batch concentration experiment on a laboratory unit and concentrating the feed to the same end-concentration as is required for the full-scale unit.

The uncorrected flux versus time data obtained on the laboratory experiment can then be used to determine the production rate during the run. Subsequently the average flux is established. Thus using the average flux obtained from the laboratory experiment and solving for A in Equation 6.4, the membrane area required to perform the given duty is obtained.
In order to evaluate the average flux method, pilot plant batch concentration experiments and laboratory-scale batch concentration experiments were performed.

1. **Pilot Plant** (considered full-scale for the purpose of this study)
   Batch concentration experiments were performed over four different concentration ranges (the intention being to cover as wide a range of feed concentrations as possible). These experiments were performed using the same membrane area (0.6 m^2) and initial feed volume for each experiment. The system was operated at a water recovery of ≈ 80

% for each batch concentration experiment. These curves are the reference curves reported earlier.

2. Laboratory Scale

Batch concentration experiments were performed over the same four concentration ranges as the pilot plant experiments. These experiments were also performed at the same operating conditions as the pilot plant experiments, i.e. a pressure of 2 bar and crossflow velocity of 2 m/s.

The laboratory-scale experiments had to be carefully designed so that the same final concentration is achieved within the operating specified time for the full-scale unit using a small membrane area (0.1 m^2). As discussed earlier, the time parameter is an important variable to keep constant in order to maintain similar average fluxes on the laboratory and full-scale units.

The results obtained from the laboratory-scale experiments were used to predict the membrane area required to perform the required production on the full-scale unit. The predictions obtained using the average flux method can be seen from the illustrative example below.

Illustrative Examples

A feed volume of 180 L with an initial concentration of 2 g/L needs to be processed in 270 min. A water recovery of 80 % is specified. What membrane area is required to perform the filtration duty / dewatering?

Solution:

$$WR = \frac{V_p}{V_o}$$

V_p = 0.8 x 180

V_p = 144 L

$$\therefore V_F = V_o - V_p$$

= 180 – 144

= 36 L

From the laboratory experiment, an average flux of 56.2 LMH was obtained.

Therefore from the design **Equation,**

$$A = \frac{V_o - V_F}{\tilde{J} \times t}$$

$$= \frac{180 - 36}{56.2 \times (270/60)}$$

A_{pred} = 0.57 m^2

A_{act} = 0.59 m^2

From the above example it can be seen that the predicted area correlated well with the actual area required. Furthermore, the accuracy associated with this prediction was quite good with an error of 3.4 %.

A similar design procedure was followed for the batch concentration runs over the other concentration ranges and these predictions are detailed in Table 6.5 below.

Table 6.5: Summary of Predicted Batch Designs Using the Average Flux Method

	Batch – 2 g/L	**Batch – 3 g/L**	**Batch – 4 g/L**
V_i (L)	180	180	180
WR (%)	80	80	80
C_f (g/L)	10	15	20
t (min)	270	280	300
J (LMH) – from lab expt	56.2	56.1	44.4
A_{pred} (m^2)	0.57	0.55	0.65
A_{act} (m^2)	0.59	0.59	0.59
% error	3.2	6.8	9.2

6.6 Comparison of Design Methods

The criteria used to compare and evaluate the predictive methods was based on the time required to execute each method and the accuracy associated with each prediction.

i. Constant Concentration Approach

a) Pseudo steady state flux method

Due to the long-term flux decline in MF systems, there is uncertainty when a pseudo steady state flux is reached. The results from the numerical solutions of the pseudo steady state flux method indicated that the predicted performance profiles are time dependant and inaccurate. Also the experimental work required is quite significant and the numerical solution procedure for the pseudo steady state flux method is quite intensive. Thus the pseudo steady state flux method is not a feasible means for the design of larger-scale MF units.

b) Rigorous Method

In the rigorous method the long-term flux decline as well as the concentration effect was simultaneously taken into account. As a result, very good predictions of the concentration-time and flux-time profiles were obtained. However, this method is time consuming for normal application but could be used for the design of full-scale systems under certain circumstances.

ii. Average Flux Approach

In these batch concentration experiments the final concentration is the main criterion. To obtain a good prediction using the average flux method, both the run time (processing) and final concentration must be maintained constant. From the predictions obtained (Table 6.5), it can be seen that the accuracy associated with this method is good. Further, the experimental time required was also shorter. The results obtained with the above three methods are summarised in Table 6.6.

Table 6.6: Comparison of Methods to Determine Filtration Area

Design Method	**Time Required**	**Accuracy**
Pseudo steady state	High	Poor
Rigorous	Very High	Very Good
Average Flux	Medium	Good

7. Conclusions

The final conclusions from work done on sludge dewatering (tubular filter press) and water filtration (cross-flow microfiltration) are presented in this section.

7.1 Tubular Filter Press

7.1.1 Laboratory tests especially planar filtration tests, are useful as an initial screening tool, to establish whether a sludge is amenable to dewatering by tubular filter press. More accurate process information including generation of design data requires pilot plant studies to be undertaken over a reasonable period.

7.1.2 Tubular filter press technology has potential in some industrial applications such as electroplating sludges.

7.1.3 Investigation into the poor performance of a full-scale tubular filter press in a textile application and subsequent pilot plant studies, indicated that efficient dewatering of industrial sludge by tubular filter process was strongly influenced by upstream chemical pre-treatment for sludge thickening. Sludge feed variability with respect to concentration and composition adversely affected Tubular Filter Press performance.

7.1.4 A design procedure has been compiled. The suggested procedure incorporates preliminary laboratory characterisation of the sludge, single tube pilot-plant data and field experiences.

7.1.5 Comparison of the Tubular Filter Press with other mechanical dewatering processes, indicated that the most feasible methods for sludge dewatering in a waterworks environment are the vertical Tubular Filter Press and the centrifuge.

7.1.6 Comparison of cost implications including estimated capital and operating costs, of the tubular filter press and the centrifuge, indicated that there was no significant cost difference between the two processes.

7.1.6.1 The high curtain replacement costs, coupled with the unproven life expectancy of the curtain weighs heavily against the tubular filter press technology in favour of the more robust and proven centrifuge.

7.1.6.2 The Tubular Filter Press also suffers from the disadvantage of mechanical complexity for large scale applications compared to the centrifuge.

7.1.6.3 Trials, conducted on the Tubular Filter Press by spiking the sludge feed to the Tubular Filter Press with giardia cysts, indicated that the Tubular Filter Press process can form a barrier that prevents the passage of giardia cysts into the permeate. While there was excellent reduction in giardia cycts in the permeate, detection of the giardia cysts was unsatisfactory due to limitations in the analytical procedure at the time of the experiments. More process control was deemed necessary to ensure that the relatively poor quality permeate produced at the start of the run, during the cake formation and consolidation stage, is re-cycled into the feed tank until the permeate turbidity has improved and the operating pressure has stabilised.

7.2 Cross-flow Microfiltration

7.2.1 Investigations into design protocols for Cross-flow Microfiltration systems produced a cost-effective procedure for the accurate estimation of the required filtration area for the sizing of a cross-flow microfiltration unit. It was concluded that:

7.1.1.1 For the design of a MF system, where the final conditions are exactly known, the average flux method may be used because of its simplicity and accuracy.

7.1.1.2 Where the final conditions are unknown, the rigorous method is appropriate, since more reliable concentration-time and flux-time profiles are obtained with the rigorous method.

8. Recommendation

8.1 The Vertical Tubular Filter Press is recommended for small batch-scale operations, where other mechanical dewatering systems are uneconomical.

8.2 Tubular Filter Press can be applied after careful investigations, to industrial applications where the sludge feed composition is uniform. Favourable results were obtained using an electroplating sludge.

8.3 It is recommended that efforts be made to improve the operation of the single-tube pilot-plant to make it more versatile in the production of accurate design data.

8.4 The Vertical Tubular Filter Press at the Umgeni Water's Hazelmere Waterworks should be upgraded to operate as a full-scale plant with two curtain modules. The unit will easily handle present dewatering requirements where sludge production is very much lower than the design capacity of the centrifuge. Important operating data and experience pertaining to the Tubular Filter Press performance during 24-hour operation may be obtained. Only through continuous operation, under plant operating conditions, can the curtain life be assessed.

8.5 The design procedure for Cross-flow microfiltration should be tested rigorously using real suspensions. Trials need to be performed on a range of non-newtonian suspensions including biological and gelatinous suspensions.

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Appendix 1

WIGGINS WATERWORKS	2002	RAW			FINAL		
DETERMINAND	**UNIT**	**MEAN**	**5TH Percentile**	**95TH Percentile**	**MEAN**	**5TH Percentile**	**95TH Percentile**
FREE CHLORINE	mg/l				1.02	0.9	1.2
TOTAL CHLORINE	mg/l				1.26	1.1	1.4
COLIFORMS	per 100 ml	17.44	0	84	0	0	0
E.COLI	per 100 ml	2.36	0	12	0	0	0
FAECAL STREPTOCOCCI	per 100 ml	21.33	0	46	0	0	0
ALGAE COUNTS	CELLS/ml	572.64	68	2414	0.35	0	1
pH			7.3	7.8		7.7	8
COLOUR	°H	5.78	0.5	13.8	0.82	0.5	2.35
TURBIDITY	NTU	3.16	1.22	8.22	0.16	0.08	0.32
CONDUCTIVITY	mS/m	19.34	17.9	21	20.5	18.8	22.4
TOTAL ALUMINIUM	µg/l	91.65	34.7	218	41.74	5	101
ALKALINITY	mg/l $CaCO_3$	48.18	46.7	50.6	50.31	48	54
TOTAL HARDNESS	mg/l $CaCO_3$	49.51	46.25	51.5	51.13	48.08	54.5
CALCIUM	mg/l	10.32	9.5	10.9	10.93	10.2	11.6
MAGNESIUM	mg/l	5.69	5.4	6	5.72	5.2	6.6
SODIUM	mg/l	20.5	19	22	21.75	19	24
POTASSIUM	mg/l	2.19	2.1	2.4	2.18	2	2.3
IRON	mg/l	0.13	0.06	0.23	0.01	0.01	0.03
MANGANESE	mg/l	0.04	0.01	0.13	0.01	0.01	0.01
SILICA	mg/l	4.5	4	5	4.5	4.3	4.9
NITRATE	mg/l as N	0.61	0.41	0.83	0.61	0.47	0.67
AMMONIA	mg/l as N	0.03	0.01	0.05	0.01	0.01	0.04
CHLORIDE	mg/l	24.48	23.2	26.4	25.4	24.1	26.8
SULPHATE	mg/l as SO_4	11.03	8.7	12.7	11.01	9.85	12.6
TOTAL DISSOLVED SOLIDS	mg/l	12.07	91.2	158	112.95	44.6	154
SUSPENDED SOLIDS	mg/l	5.55	2	16.8			
TOTAL ORGANIC CARBON	mg/l as C	3.06	2.34	4.33	2.15	1.39	3.47
TOTAL TRIHALOMETHANES	µg/l				28.88	20.2	37.5
CHLOROFORM	µg/l				4.18	1.5	7.69
BROMODICHLOROMETHANE	µg/l				7.55	4.9	10.6
DIBROMOCHLOROMETHANE	µg/l				12.21	9.5	14.2
BROMOFORM	µg/l				4.96	3.2	6.65

Appendix 2

MIDMAR WATERWORKS	2002	RAW			FINAL		
DETERMINAND	**UNIT**	**MEAN**	**5TH Percentile**	**95TH Percentile**	**MEAN**	**5TH Percentile**	**95TH Percentile**
FREE CHLORINE	mg/l				0.19	0.05	0.6
TOTAL CHLORINE	mg/l				1.85	1.2	2.5
COLIFORMS	per 100 ml	6.08	0	18	0	0	0
E.COLI	per 100 ml		0	8	0	0	0
FAECAL STREPTOCOCCI	per 100 ml		0	12	0	0	0
ALGAE COUNTS	CELLS/ml		46	1503	1.56	0	8
pH			7.3	8.1		8.2	9.2
COLOUR	°H	6.87	3	10.9	1.29	0.5	3.16
TURBIDITY	NTU	7.93	2.73	15.8	0.3	0.19	0.46
CONDUCTIVITY	mS/m	6.39	6.06	6.84	8.3	7.53	9.05
TOTAL ALUMINIUM	µg/l	71.49	5	139	35.64	5	81.4
ALKALINITY	mg/l $CaCO_3$	24.25	22.3	26.9	29.71	26.8	33.6
TOTAL HARDNESS	mg/l $CaCO_3$	20.99	20	22.25	29.97	27.5	33.5
CALCIUM	mg/l	4.28	4	4.5	7.88	7	9.4
MAGNESIUM	mg/l	2.47	2.4	2.7	2.46	2.3	2.6
SODIUM	mg/l	4.45	3.9	4.9	4.52	4.1	4.8
POTASSIUM	mg/l	1.18	1.1	1.2	1.17	1	1.2
IRON	mg/l	0.23	0.11	0.53	0.02	0.01	0.04
MANGANESE	mg/l	0.01	0.01	0.04	0.01	0.01	0.01
SILICA	mg/l	4.65	4.3	5.2	4.49	4.2	4.8
NITRATE	mg/l as N	0.24	0.13	0.32	0.22	0.11	0.34
AMMONIA	mg/l as N	0.04	0.01	0.09	0.33	0.04	0.66
CHLORIDE	mg/l	4.49	3.82	5.11	7.4	6.36	8.22
SULPHATE	mg/l as SO_4	1.76	1.39	1.97	1.68	1.16	2.03
TOTAL DISSOLVED SOLIDS	mg/l	46.38	37.5	59	53.52	46.3	64.1
SUSPENDED SOLIDS	mg/l	7.61	2	21.5	2.66	2	6.67
TOTAL ORGANIC CARBON	mg/l as C	2.87	2.24	3.91	2.54	1.83	3.48
TOTAL TRIHALOMETHANES	µg/l				38.17	22.9	61.7
CHLOROFORM	µg/l				26.06	16.4	45
BROMODICHLOROMETHANE	µg/l				8.92	4.8	12.2
DIBROMOCHLOROMETHANE	µg/l				3.19	1.7	4.5
BROMOFORM	µg/l				0.05	0.05	0.05

Appendix 3

HAZELMERE WATERWORKS	2002	RAW			FINAL		
DETERMINAND	**UNIT**	**MEAN**	**5TH Percentile**	**95TH Percentile**	**MEAN**	**5TH Percentile**	**95TH Percentile**
FREE CHLORINE	mg/l				0.06	0.05	0.1
TOTAL CHLORINE	mg/l				1.47	1	1.8
COLIFORMS	per 100 ml	22.56	2	150	0	0	0
E.COLI	per 100 ml	11.72	0	36	0	0	0
FAECAL STREPTOCOCCI	per 100 ml	11.94	0	22	0	0	0
ALGAE COUNTS	CELLS/ml	432.34	0	1685	1	0	6.5
pH			7	7.7		8.6	9.4
COLOUR	°H	66.16	16.6	175	1.84	0.5	3.88
TURBIDITY	NTU	40.47	6.01	98.75	0.32	0.17	0.5
CONDUCTIVITY	mS/m	14.93	13.9	16.2	17.64	16.5	18.7
TOTAL ALUMINIUM	µg/l	309.92	86.8	723	48.39	5	97.6
ALKALINITY	mg/l $CaCO_3$	34.23	27.6	40	45.46	41	49.6
TOTAL HARDNESS	mg/l $CaCO_3$	32.21	28.75	35.75	47.33	43.83	51.17
CALCIUM	mg/l	5.18	4.5	5.8	11.25	9.5	12.5
MAGNESIUM	mg/l	4.63	4.2	5.1	4.61	4.1	5.2
SODIUM	mg/l	17.58	16	19	17.75	16	19
POTASSIUM	mg/l	1.44	1.3	1.6	1.44	1.3	1.6
IRON	mg/l	0.7	0.34	1.08	0.02	0.01	0.05
MANGANESE	mg/l	0.02	0.01	0.05	0.01	0.01	0.01
SILICA	mg/l	8.65	8.4	9	8.13	7.6	8.8
NITRATE	mg/l as N	0.62	0.43	0.74	0.67	0.45	0.81
AMMONIA	mg/l as N	0.04	0.01	0.08	0.21	0.06	0.31
CHLORIDE	mg/l	21.61	20.4	23.1	25.06	23.8	26.6
SULPHATE	mg/l as SO_4	5.14	3.8	6	5.09	4.18	6.09
TOTAL DISSOLVED SOLIDS	mg/l	13.35	95.2	184	111.91	102	128
SUSPENDED SOLIDS	mg/l	10.39	2	28.4			
TOTAL ORGANIC CARBON	mg/l as C	4.23	2.88	6.14	2.64	1.56	3.65
TOTAL TRIHALOMETHANES	µg/l				30.9	10.9	55.1
CHLOROFORM	µg/l				15.48	7.24	27.5
BROMODICHLOROMETHANE	µg/l				9.71	2.59	16.4
DIBROMOCHLOROMETHANE	µg/l				5.37	1.11	9.56
BROMOFORM	µg/l				0.39	0.05	1.92