THE DEVELOPMENT OF A CROSSFLOW MICROFILTRATION UNIT TO IMPROVE THE PERFORMANCE OF ANAEROBIC DIGESTORS AT WASTE WATER TREATMENT WORKS

Final Report

to the
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by

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EXECUTIVE SUMMARY

1 Introduction

In a pilot plant study at the Durban Corporation's Northern's Waste Water Treatment Works (NWWTW), a woven fibre cross-flow microfiltration (CFMF) unit was coupled to a pilot plant digester. The solids-free permeate from the CFMF unit was discarded while the concentrated biomass stream was recycled to the digester. The CFMF unit thus enabled the selective retention of biomass in the digester. The major effect was that the liquid residence time (LRT) was decoupled from the solids residence time (SRT) enabling the volumetric throughput of the digester to be increased while still maintaining a constant SRT. The second effect was that the biomass concentration in the digester was increased, enabling the digester to operate at an increased biomass loading per unit digester volume.

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

The overall aim of the project was to develop and demonstrate a cross-flow microfiltration unit for the improvement of anaerobic digesters at Waste Water Treatment Works. The project was initiated in January 1993 and ended in December 1996, following an extension of one year due a variety of mechanical problems experienced.

The project was divided into three stages :

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

2 The Economic Evaluation

The basis of the evaluation was to compare the cost of the coupled CFMF digester system with the cost of a conventional anaerobic digestion system. The conventional system considered was based on the existing plant at the Northern Waste Water Treatment Works (NWWTW). In the scenario investigated in the evaluation, a flowrate of settled primary sludge of 15000 kg/day was considered, representing 1,5 time the current capacity of the NWWTW.

Experiments were performed on sludge obtained from the full scale digestor at NWWTW to obtain flux data required for design of the CFMF unit and to obtain an indication of system stability and reliability. The capital costs and operating and maintenance requirements for each process were obtained from NWWTW personnel and EXPLOCHEM, the local agents for woven fibre CFMF unit, Exxflow. Labour, electricity and monetary rates were obtained from NWWTW. The capital, annual and total costs for each process were then calculated using a method approved of by NWWTW personnel. A project life of 20 years was assumed.

For the scenario considered, the conventional process would consist of a primary thickener, three primary digesters and one secondary digester while the coupled process would consist of a primary thickener and two primary digester linked to a CFMF unit.

The capital costs of the coupled CFMF/digester system is 27 % lower than that of the conventional process equipment. The labour, electricity and maintenance for the CFMF are higher than that of the conventional equipment. Over a project life of twenty years, however, the total project cost for the coupled system is 12 % lower than that of the conventional system. Hence, the coupled CFMF/digester system is economically feasible and is in fact more attractive than the conventional treatment equipment.

A sensitivity analysis on labour, on electricity and monetary rates indicates that this favourable position is maintained even when a worst case scenario disfavouring the coupled CFMF is considered.

Overall, the evaluation of the coupled CFMF/digester system indicates that the process is economically feasible. Accordingly, further large scale development of the process should be pursued, to establish the full scale performance, reliability and operability of the process.

3 The Microbiological Evaluation

The main aims of this study were to determine the biodegradability of NWWTW sludge, and to assess the positive and negative effects of operating an anaerobic digestor at elevated solids concentrations.

An essential preliminary investigation conducted was the biodegradability study. In this study the biodegradation potential of primary sludge from Northerns Waste Water Treatment Works, Durban, was assessed in flask cultures. The initial VS content of NWWTW sludge is approximately 76 %. The lower VS limit for digested NWWTW sludge was determined to be 50 %. The ultimate volatile solids reduction after 90 days was computed as 57 % and 68 %, giving an average destruction of 62,5 %. The volume of gas produced per unit mass of VS destroyed was computed as 0,85 L and 0,92 L, giving an average of 0,89 L gas/g VS destroyed.

Since the residence time of the solids in the digester is longer, the microorganisms have the potential to increase the volatile solids reduction of the substrate. The lower VS solids limits of approximately 50 % can therefore be used to assess the efficiency of VS destruction in the anaerobic digester/CFMF unit. Furthermore, the ratio of gas production per gram VS catabolised can be used to assess the biodegradation potential of the full-scale digester coupled to the microfiltration unit at NWWTW.

The evaluation of the effects of seven different solids concentrations on microbial activity indicated that the operation of a full-scale anaerobic digester of solids concentration > 2 % should improve digester efficiency. It was further deduced that an increase in solids concentration greater than 6,6 % (m/v) was unfavourable due to limitations in mass transfer and the inability to maintain homogeneity within the digester. It is however; improbable that digester would be operated with high solids concentrations due to difficulties in pumping of slurries and the highly viscous nature of the sludge. Thus for a full-scale digester operating at solids concentration between 3 to 6 % (m/v), there would be no reduction in microbial activity.

The results of four semi-continuous digesters operated at different solids concentrations revealed increased solids concentrations did not affect volatile solids destruction or gas production. The coupling of an anaerobic digester and CFMF unit would result in greater quantities of solid per unit volume could be treated with concomitant higher gas production rates. Thus, an increase in solids concentration should not benefit nor impede volatile solids destruction and microbial activity. It can be further concluded that as increased solids concentration did not reduce microbial activity, it would be beneficial to operate a full-scale digester at increased solids concentrations.

4 The Full-scale Trials

The main aims of this stage were to construct a full-scale microfilter and couple it to a full-scale digestor at NWWTW, and then to optimise and assess the performance of the coupled full-scale system.

The on-site engineering of the coupled CFMF/digestor system proved to be significantly more difficult, and protracted, than was planned for. This was primarily due to problems with two aspects, viz. development of an effective cleaning system, and engineering a blockage-free operation.

The system was originally designed for a brush cleaning system. This proved to be ineffective, and prompted the installation of squeegees that would have a similar cleaning action as rollers. However, significant mechanical problems were experienced with the engineering of the squeegee system. When these mechanical aspects were eventually overcome, it was found that the squeegees had a limited effectivness in removing foulants from the tube wall. Following experiences from other woven fibre microfiltration projects, a simple pulse cleaning technique was subsequently investigated. This proved to be at least as effective as the squeegee system. Combining the pulse cleaning with spraying water onto the outside of the tubes proved to be the most effective cleaning technique, and was subsequently implemented on the unit.

From the initiation of experiments on the digestor sludge, numerous blockages were experienced on the unit. Investigations indicated that these stemmed from hair accumulating in the inlet manifold, and not from blockages within the tubes themselves. A detailed investigation into the manifold blockages indicated that the problem was complex, and could not be easily correlated with geometric or operating factors. A theory of how blockages form was proposed, together with a proposal for improving the manifold design. Due to time constraints, however, this could not be developed further. Options to reduce the blockage potential of the fibres were investigated. This involved, inter alia, investigation the installation of a macerator just upstream of the microfiltration unit. However, discussions with vendors and NWWTW personnel indicated that this was unlikely to be successful. Eventually, to enable progress on the rest of the project, a simple "hair catcher" was designed and installed before the CFMF unit. In the few successful runs performed before the project was terminated, the hair catcher devise proved successful in preventing blockages.

Due to the setbacks experienced with the on-site engineering of the system, only a limited number of runs were performed with the microfilter coupled to the digestor. These runs were performed with the hair catcher device installed, and indicated that the process could operate stabily when the problem of blockages was obviated. The permeate fluxes obtained over 14 sucessful runs ranged from 6 LMH to 22 LMH, with an average of about 10 LMH. This is well below the average value of 40 LMH obtained in pilot plant trials, at similar solids concentrations. This significant difference could be ascribed to high evaporation rates from the curtains, reducing the permeate flow, as well as a difference in operating point. The pilot plant trials were performed with a tube velocity of about 2 m/s, whereas the full-scale trials were performed at a tube velocity of about 0,9 m/s. This was due to difficulties with setting operating points on the full-scale unit, as well as partially to operator error. The full-scale runs did however also indicate that there was no significant irreversible fouling of the membranes over the two month test period. This indicated that the pulse-spray cleaning strategy was effective in removing foulants from the curtains.

5 Conclusion and Recommendations

At the end of the day, the project has failed to demonstrate to potential users that the coupled CFMF/digestor system is reliable, robust and easily operable. It could be argued that most of the problems with the coupled process have been ironed out, and that the above demonstration could have been met if the project had been extended. The reality however is that various unexpected problems did arise during the project, resulting in a decrease in process confidence, and this warrants a re-evaluation of the potential applicability of this technology.

Most of the problems experienced could be described as "engineering" problems, and hence can be easily avoided in future designs. However, the problem of blockages is an inherent "process" problem. While this was obviated in the current project by the installation of a hair catcher device, this is not regarded as a permanent solution to the problem. The hair catcher itself is prone to blockages, depending on the nature of the sludge. It would require regular cleaning, and is thus labour intensive. It also introduces the additional problem of disposal of the hair together with unstabilised solids that are trapped with the hair. It is thus an added unit process to what operators at NWWTW regarded as an already complex process, and is unlikely to find favour with end users.

On site experiences at NWWTW during the course of this project also enlightened project personnel to the "nature of the monster" that we have to deal with. On one occasion a 60 cm outlet pipe from the digestor had become completely blocked up with hair. It took operators approximately a day to clear this out. They were extremely sceptical of whether the CFMF unit, with tubes and pipes ranging from 2,5 cm to 25 cm, would handle the sludge.

The project team is forced to conclude that coupling an anaerobic digestor to an external microfilter is not likely to be viable in instances where there is a significant amount of hair/fibres in the digestor sludge. This would preclude operation at most waste water treament works. The coupled process could however be viable when the sludge does not contain fibrous material. The process could thus be applicable in digestors treating industrial effluents.

It is recommended that :

(1) No further work should be performed at waste water treatment works, unless an innovative solution to the blockage problem can be found. Immersed membrane systems could be more suited to digestors at waste water treatment works, since they obviate the problem of hair blockages.

(2) Application of the coupled CFMF/digestor system to industrial effluent treatment should be investigated.

(3) For completeness, the microbiological study should be extended to include the aspects of control, stability, and resistance to toxicity at elevated concentrations.

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Prof G A Ekama - University of Cape Town
Mr K Treffry-Goatley - Explochem
Prof E Senior - University of Natal

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(iii) Durban Municipality, for making facilities at the Northern Waste Water Treatment Works available to the project

(iv) The staff of the Northern Waste Water Treatment Works

(v) The workshop staff in the Department of Chemical Engineering

(vi) Staff of the Pollution Research Group, University of Natal

(vii) Students of the Water Technology Group, M L Sultan Technikon

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I 1.1. Conventional Anaerobic Digestors

Anaerobic digesters are widely employed at Waste Water Treatment Works, for the destruction of volatile solids (VS) in settled primary sludge. The conventional anaerobic digester is a single pass reactor, with no selective solids recycle. Hence, the liquid residence time (LRT) is equal to the solids residence time (SRT). In general, a relatively long SRT is required for effective VS destruction (15 to 30 days). For a digester of specified volume, therefore, the volumetric throughput is limited by the required SRT. Conventional digesters operate at relatively low biomass concentrations (1,5 to 3% m/m). This reduces the biomass loading per unit volume, and requires that the effluent sludge undergoes further thickening prior to the de-watering step.

I 1.2. Woven Fibre Cross-flow Microfiltration

Cross-flow microfiltration (CFMF) is a membrane process that enables the continuous filtration of particulate suspensions. In general, microfilters are capable of removing particles down to the sub-micron level.

The suspension is pumped into a porous tube (Figure I1).

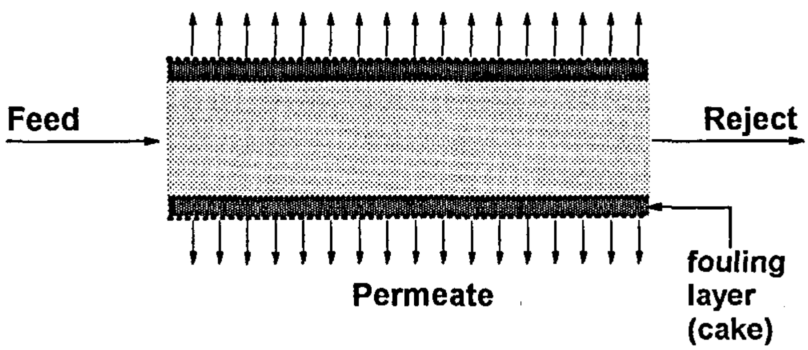

Figure I1 : Schematic of Crossflow Microfiltration

Clear liquid permeates the tube wall, driven by the pressure difference across the wall, and is recovered as the permeate. This flow of fluid normal to the wall convects particles to the wall where they accummulate to form a polarized layer, the cake. The çake constituting an increase in the hydraulic resistance, decreases the permeate flux. However the flow of the bulk suspension tangential to the cake tends to limit its growth, eventually resulting in a cake thickness, and hence permeate flux, that is relatively constant with time - the steady-state condition.

Porous supports utilized in CFMF include stainless steel, ceramic, rigid plastic, polymeric and flexible woven fibre tubes. Woven fibre tubes can be produced relatively inexpensively in large lengths. This potentially extends the economical viability of CFMF to large-scale high-volume applications, e.g. the production of potable water and the treatment of waste water.

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

Commercially, woven fibre microfiltration membranes are produced in the form of vertical arrays of collapsed tubes. Under pressure, this forms a vertical array of tubes known as a curtain (Figure I2).

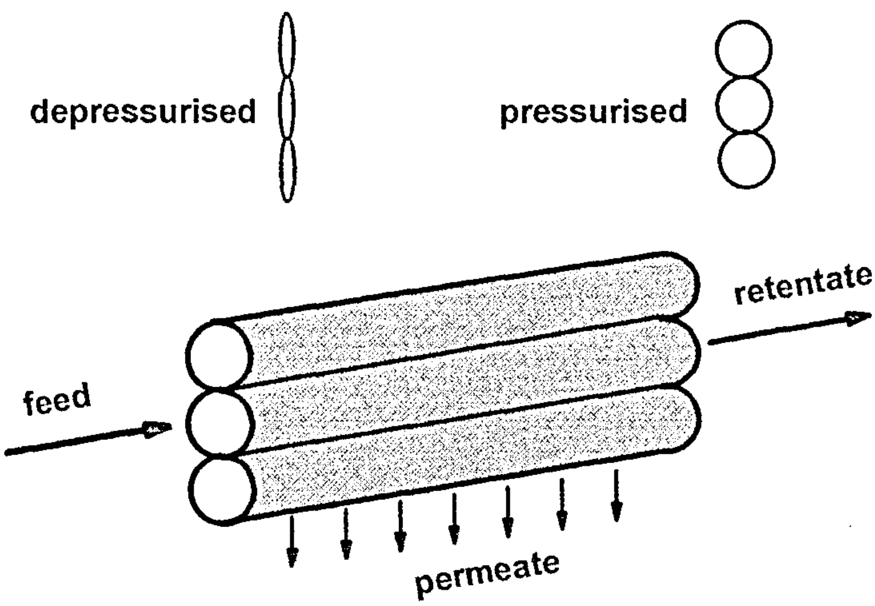

Figure I2 - Schematic of Woven Fibre Curtain

I 1.3. The Coupled Digestor/Microfilter System

In a pilot plant study at the Durban Corporation's Northern's Waste Water Treatment Works (NWWTW), a woven fibre cross-flow microfiltration (CFMF) unit was coupled to a pilot plant digester [Bindoff et.al. (1987)] . The solids-free permeate from the CFMF unit was discarded while the concentrated biomass stream was recycled to the digester (Figure I3).

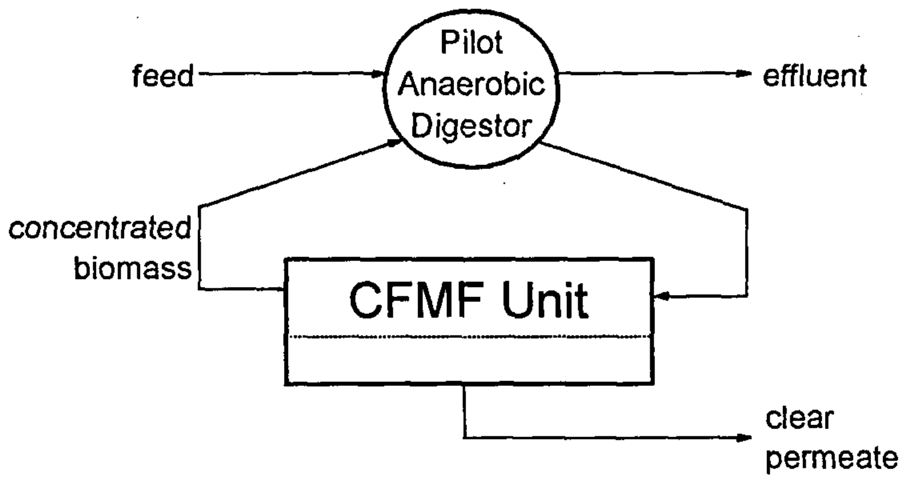

Figure I3 - Coupled Microfilter/Digestor System

The CFMF unit thus enabled the selective retention of biomass in the digester. The major effect was that the LRT was decoupled from the SRT enabling the volumetric throughput of the digester to be increased while still maintaining a constant SRT. The second effect was that the biomass concentration in the digester was increased, enabling the digester to operate at an increased biomass loading per unit digester volume.

The implication of these pilot plant trials is that existing digesters could be operated at volumetric flowrates which would exceed their current maximum values, while still obtaining the same extent of volatile solids destruction. This would enable Waste Water Treatment Works to cope with increases with inflows and delay the necessity to construct new digesters. This is of particular importance in the South African context, where rapidly changing demographics may result in inflows to WWTW exceeding the design capacities of those works.

In addition to increasing the capacity of the digestors, there would be indirect advantages to the operation of the digestor itself, as well upstream and downstream processes :

(i) The increased turnover of the digestor contents could improve fluid flow patterns within the digestor, and reduce the occurrence of bypassing and dead-zones.

(ii) The effluent from the digester would have a higher solids concentration, reducing the volumetric load to downstream sludge concentration and de-watering equipment.

(iii) The supernatant liquor that is returned to the head of the works, i.e. the permeate from the CFMF unit, would have a negligible suspended solids content, reducing the re-circulating solids load and leading to improvements in the performance of unit processes upstream of the digester.

Further development of the coupled membrane process will entail establishing and demonstrating its performance on a larger scale, as well as assessing its long term reliability and operability. This project concerned the development of the coupled CFMF/digester system to a full scale process.

The overall aim of the project was to develop and demonstrate a cross-flow microfiltration unit for the improvement of anaerobic digesters at Waste Water Treatment Works. The project was initiated in January 1993 and ended in December 1996, following an extension of one year due a variety of mechanical problems experienced.

I 2 APPROACH

The project was divided into three parts :

Part A - Economic Evaluation of the Coupled CFMF/Digestor System

As noted in the Introduction, further development of the coupled process would have to occur on a larger scale, to identify and solve the engineering problems associated with full-scale systems. Prior to investigation on a larger scale, however, the economic feasibility of the coupled process needs to be established. If the coupled system offered no significant economic advantage over conventional systems, the full-scale investigation would not be warranted at this stage.

A desk study of the coupled system was performed. This economic evaluation of the coupled system is presented in Part A.

Part B - Microbiological Evaluation of the Coupled CFMF/Digestor System

The coupled system would result in digestors operating at elevated biomass concentrations. It is thus important to know what effects, if any, operation at elevated concentrations would have on the biomass viability, and the operation and control of the digestor. A laboratory study into the effects of operating a digestor at elevated concentrations is presented in Part B.

Part C - Evaluation of the Full-Scale Coupled CFMF/Digestor System

This final part concerns constructing a full-scale cross-flow microfilter and coupling it to the full-scale digestor at NWWTW. The coupled system would then be engineered to operated at an elevated concentration and the viability and performance of the coupled system would be assessed. This is discussed in Part C.

PART A
ECONOMIC EVALUATION

The detailed economic evaluation is available in Pillay (1993). Essential aspects are summarised below.

The basis of the evaluation was to compare the cost of the coupled CFMF digester system with the cost of a conventional anaerobic digestion system. The conventional system considered was based on the existing plant at the Northern Waste Water Treatment Works (NWWTW). In the scenario investigated in the evaluation, a flowrate of settled primary sludge of 15000 kg/day was considered, representing 1,5 time the current capacity of the NWWTW. The inputs and specifications to the processes are summarised in Table A1.

Table A1 - Inputs and Specifications to the Processes to be Evaluated

Total sewage flowrate into works	60 Mℓ/day
Flowrate of primary settled sludge	15 000 kg/day
Solids content of feed to digestor	5,6 %
Volatile solids content of the primary settled sludge, as a percentage of the total solids	81 %
Minimum acceptable solids residence time in digestor	26 days

Experiments were performed on sludge obtained from the full scale digestor at NWWTW to obtain flux data required for design of the CFMF unit and to obtain an indication of system stability and reliability. The capital costs and operating and maintenance requirements for each process were obtained from NWWTW personnel and EXPLOCHEM, the local agents for woven fibre CFMF unit, Exxflow. Labour, electricity and monetary rates were obtained from NWWTW. The capital, annual and total costs for each process were then calculated using a method approved of by NWWTW personnel. A project life of 20 years was assumed.

For the scenario considered, the conventional process would consist of a primary thickener, three primary digesters and one secondary digester (Figure A1) while the coupled process would consist of a primary thickener and two primary digester linked to a CFMF unit (Figure A2).

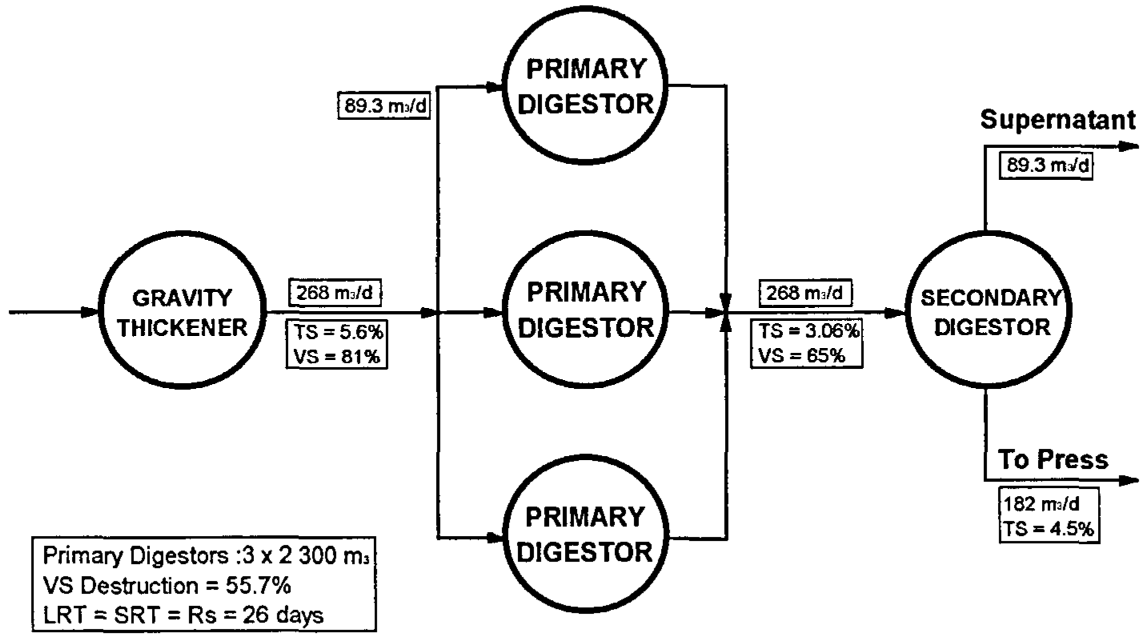

Figure A1 - Conventional Process to Handle Inputs in Table A1.

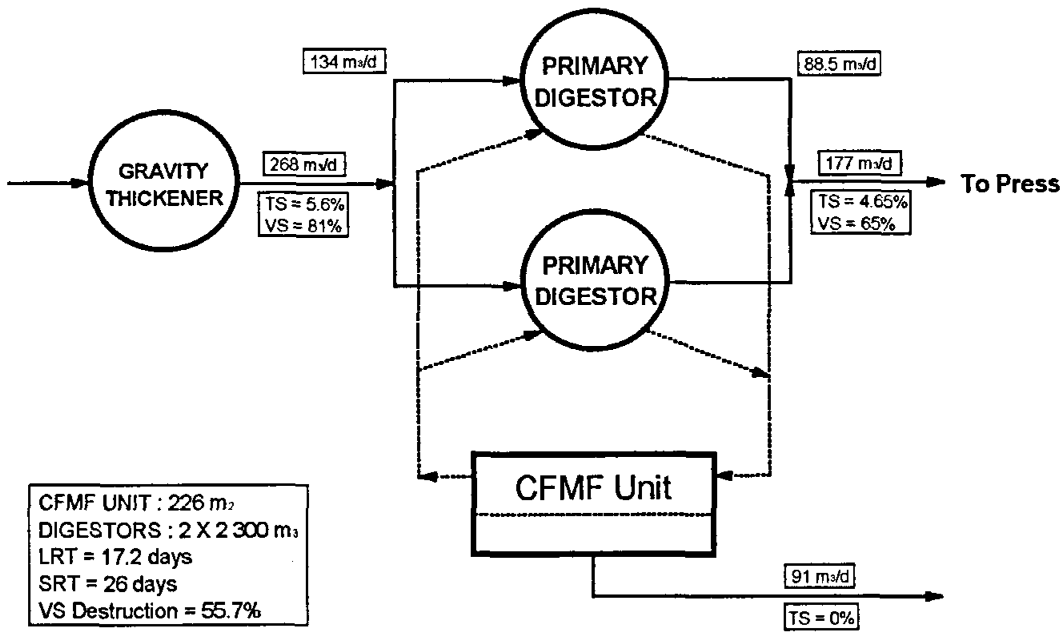

Figure A2 - Coupled Microfiltration/Digestor to Handle Inpute of Table A1.

The evaluation is summarised in Table A2.

Table A2 - Summary of Capital and Operating Costs (Present Value : 1992 Rands)

	Process 1 (Conventional)	**Process 2 (CFMF/Digestor)**
Capital	5 751 000	4 170 000
Annual capital repayment	1 021 897	740 969
Annual electricity charge (Present Value)	27 064	37 913
Annual labour charge (PV)	94 690	100 311
Annual maintenance charge (PV)	53 157	67 374
TOTAL PROJECT COST (PV) (for 20 years)	8 679 754	7 611 551
Capital savings *		27 %
Savings on total project cost *		12 %
$*((\frac{conventional-coupled}{coupled}) \text{ x } \frac{100}{1})$		

The capital costs of the coupled CFMF/digester system is 27 % lower than that of the conventional process equipment. The labour, electricity and maintenance for the CFMF are higher than that of the conventional equipment. Over a project life of twenty years, however, the total project cost for the coupled system is 12 % lower than that of the conventional system. Hence, the coupled CFMF/digester system is economically feasible and is in fact more attractive than the conventional treatment equipment.

A sensitivity analysis on labour, on electricity and monetary rates indicates that this favourable position is maintained even when a worst case scenario disfavouring the coupled CFMF is considered (Table A3).

Table A3 - Sensitivity Analysis

Sensitivity Analysis on Economic Evaluation - Based on Conditions in Table A1.

(all costs expressed in Millions of 1992 Rands)

Scenarios Considered	Capital Costs		Total Project Costs		Percentage Saving *	
Process 1 : Conventional Process *Process 2 : Coupled CFMF/AD*	Process 1	Process 2	Process 1	Process 2	Capital	Total Project
Base Case (for costs and rates as in Tables 3,4 and 5)	5,751	4,170	8,68	7,612	27,5	12,3
Increase capital cost of CFMF unit by 10%	5,751	4,213	8,68	7,671	26,7	11,6
Increase labour rates by 10%	5,751	4,170	8,859	7,81	27,5	11,8
Increase electricity rates by 10%	5,751	4,170	8,725	7,674	27,5	12
Increase inflation from 15% to 17%	5,751	4,170	9,244	8,275	27,5	10,5
Decrease inflation from 15% to 13%	5,751	4,170	8,223	7,075	27,5	14
Increase interest rate from 17% to 19%	5,751	4,170	8,237	7,091	27,5	13,9
Decrease interest rate from 17% to 15%	5,751	4,170	9,244	8,275	27,5	10,5
Worst Case Scenario: Increase capital cost of CFMF unit by 10% Increase labour rates by 10% Increase electricity rates by 10% Increase inflation from 15% to 17% Decrease interest rate from 17% to 15%	5,751	4,170	10,280	9,557	26,7	7,0
*[[(Conventional - Coupled) / Coupled] * 100]						

The effect of feed solids content and total primary sludge flowrate on the economic feasibilty was determined. The economic favourability of the coupled CFMF/digester system improves as the feed solids concentration decreases (Figure A3). In considering the settled sludge flowrate, the coupled CFMF/digester system is in general more economically attractive than the conventional equipment (Figure A4). However, there does exist a region were the coupled process is more expensive than the conventional treatment equiment.

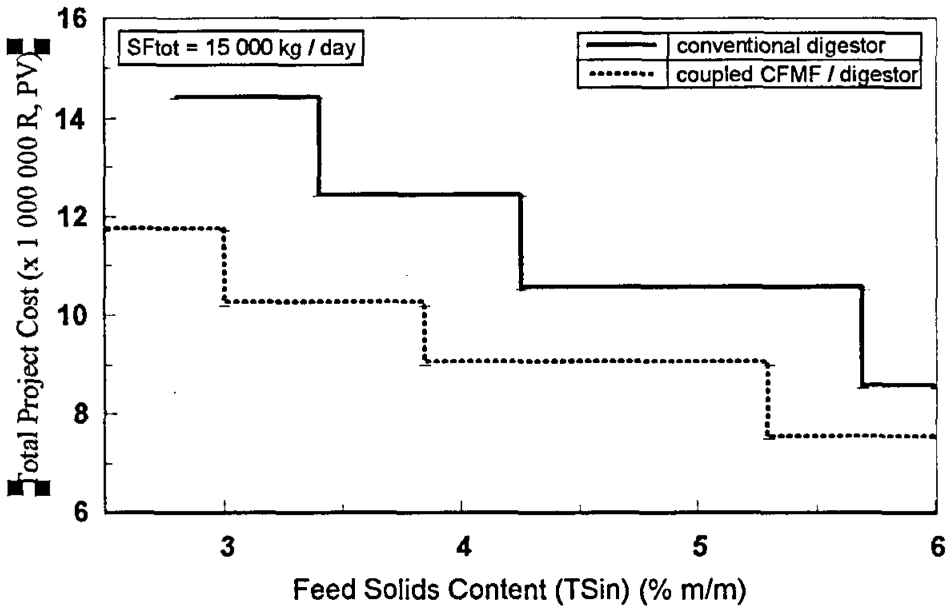

Figure A3 - Effect of Feed Solids Concentration on Total Project Cost

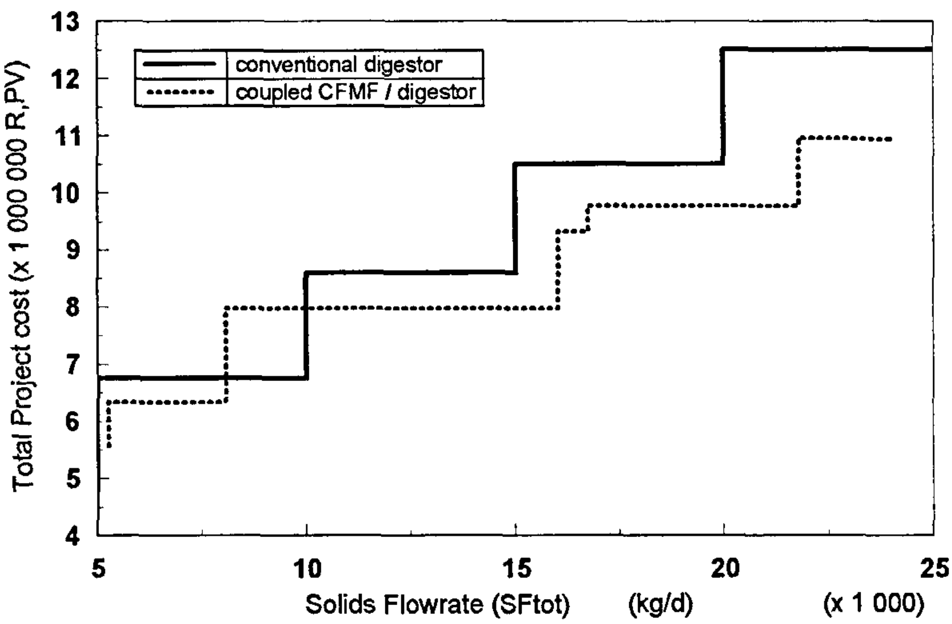

Figure A4 - Effect of Total Solids Flowrate on Total Project Cost

Overall, the evaluation of the coupled CFMF/digester system indicates that the process is economically feasible. Accordingly, further large scale development of the process should be pursued, to establish the full scale performance, reliability and operability of the process.

PART B
EVALUATION OF MICROBIOLOGICAL ASPECTS

The laboratory study into the operation of anaerobic digestors at elevated biomass concentrations was performed as part of an MSc(Eng) study in the Department of Chemical Engineering, University of Natal, by Ms V Naidoo (1995).

A Summary is presented here.

B 1 PROJECT OBJECTIVES:

In the coupled microfilter/anaerobic digestor system, solids are selectively retained within the digestor, leading to digestors operating at elevated biomass concentrations. It is thus important to know what effects, if any, operation at elevated concentrations would have on the biomass viability, and the operation and control of the digestor.

The objective of this section was to determine the effects that an increase in solids concentration would have on microbial activity and anaerobic digestion efficiency. To achieve this goal the following experiments were conducted :

B 1.1.1.The Biodegradability Study

The objective here is to determine the biodegradation potential of the primary sludge in the substrate. Characteristics of primary sludge vary from plant to plant, therefore it was important to establish what percentages of the substrate were biodegradable and recalcitrant. Experiments were analyzed routinely for volatile solids, total solids, pH, and volatile acids/alkalinity and gas production using batch digesters. These experiments determine the minimum volatile solids concentration obtainable after ninety days of digestion and produced an estimate of the ratio of gas produced per g volatile solids destroyed.

B 1.1.1.The effects of higher solids concentration on microbial activity

Microbial activity was estimated by measuring the volume of gas produced and the rate of biogas production. The aim of this experiment was to determine if the solids concentrations produced different volumes of gas at different rates. This study identified which solids concentrations resulted in an increase in microbial activity and which could be maintained in semi-continuous or continuous anaerobic digesters to improve the efficiency of the process.

B 1.1.2. Operation of Semi-continuous Digesters with different solids concentrations

The objective of this experiment was to determine if a digester with increased solids concentration performed more or less efficiently than a standard digester (2 to 2.6% total solids - the control). A digester with increased solids concentration which performed as well as the control was also considered as a positive.

B 2 The Biodegradability of Primary Sludge from Northerns Waste Water Treatment Works (NWWTW)

B 2.1. Experimental Procedure

Two biodegradability studies to determine the upper and lower limits of volatile solids destruction and gas production were undertaken in batch digesters (3L Erlenmeyer flasks). The gas produced from waste stabilisation was collected in a separate gas collection system and measured by the displacement of 0,5 M HCl.

Sludge used in the investigation comprised of substrate (primary sludge) and innoculum (digested sludge). A substrate : inoculum ratio of 4:1 and 2:3 were used for trial 1 and 2 respectively. Different ratios were investigated since the substrate: inoculum ratio used in trial 1 resulted in an acid generation/consumption imbalance. Weekly analysis of volatile solids (VS), total solids (TS), pH and volatile acids/alkalinity (VA/ALK) ratio were performed on trials 1 and 2.

B 2.2. Results and Discussion

B 2.2.1. Monitoring and Control of the Digester:

Optimal anaerobic digester efficiency is maintained within pH range 6,8 to 7,4. The first biodegradability experiment (trial 1) indicated an initial pH of 5,5 accompanied by a VA/ALK ratio of 0,4 to1,1. A permissible VA/ALK ratio for anaerobic digester is 0,3. Thus the high ratio obtained was possibly as a consequence of high acid concentration, a low methane yield, a high carbon dioxide yield and low gas production. Chemical addition of lime was therefore necessary to stabilise the system to an acceptable pH level. The digester was allowed to recover over a period of 23 days with pH stabilising at 7,1 and VA/ALK ratio levelled of at 0,2 during the latter period of trial 1 (day 64-89).

The substrate: inoculum ratio in trial 2 was increased to counteract a long lag period experienced in trial 1. The initial pH in trial 2 was 7,6 but subsequently dropped to 6,8. This prompted the addition of sodium bicarbonate to neutralise acid produced during the hydrolysis-fermentation stage of digestion. Unfavourable conditions were further emphasised by high VA/ALK ratios above 0,3. After a nine day lag period digester conditions stabilised to a pH of 7,0 to 7,3 and a VA/ALK ratio of 0,2 to 0,3.

The consequences of the anaerobic digesters operating at non-optimal conditions were negligible volatile solids removal and minimal gas production.

B 2.2.2. Volatile Solids Destruction and Total Gas Production:

In trial 1, poor volatile solids destruction was prevalent in the initial stages with the VS content decreasing from 76%(m/m) to 74%(m/m) over a 4 week period. This coupled with low gas production, 8 330 ml over a 40-day period, was probably a result of unfavourable environmental conditions within the digester and was indicative of a long lag period. Following a recovering period, rapid VS destruction (63%VS) accompanied by increased total gas production (23 490 ml), by day 70, implied digester stabilisation. After 85 days, the VS in samples decreased to 50% VS with no further significant decrease in VS or gas production. Thus, 50% VS was proposed as the lower VS limit for sludge treated at NWWTW.

In trial 2, unfavourable environmental conditions were minimised by the change in substrate: inoculum ration and the addition of sodium bicarbonate. Over a 30-day period, the VS were reduced from 70% to 54% with 16949ml of gas being generated. The VS levelled out at 50% after 80 days, and thus 50 % is regarded as a reasonable lower VS limit.

The volatile solids reduction for trial 1 and 2 were computed as 57% and 68% respectively. At the end of each trial, the volume of gas produced per gram volatile solids removed was calculated. The anaerobic digester norm is 1 m^3 gas produced per kilogram VS destroyed. For trial 1 and 2 this was computed to be 0,92 L gas/g VS destroyed and 0,85 L gas/g VS destroyed respectively.

B 3 The Effects of Increased Digested Sludge Concentrations on Microbial Activity

Concentrating digested sludge produced two advantages to the process of anaerobic digestion: increasing the biomass concentration, and reducing the unit volume required for a given quantity of solids. This study determined the differences in gas production volumes and rates in the presence of different digested sludge concentrations. It is important to know if cumulative gas production increased with higher digesters sludge concentration or if concentrating digested sludge produces a negative effect on the process of anaerobic digestion. This study examined seven different total solids concentrations, their respective gas production volumes and the gas production rates.

B 3.1. Experimental Procedure

Serum bottles (125 ml) were used as batch digesters. Each bottle was filled with 25 ml of substrate (primary sludge) (6% TS; 80% VS) and 45 ml digested sludge (with different total solids concentrations; 60% VS). The sludge was concentrated in a Beckham centrifuge at 10 000-rpm xg for 25 minutes to 13% TS. The centrate was used to prepare digested sludge solutions of 3%, 4%, 5%, 6.5% and 11% TS. The digested sludge with 2% TS was used as the control. The digesters contained a working volume of 70 ml and a gas headspace volume of about 50 ml. Each bottle was then overgassed with oxygen-free nitrogen to displace the air from the bottle and promote the onset of anaerobiosis. The bottles were sealed with a butyl rubber septum and an aluminum cap and placed in an incubator at 35 ^{0}C and a disposable syringe and hypodermic needle was inserted through the septum to measure the gas produced daily. All experiments were conducted in quadruplicate.

B 3.2. Results and Discussion

Increased digested sludge concentrations produced greater volumes of gas during the anaerobic digestion of primary sludge. The digesters that operated with initial digested sludge concentrations of 6 % produced up to 300 ml more gas than the control (2 % TS).

Increased digested sludge concentrations also produced gas at a faster rate since the more concentrated sludge degraded the primary sludge more rapidly than the control (2% TS).

Using anaerobic digestion figures of 0,88 L (experimental value) and 1,0 L (standard anaerobic digestion value for primary sludge) gas produced per g volatile solids destroyed, the mass of volatile solids accounted for by the bacterial population was estimated. The percentage volatile solids catabolized increased as the concentration of digested sludge increased up to 6% TS, after which there appeared to be little difference in the efficacy of the batch digesters with 6%, 11% and 13% TS.

B 4 Operation of four Semi-Continuous Anaerobic Digesters with Different Solids Concentrations

B 4.1. Experimental Procedure

Four semi-continous anaerobic digesters were operated simultaneously to determine the efficiency of digestion with varying solids concentration. Each 2 L digester had a working volume of 1,5 L with no mechanical mixing device. Thus, over the 30-day experimental period, each digester was shaken during daily sampling. The digesters were kept in a water bath at a constant temperature of 35 °C and connected to gas collection systems, as well as influent and effluent channels for the removal of waste and the addition of fresh substrate.

The digestors were operated at 2 % TS (Run 1), 3 % TS (Run 2), 3,8 % TS (Run 3) and 4,7 % TS (Run 4). Higher solids concentrations proved to be difficult to handle on a laboratory scale, with sampling almost impossible in a 2 L digestor.

Run 1 was the control (2 % TS). To obtain the higher concentrations required in Runs 2,3 and 4, the effluent removed on each day was concentrated in a centrifuge and the concentrate recycled to the digestor. The concentration was performed in a Beckman centrifuge at 10 000 rpm xg for 25 minutes, and the centrate was used to prepare suspensions of 3 %, 3,8 % and 4,7 % TS.

Each day, 50 ml of sludge was removed from Run 1 and replaced with 50 ml primary sludge possessing a TS of 5% and VS between 70% and 80%. Approximately 150 ml of digested sludge was removed daily from Runs 2,3 and 4. This was then replaced with 100 ml of concentrated sludge (at the appropriate concentration), and 50 ml of primary sludge. Since Runs 2,3 and 4 were also initiated with a TS of 2 %, this procedure of removal of sludge, concentration and recycling was continued until the solids concentration within each digestor reached a steady state.

Samples (50 ml digested sludge) were removed from each digestor daily, and subjected to daily analysis of VS, TS, VA, alkalinity, pH and gas measurement.

B 4.1.1. Results and Discussion

Throughout the 30-day period the investigation was undertaken, gas production fluctuated for all 4 digesters of varying solids concentration. The rate of gas production increased from 631 ml/day for 2 % TS to 856 ml/day for 3,8 % TS. This implied that a doubling of solids concentration did not effect a doubling in gas volume production. The digester operated with a solids concentration of 4,7 % TS produced gas at a lower rate than Run 3 (3,8 % TS). This could indicate that the high solids concentration was negatively affecting microbial activity. Alternatively, due to inefficient mixing of the digester, gas could be trapped within the viscous sludge leading to inaccurate gas measurement. Inefficient mixing could have also resulted in a non-uniform distribution of substrate to the microorganisms that could have influenced microbial activity. The lack of homogeneity within the digester could have possibly led to the concentration of inhibitory products produced during anaerobic digestion.

Volatile and Total Solids Analysis:

Total solids analysis of digested sludge indicated a relatively stable total solids concentration in the digesters during the 30-day experimental period. Minor fluctuations in TS concentrations could be attributed to the inability to attain homogeneity in the digesters. All four digesters indicated a volatile solids concentration between 60-65%.

Volatile Acids, Alkalinity, pH and Volatile Acids/Alkalinity Ratio:

During the continuous or semi-continuous operation of anaerobic digesters, there is always a threat of toxic or volumetric overload. Overloading is manifested in various ways such as pH, volatile acids and alkalinity changes. Thus, monitoring changes within the chemical environment of the digester can avert stress and impending digester failure.

Volatile acid concentrations for Runs 1 and 2 fluctuated between 400 mg/L to 600 mg/L, while Runs 3 and 4 exhibited VA concentrations between 700 mg/L and 800 mg/L. Thus the digesters operated under increased solids concentrations produced higher volatile acids.

The pH for each digester remained constant throughout the investigation, although increases in VA for Runs 3 and 4 were recorded. The VA/ALK ratio, which is critical for monitoring digester behaviour due to its sensitivity to changes in VA concentration and buffering capacity, remained below permissible levels. Runs 1 and 2 displayed VA/ALK ratios ranging between 0,1 to 0,14, while Runs 3 and 4 recorded VA/ALK ratios >0,15.

B 5 Summary

An essential preliminary investigation conducted was the biodegradability study. In this study the biodegradation potential of primary sludge from Northerns Waste Water Treatment Works, Durban, was assessed in flask cultures. The initial VS content of NWWTW sludge is approximately 76 %. The lower VS limit for digested NWWTW sludge was determined to be 50 %. The ultimate volatile solids reduction after 90 days was computed as 57 % and 68 %, giving an average destruction of 62,5 %. The volume of gas produced per unit mass of VS destroyed was computed as 0,85 L and 0,92 L, giving an average of 0,89 L gas/g VS destroyed.

Since the residence time of the solids in the digester is longer, the microorganisms have the potential to increase the volatile solids reduction of the substrate. The lower VS solids limits of approximately 50 % can therefore be used to assess the efficiency of VS destruction in the anaerobic digester/CFMF unit. Furthermore, the ratio of gas production per gram VS catabolised can be used to assess the biodegradation potential of the full-scale digester coupled to the microfiltration unit at NWWTW.

The evaluation of the effects of seven different solids concentrations on microbial activity indicated that the operation of a full-scale anaerobic digester of solids concentration > 2 % should improve digester efficiency. It was further deduced that an increase in solids concentration greater than 6,6 % (m/v) was unfavourable due to limitations in mass transfer and the inability to maintain homogeneity within the digester. It is however; improbable that digester would be operated with high solids concentrations due to difficulties in pumping of slurries and the highly viscous nature of the sludge. Thus for a full-scale digester operating at solids concentration between 3 to 6 % (m/v), there would be no reduction in microbial activity.

The results of four semi-continuous digesters operated at different solids concentrations revealed increased solids concentrations did not affect volatile solids destruction or gas production. The coupling of an anaerobic digester and CFMF unit would result in greater quantities of solid per unit volume could be treated with concomitant higher gas production rates. Thus, an increase in solids concentration should not benefit nor impede volatile solids destruction and microbial activity. It can be further concluded that as increased solids concentration did not reduce microbial activity, it would be beneficial to operate a full-scale digester at increased solids concentrations.

PART C
FULL-SCALE COUPLED SYSTEM

C 1 OVERALL PROJECT PLAN

This part of the project was divided into four sequential stages :

C 1.1. Design and Construction of CFMF Unit :

The CFMF was to be designed and fabricated in the workshops of the Department of Chemical Engineering. Therafter it was relocated to the Northern Waste Water Treatment Works and integrated with the No. 2 Digester on site.

C 1.2. On-site Engineering of CFMF Unit

This stage concerned the adaptation and engineering of the cleaning mechanisms, flow path, control equipment and control strategy to provide reliable, fully automated operation, as well optimization of the CFMF unit operation.

C 1.3. Investigations into the Performance of the Coupled CFMF/Digestor

In the third stage, the concentration in the digester was to be increased and the flow distribution and reaction thermodynamics and kinetics were to be monitored. Any problems resulting from the coupling of the CFMF unit to the Digester was to be identified and engineered out.

C 1.4. Demonstrations

The coupled process was to be operated continuously in a fully automated mode, and was to be demonstrated to potential users.

C 2 OVERVIEW

The design and construction of the CFMF unit proceeded relatively smoothly, except for unexpected delays due to lack of details on the brush clenaing system, and the unavailability of workshop staff. The unit was then relocated to the NWWTW in January 1994, and on-site installation was continued. The unit was fully operational by March 1994, and the on-site engineering of the system was initiated.

The development of an effective cleaning system and a blockage free system ended up being significantly more complex than was anticipated, and taking a significantly longer period than expected. In addition, various sundry mechanical and operational problems were experienced on the CFMF unit. This necessitated the project being extended for a further year, till the end of December 1996.

All major problems had been addressed by June 1996, and runs to evaluate the combined system were initiated in the second half of 1996 and proceeded relatively smoothly thereafter. However, attempts to extend the project for a further year were unsuccessful. Accordingly, the project was terminated in December 1996 without project objectives C 1.3 *Investigations into the Performance of the Coupled CFMF/Digestor System*, and C 1.4 *Demonstrations* being met.

The design, construction and on-site installation of the CFMF unit are discussed in Section C 3. The onsite engineering is discussed in Section C 4, together with the performance data obtained before the project was terminated.

C 3 DESIGN AND CONSTRUCTION OF THE CFMF UNIT

The elements of the design were as follows :

(i) The unit will be designed for four 25 mm curtain modules fed by one feed pump. In the first phase only two modules will be installed, the remainder to be added during the third stage of the project, i.e. *Investigations into the effect on digestor performance*. However the control system and frames will be designed to accommodate all four curtain modules.

(ii) The unit will utilise the brush cleaning system developed by Renovexx, a British company that was also utilising woven fibre microfiltration technology.

The design and construction was overseen by Mr B Townsend, of the Pollution Research Group (PRG), University of Natal. The unit was constructed in the workshops of the Department of Chemical Engineering, and moved to the Northern Waste Water Treatment Works in January 1994. On site installation continued through January. The scheduled date for the completion of the CFMF unit's construction was September 1993, and the rig was to have been commissioned during December 1993 and operating continuously by February 1994. The delay in construction and commissioning of the rig was primarily due to two factors :

(i) Difficulty in obtaining details of the brush cleaning system

The construction of the brush cleaners was to have followed the plans obtained from Renovexx. However, the plans did not include certain critical dimensions and details. On communicating with Renovexx, it was established that the plans had been drawn by a company that Renovexx had subsequently ceased dealings with. Hence, Renovexx had also been hampered by the lack of plan details. Renovexx had also effected significant design changes which had not yet been reflected on the plans due to a lack of available manpower.

The problem of the lack of details was partially solved when a member of the PRG, who was in England at the time, visited Renovexx and obtained the necessary details. The development of the brush cleaning system is discussed further in Section C 3.2.

(ii) Unavailability of workshop staff

All construction was to be performed by the Department of Chemical Engineering workshop staff. The Department's policy is that priority will be given to tasks required for undergraduate students and then to post-graduate students. Accordingly, especially in the beginning of the academic year, workshop staff had not been able to work on the project.

The problem had been partially alleviated by asking workshop staff to perform tasks on the critical path as a private remunerative task after hours.

Following the relocation of the unit to NWWTW, various tasks concerning the on-site installation were attended to. The rig was eventually fully operational in March 1994.

A schematic diagram of the final unit is given in Figure C1. Details of the piping of the modules are shown in Figure C2. An equipment list and the design operating conditions are given in Table C1.

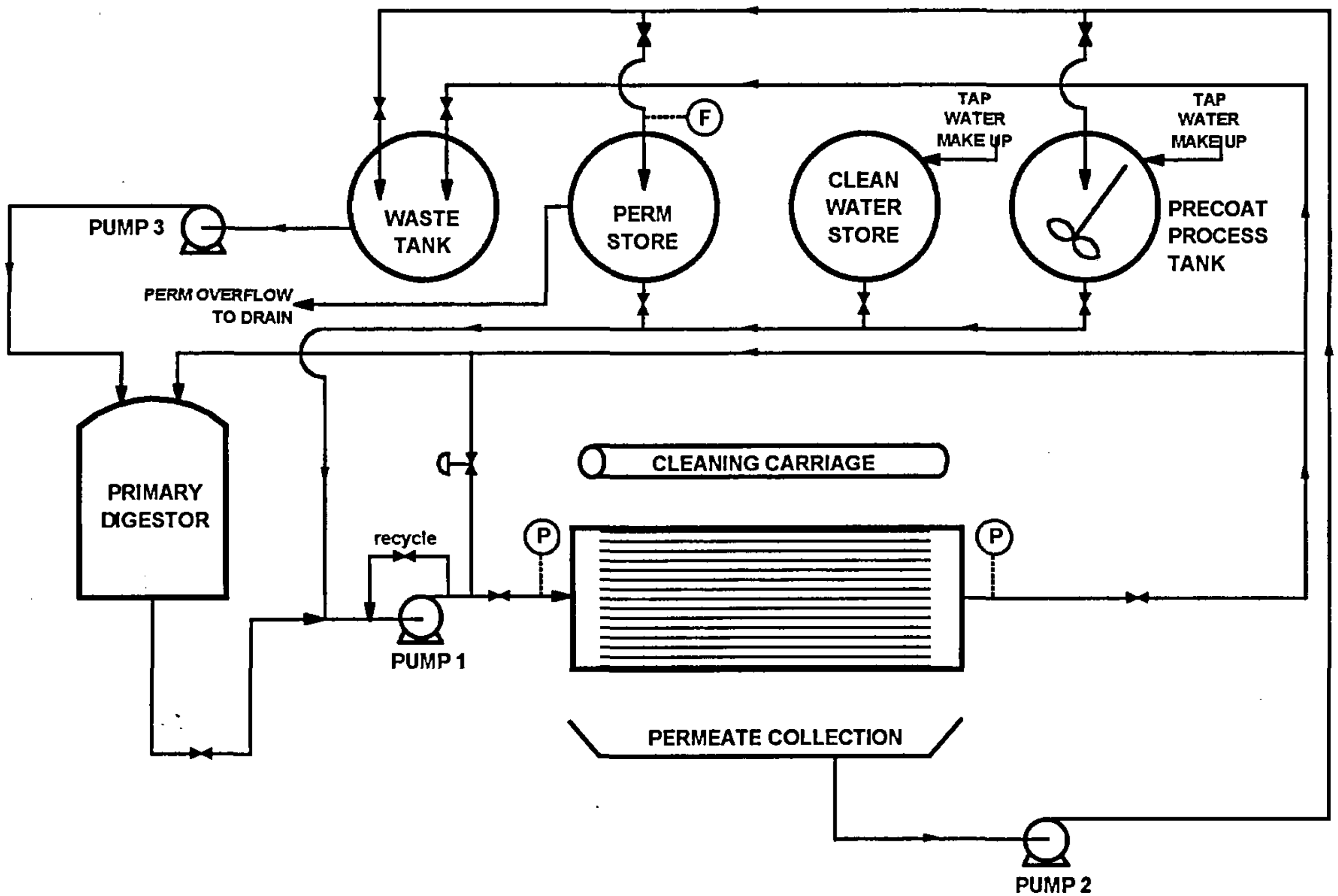

Figure C 1 - Schematic of Microfiltration Unit

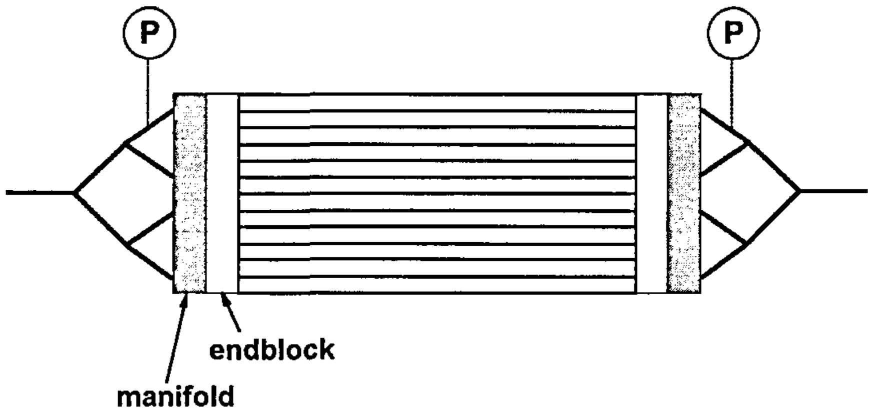

Figure C 2 - Details of Module Piping

Table C1 - Elements of Crossflow microfiltration Unit Installed at NWWTW

Element	**Details**
precoat tank	7 m^3 , fitted with agitator and level probes. Used for make-up and storage of precoat
clean water store	5 m^3 . Stores municipal water for cleaning cycle,
permeate store	5 m^3 , with overflow to drain. Stores permeate for cleaning
waste tank	5 m^3, fitted with level probes and connected to waste pump. Stores permeate and reject during cleaning cycle. This is then returned to the digestor by the waste pump, controlled by the level probes
feed pump	centrifugal pump, rated for 400 m^3/h at 6 bar. Designed with large gap between impeller and casing to pump fibrous suspensions. Fitted with recycle for operation on two modules (200 m^3)
permeate collection system	permeate tank fitted with level probes, connected to permeate pump. Level probes activate permeate pump when tank is full, and switches off pump when tank empties.
cleaning system	cleaning carriage connected to a chain drive driven by electric motor. Limit switches at extremities activate/deactivate cleaning motor.
valves and piping	piping and fittings all PVC. All valves pneumatically actuated.
control system	programmable logic controller (PLC) controlling starters for pumps and motors, and solenoid actuators for pneumatic valves. Operation may be fully automated
modules	25 mm tubes, 30 tubes per module. module length = 8 m

DESIGN OPERATING CONDITIONS	
tube velocity	2 m/s
flowrate	approximately 100 m^3 per curtain
operating pressure	2 bar (average along tube)

The operating cycle for the unit is summarised in Table C2.

Table C2 - Operating Cycle

Cycle Stage	Description
Precoating	Precoat suspension is made up in the precoat tank, under agitation. The suspension is then pumped through the tubes via the main feed pump. The permeate and reject are returned to the precoat tank.
Filtration	The feed valve from the digestor is opened and the feed valve from the precoat tank is closed, i.e. the feed switches to digestor sludge without the system depressurising. After a short lag, to clear out the precoat from the system, the reject valve to the digestor is opened and the reject valve to the precoat tank is closed. The permeate valve to the precoat tank is closed and that to the permeate storage tank is opened.
Cleaning	The feed pump is switched off, depressurising the tubes. Permeate is pumped through the curtains via the main feed pump, the reject being directed to the waste tank. The waste permeate is also directed to the waste tank. The system is then shut down and the clean repeated with municipal water from the municipal store. The waste from the waste tank is pumped up to the digestor via the waste pump, controlled by level probes within the tank.

C 4 ON-SITE ENGINEERING OF CFMF UNIT

There are various hardware engineering aspects which are strongly scale dependant, and thus need to be addressed on the full-scale CFMF unit. These include :

(i) Blockage free operation

The pilot-scale experimental study identified potential operational problems, associated with the fibrous nature of the sludge. In particular, there is a tendancy for material to accumulate at restrictions in the flow path, e.g. valves, and hence lead to blockages. The possibility of blockages was also a concern voiced by Durban Corporation personnel. Hence it is necessary to identify and eliminate regions in the flow path of the full-scale unit that could encourage the formation of blockages.

(ii) Optimisation of the Cleaning System

There has been no previous experience with running a woven fibre microfiltration system on digestor sludge. Methods to clean the curtains have been developed and optimised for other systems, but further on-site investigations on the full-scale are required to select and optimise the appropriate method for the coupled CFMF/digestor system.

(iii) Optimisation of the Operating Point

The single tube pilot test rig was to be used to perform investigations into the following :

- typical flux-time curves
- effect of precoat type and precoating technique
- effect of velocity on flux
- effect of pressure on flux

The flux-time curves would be compared to those obtained on the full-scale rig to establish the correlation between the units. From the investigations into the effect of pressure on flux and the effect of velocity on flux an optimal operating point was to be chosen. This optimal will be based on the flux as well as the energy requirements. The flux-time curves obtained at the optimal operating point was to be utilized to optimise the run/clean cycle. These optimal conditions were then to be implemented on the full-scale unit.

(iv) Process automation and control

It is desirable that the full-scale process should be automated and require minimum operator input. Control and automation strategies would have to be developed on the full-scale unit, and will have to account of the real time response lags in the system.

C 4.1. Overview

The development of an effective cleaning system and a blockage free system ended up being significantly more complex than was anticipated, and taking a significantly longer period than expected. In addition, various sundry mechanical and operational problems were experienced on the CFMF unit. This necessitated the project being extended for a further year, till the end of December 1996. All major problems had been addressed by June 1996, and runs to evaluate the combined system were initiated in the second half of 1996 and proceeded relatively smoothly thereafter. However, attempts to extend the project for a further year were unsuccessful. Accordingly, the project was terminated in December 1996 without various project objectives being met.

The development of the cleaning system and engineering of blockage free operation are discussed in Sections C 4.2 and C 4.3 respectively. The sundry mechanical and operational problems are discussed in Section C 4.4. The performance of the coupled system in the second half of 1996 is summarised in Section C 4.5.

C 4.2. Cleaning System

The unit was initially designed to employ the brush cleaning system, as used by Renovexx. Following some delays details of the Renovexx system were finally obtained in the first quarter of 1994. In March 1994, the cleaning brushes were fabricated and installed.

However, a closer examination of the cleaning sequence employed by Renovexx indicated that the brushes may not be applicable to the coupled digestor system. The cleaning sequence employed by Renovexx was as follows (Figure C3 a and b):

(i) The process pumps were switched off and the system was allowed to drain.

(ii) The brushes were engaged and the cleaning carriage was moved along the curtain. During this stage, fluid was not being pumped through the tubes, ie. the tubes were slack.

(iii) Hot air was then blown into the tubes, and the tubes were allowed to dry.

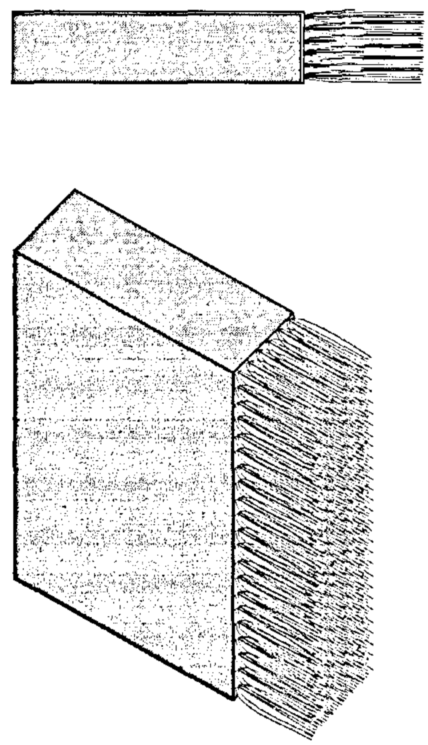

Figure C 3 a - Brushes Employed by Renovexx

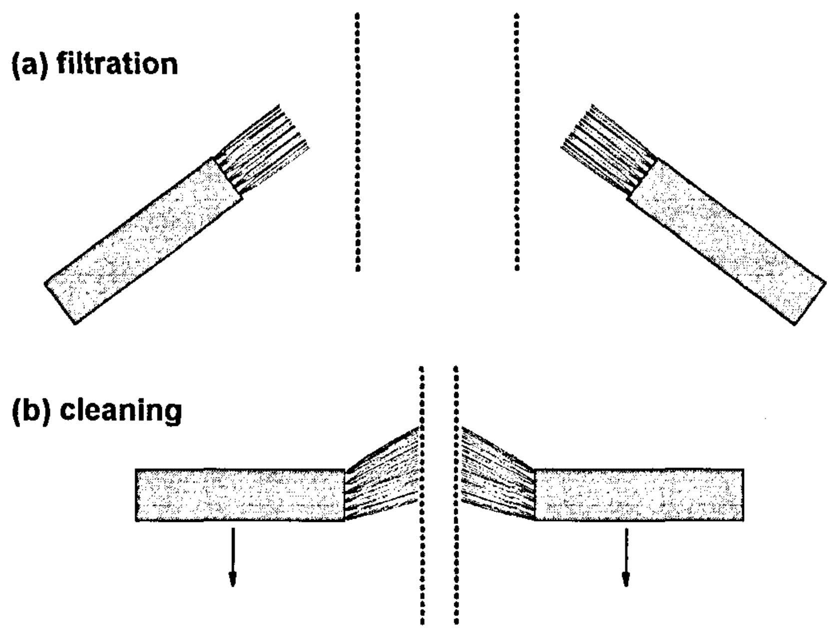

Figure C 3 b - Brush Cleaning System

It emerged that the main purpose of the brushes was to remove biologically active material from the outside of the tubes, and not to remove foulants from the tube itself. The latter was effected by allowing the tubes to dry, and the dried foulants were subsequently flushed out when the system was restarted. This cleaning method departs radially from that employed by the PRG, where permeate is utilized to flush the fouling layer out of the tube

It was highly questionable whether the above cleaning sequence would be successful on the coupled digestor system. In the Renovexx applications a very thin fouling layer exists, and is effectively removed by the brushing and drying technique. In the digestor application, there is a distinct cake which cannot be easily squeezed out of the tube without tube blockages occurring. Some form of flushing is required for foulant removal.

One option was to employ the brushes together with a permeate flush, i.e. utilise the brushes to constrict the curtain while permeate was pumped through the tubes. In this instance, the brushes would act similar to the rollers employed at the H D Hill Tubular Filter Press unit, while simultaneously removing biological growth from the outside of the tubes.

The cleaning system was modified to reduce the gap between the brushes and the above cleaning strategy was attenpted. However, it was found that the brushes were incapable of constricting the tubes while flush water flowed through the tubes, even at relatively low tube pressures. Clearly, the brushes did not have sufficient mechanical strength to be used as rollers. .

Following discussions on the failure of the brushes the Steering Committee recommended that the brushes be abandoned in favour of the squeegee or roller system. Since a squeegee system would be easier to implement this would be attempted first (Figure C4 a and b).

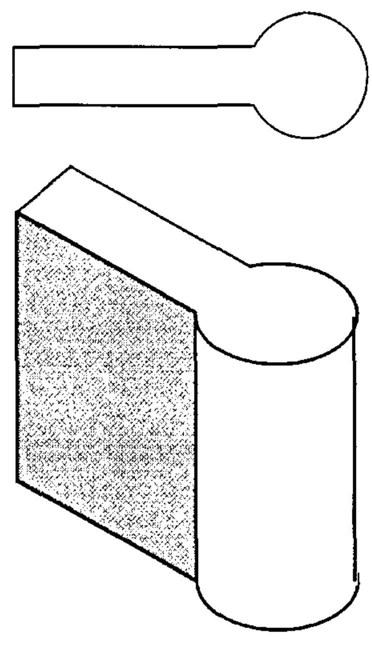

Figure C 4 a - Views of "Squeegee"

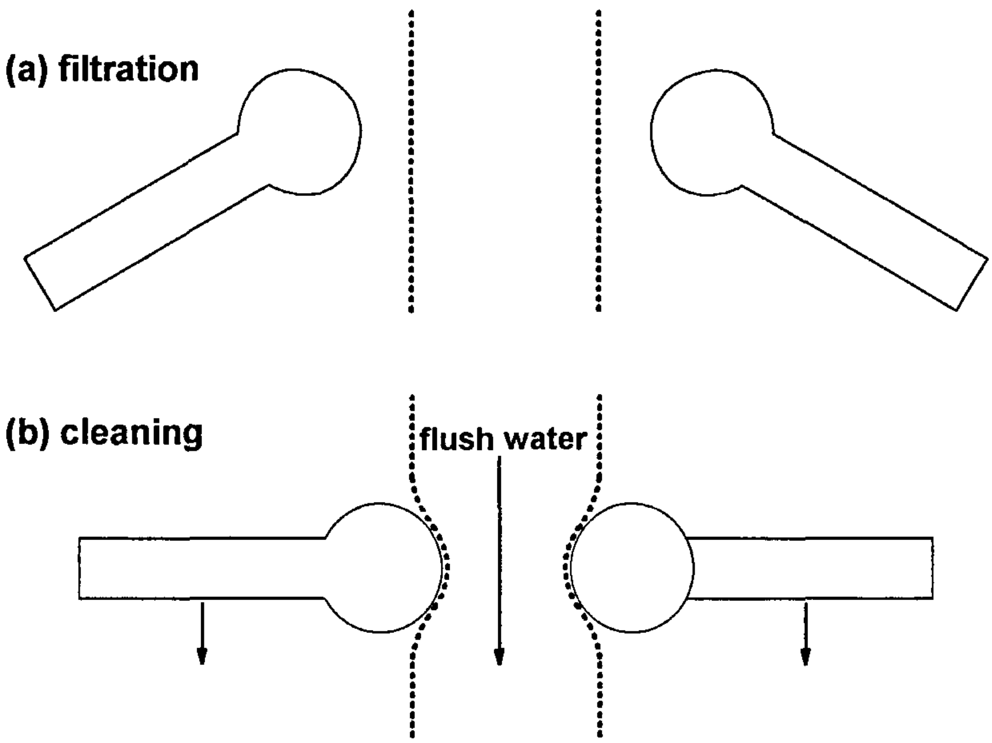

Figure C 4 b - Squeegee Cleaning System

In June 1994, the brushes were removed and replaced with a new system that would enable both squeegees and brushes to be used. The mechanical aspects of the squeegee design were done in collaboration with the Dept. of Chemical Engineering workshop staff. The cleaning sequence in this system would consist of two steps. In the first step, the squeegees would be activated to squeeze the tubes, form a vortex, and remove the spent precoat. In the second step, the brushes were to be activated to remove biological growths from the outside of the tubes.

In the first stage of the implementation of this new system, only squeegees were installed. Initially, the squeegees were fabricated to give a gap of 5,0 mm, but the design included the facility to easily change this. In the original brush system, the brushes on either side of the curtain both closed in an anti-clockwise direction. In the new system, the cantilever was replaced with one that enabled the squeegees on either side of each curtain to be closed from opposite directions.

When the new system was tried out on curtains that had been preocoated with limestone, two problems emerged. The existing 50 mm pneumatic ram could not close the squeegees against the pressure in the tubes, even when the pressure within the tubes was as low as 0,3 bar. Further, the squeegees were pushed far apart by the pressure in the giving gaps of up to 20 mm. Accordingly, the squeegees were completely ineffective in cleaning the curtains. Investigations indicated that a significant force was required to close the squeegees, and that insufficient torque was delivered by the ram and cantilever system. Option to solve this included redesigning the cantilever system to deliver more torque, or increasing the size of the ram. Since the latter was the quicker and easier option, the ram was replaced with a 100 mm one.

With the larger ram, the squeegees were able to close more effectively against the pressurised tubes. However, the pressure in the tubes still pushed the squeegees apart, once again giving gaps of about 20 mm at the top of the curtains. The problem obviously stemmed from a lack of lateral support for the squeegees at the top. It was decided that angled iron supports would be attached to the top of the frame, to constrict the movement of the squeegees at the top, and to prevent them from being pushed apart due to the pressure in the curtain. Rollers would be installed onto the top of these rods, to enable easy movement against the angle iron. A bridge piece would be installed over the top of the two cleaning rods between the curtains. Since the pressure from module 1 and module 2 would act in opposite directions, the bridge piece would prevent these inner rods from deflecting under pressure.

The installation of angle iron, rollers and bridge piece was duly implemented. The angle iron was installed parallel to the sides of the frame, ie. "true" to the frame. The positions of the squeegees were changed were changed to give a gap of 2 mm when fully closed.

On trying out the cleaning system with these modifications, it emerged that the problem had worsened. As the cleaning carriage travelled along the curtain, the gap between the squeegees varied widely. At some point, the squeegees actually crossed over each other, while at other times they were far apart. Detailed investigations indicated the following :

(i) the three frames of the unit were not aligned properly, although the alignment was only off by a few millimetres at worst

(ii) the gap between the sides of each frame varied by up to 4 mm along the length of each frame

(iii) the square rods used for the cleaning rods curved slightly over their length

(iv) the cleaning carriage did not track parallel to the side of the frame. At worst, the tracking was off by 4 mm. Hence, the tops of the cleaning rods were being restrained by angle iron which was parallel to the sides of the frame, while the bottoms of the rods were fixed to a carriage that was moving at some angle to the sides of the frame.

The workshop technicians indicated that the above deviations were well within the tolerances expected for a unit of this size. While these errors were insignificant from a point of view of mechanical fabrication, they were obviously unacceptable when a squeegee gap width of 2 mm is being sought. To reduce the above problems, the frames were re-aligned and the square rods from the cleaners removed and straightened in a lathe. The position of the angle iron was changed so that it followed the track of the cleaning rods and not the frame.

On testing these modifications, it was found that the squeegees closed to a gap of about 5 mm and did not bend out under pressure. However, two further problems emerged due to the increased friction between the squeegees and the curtains, the carriage motor could not move the carriage smoothly. Further, since only two curtains were installed, there was increased resistance on one side of the carriage. This caused the carriage to swing around and jam against the frame. The above were solved by changing the gearing on the motor, and by attaching long 'legs' to the carriage to prevent it swinging around.

With the above modifications, the squeegees closed to a gap of about 5 mm. The carriage moved smoothly along the curtain, and an approximately constant gap was maintained.

In retrospect, the problem experienced with the implementation of the squeegees were mainly due to the following :

(i) the design for the squeegees evolved from the progressive modifications of the brush cleaner design. The stresses involved in the squeegee system are however significantly greater than those that are associated with the brush system. This was only realised when failures occurred.

(ii) unrealistically fine tolerances were expected from the relatively light gauge materials used in the construction of the unit. The HD Hill tubular filter press, which utilises roller cleaners, uses fairly heavy gauge materials of construction, which make the achievement of constant roller gap widths easier.

(iii) the design of the frame does not enable the easy implementation of changes to the cleaning system. From this respect, the design of the frame could have been significantly improved.

The modified squeegee system was tested in November 1994. Initially, the performance of the system was tested on a system containing limestone and bentonite. These tests indicated that the squeegees were capable of removing the fouling layer from the tubes.

In December 1994, the unit was run on digester sludge for the first time. During the cleaning cycle, it was observed that a significant increase in flux was achieved after the squeegees were activated. However, after the clean, it was noted that there was still a presence of foulants in the tubes, especially in the tubes towards the bottom of the curtains. It is not necessary for all the foulant to be removed for the cleaning cycle to be deemed effective. It is however necessary that the cleaning cycle should prevent a progressive buildup of residual foulants with time. Accordingly, it was not possible to determine the effectiveness of the cleaning methods from these initial tests. It was decided that the effectiveness of the squeegees would be determined by monitoring the flux-time responses over a long period of time.

In 1995, very few sludge runs were performed, primarily due to the significant downtime experienced by the plant. In these runs, the following were observed :

(i) on switching off the process pump, the top tubes collapsed with a hissing sound, associated with air being drawn into the tubes by the drainage suction.

(ii) on pumping water through the curtains, most of the foulants from the top tubes were swept out of the system before the activation of the squeegees. Pulsing the pump yielded a significant removal of foulants from the top tubes. However, the foulants in the bottom tubes were not removed by this method.

(iii) when the squeegees were activated, there was a noticeable increase in flux just behind the squeegees. However, this increase petered off with time. After activating the squeegees a significant amount of foulants still remained in the bottom tubes. Varying the velocity of the cleaning water did not yield any improvements.

(iv) the foulants that remained in the tubes formed a slimy layer adhered to the wall. This layer was easily destroyed by rubbing the tube wall, but clearly was not being removed by the squeegees.

(v) there was a noticeable decrease in flux between runs. In early runs, fluxes of 40 ℓ/m^2h were achieved, while in latter runs fluxes dropped to around 10 ℓ/m^2h.

These observations indicated that the squeegees were not effective in cleaning the tubes.

In April 1995, these problems were discussed with Explochem. It was suggested that the gap between the squeegees be decreased and that the pressure during the clean cycle be reduced. These suggestions were implemented. The squeegees were modified to give a gap of -2mm, ie. they would have crossed over each other when fully closed. Under operational conditions, against the pressure of the curtain, this gave a gap of about 2 mm. The pressure during the cleaning cycle was reduced by opening a flange on the reject side and discharging directly into a nearby drain, rather than through the pipework leading the the waste sludge tank. The decreased gap in the squeegees effected some improvement in the amount of foulants removed. However, a significant amount of foulants still remained in the bottom tubes.

It was clearly emerging that the squegee system was not capable of effectively cleaning the tubes. An attempt was made to gauge the possible effectiveness of spray cleaners, by spraying water from the municipal supply onto the sides of the tubes with a hose pipe. This seemed to remove the slimy fouling layer from the area where the spray was applied. These tests indicated that the spray cleaners were more effective than the squeegees in removing the slimy fouling layer.

In summary,

(i) the brush cleaning system was ineffective

(ii) pulsing flush water through the tubes was effective in removing foulants from most of the upper tubes

(iii) the squeegee system had a very limited effectiveness, and offered no increase in effectiveness over merely pulsing flush water through the tubes

(iv) spraying water onto the outside of the tubes, while simultaneously flushing water through the tubes was effective in removing the remaining foulants, i.e. the slimy fouling layer from the bottom tubes.

The above indicate that the most effective cleaning system would consist of a spray onto the outside of the tubes while simultaneously pulsing flush water through the tubes. It was decided that the squeegees would be discarded and the pulse and spray method would be employed. However, a significant period of time had already been devoted to the development of a cleaning system, to the detriment of the remainder of the project. Hence, the system would not be adapted for spray cleaning, and instead the spraying would be done manually, by the operator using a hose connected to the municipal water supply.

C 4.3. BLOCKAGE FREE OPERATION

The CFMF unit was run on a single curtain on ambient concentration digester sludge to identify restrictions in the flowpath that could have potentially led to blockages. These would then be engineered out by adaptation of the flow manifolds and piping.

Various sludge runs were performed without any blockages occurring, although examination of the waste sludge indicated clearly that small agglomerates of hair were present in the process stream. However, from February 1995 onwards, blockages were experienced. In February 1995 it was found that about seven tubes were blocked in each curtain. The main cause seemed to be the presence of agglomerates of hair in the inlet manifold, leading to sludge and precoat entering the tubes from the reject end and progressively blocking them up. In April 1995, approximately half the tubes in each curtain were blocked. Once again, the main cause seemed to be agglomerates of hair in the inlet manifolds.

It must be emphasised that the source of blockages seemed to be accumulation of hair in the manifolds. There was no indication of blockages originating from material becoming "stuck" in the tubes.

There are two possible origins of these large hairballs :

(i) they may form at the point of offtake from the digester when the microfiltration unit is not in operation. Past experience at NWWTW has indicated that very large hairballs may form in regions where recirculating eddies exist.

(ii) they may exist at all times in the digester sludge.

In the former instance, hairballs could be prevented from entering the unit by activating the bypass line on the unit for a short period before beginning a run. In the latter instance, the hairballs would have to be broken up before the sludge enters the tubes. It was initially hoped that the action of the process pump impeller would assist in destroying hairballs, but this clearly was not occurring.

In subsequent runs, the system was operated with a bypass before startup, but the problem of blockages persisted. Following discussions with the technical team, the following proposals were made :

(i) installation of a macerator just upstream of the curtain

(ii) a periodic backpulse to dislodge accumulated fibrous material

(iii) redesign of the manifolds to obviate blocking.

The option of installing a macerator was investigated in July/August 1995. One supplier indicated that in their opinion, the macerator would solve the problem. A second supplier, after contacting the manufacturer in the USA, expressed caution as to whether the macerator would be appropriate. The manufacturer indicated that the fibres would most probably wrap themselves around the blades of the macerator. When a large fibrous mat had developed aroud each blade, the mat would then be cut into "chunks" by the opposite blade. Misgivings about the potential of the macerator were also expressed by personnel at the Northerns Waste Water Treatment Works, following their experiences with a macerator.

Both suppliers indicated that the cost of the macerator would be approximately R 70 000, and it was not possible to obtain one "on approval", since they were imported and were not in great demand locally. In view of the cost and the seemingly low probability of success, the installation of the macerator was not pursued further.

The next two options were to periodically change the direction of the flow in the manifolds, in order to dislodge fibrous material, and to redesign the manifold to obviate blockages. Both options required a more detailed knowledge of the nature of the blockages, how quickly after start-up they formed, and whether there was any geometric pattern to them. To obtain this information, a large number of runs would have to be performed and the occurrances of blockages recorded and analysed.

It was felt that this investigation could not be performed on the full-scale unit due to the long turnaround between runs. After each run, the manifolds would have to dismantled, the tubes cleaned out with a high pressure spray, and the entire system re-assembled before the next run. Thus, a new experimental rig was set up, consisting of the inlet piping to the feed manifold, the feed manifold, a short section representing the curtain, the reject manifold, and the associated reject piping. This rig had a significantly reduced turnaround time between runs.

Investigations on this "blockage test rig" were initiated in July 1995. Sludge was pumped through he unit for periods ranging from ten minutes to three hours. The rig was then dis-assembled and the occurrances of blockages were recorded. These experiments indicated that :

(i) in general, it was found that a high percentage of the holes in the manifold were being blocked (up to 80 %).

(ii) there was no particular geometric pattern to the blockages, the bottom half of the manifold experiencing a similar number of blockages as the top half. This ruled out the probability that blockages were due to a mal-distribution in flow across the manifold due to differences in static head.

(iii) It was expected that the mass of fibres deposited on the manifold would correlate with the cumulative flowrate through the manifold. However, it was found that there was no direct correlation between the mass of fibres deposited on the manifold and the period of flow through the manifolds.

(iv) Running the rig for 30 minutes did not yield a statistically significantly lower number of blockages than if the rig was run for 2 hours. This ruled out the possibility of a periodic reversal of flow being successful.

(v) It was also observed that blockages could form for a short while (indicated by a hissing sound and an increase in upstream pressure) and then clear themselves out (indicated by a sudden decrease in upstream pressure). This implied that the system was highly interactive, ie. the blockage of tubes reduced the possibility of blockage of the remaining tubes possibly due to the increased velocity through the remaining (open) tubes.

In January 1996, the trials on the experimental blockage were continued and it was found that the occurrance of blockages had reduced drastically. In some runs, a high number of blockages were obtained, similar to the trials in 1995. However, on other runs that lasted up to three hours, only two or three tube blockages were obtained. This indicated that there was possibly a mass of fibrous material moving slowly around the digestor. Over the period of inactivity on the rig, this mass had moved away from the point where sludge was drawn off for the rig.

In summary, therefore, the blockage phenomena is more complex than initially anticipated, and the occurrance of blockages cannot be easily correlated to geometric factors or cumulative flows.

Analysis of the form of the blockages did however indicate a possible cause. In general, blockages formed when strands of fibre straddle two or more outlet holes in the manifold. This then caused further strands to accumulate across the holes, leading to blockages. Blockages did not seem to form from a ball of fibre getting stuck in a single hole. Fluid entered the manifold via four 75 mm pipes located evenly across the height of the manifold. Fluid then left via thirty outlets of approximately 20 mm in diameter. Approximately 8 of the outlets were directly in line with the inlets. It is postulated that fibrous materials travel along the inlet pipes as "slugs" aligned parallel to the direction of flow. When fluid flows into the 8 outlets opposite the inlets, these slugs are also carried into the outlet and will continue to travel through the tubes without causing blockages. However, when fluid flows into the outlets that are offset from the inlets, these slugs are turned and form some angle to the main flow direction. The slugs would then be exposed to fluid drag forces which would tend to turn the slug almost perpendicular to the main flow. The slug would then straddle a few outlets, leading to a blockage.

If the above is the mechanism by which blockages form, then the blockages may be obviated by re-designing the manifold such that slugs are not turned significantly when flowing into the outlet tubes. This can be done by eg. increasing the length of the manifold or installing more inlets on the manifold.

Due to time constraints, however, the above proposals could not be investigated. The project was scheduled to end in December 1995, and the extended problems concerning the cleaning system and tubes blockages had resulted in the project reaching the last quarter 1995 without the "core" of the project, i.e. the evaluation of the combined CFMF/digestor operation, being initiated.

Permission to extend the project till the end of 1996 was requested of the Water Research Commission and Durban Corporation, and this was granted. To maximise the use of the remaining time on the project it was decided to install some simple device that would remove hair before it enters the CFMF. Although this would not be a permanent solution to the problem (such a device would be impractical on a fully operational plant) it would enable the CFMF/digestor system to be evaluated.

Accordingly, a "hair catcher" device was designed and installed in May 1996. The device consisted of a 500 ℓ tank which was constructed of fibre-glass with tangential inlet and outlet flows. It was approximately 1,5 m high with a diameter of 0,8 m. The inside of the tank consisted of rolls of plastic mesh screens situated in between steel gratings. As the feed flows from the bottom of the tank to the top, most of the plastic and fibrous material is trapped by the sieves (Figure C 5 a and b). The inlet piping of the main unit was modified accordingly to accommodate the haircatcher.

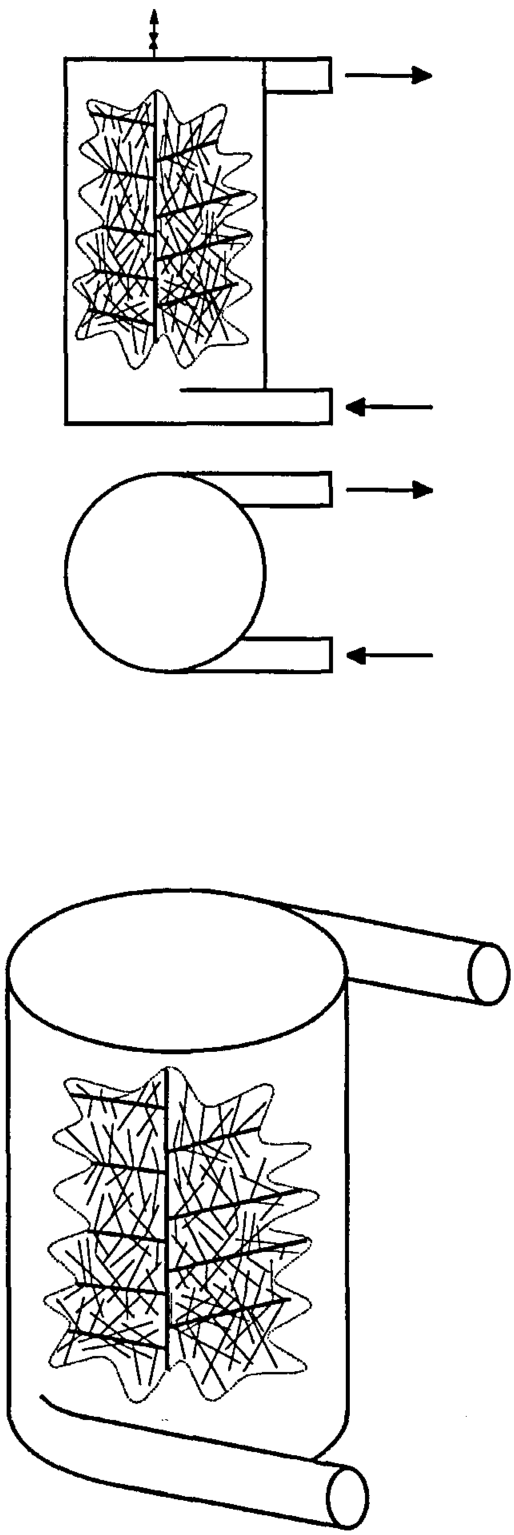

Figure C 5 - Views of "Haircatcher" Device

Initial trial runs were done on the blockage test rig (described previously). Before the device was installed, the pattern by which blockages occurred was studied over a few weeks on the extension manifold. After the device was installed, two more weeks of runs were conducted on the extension manifold. From the observations that were made, it seemed that a blockage free operation had finally been achieved.

When the feed was first run through the tank, problems were experienced with the pump cavitating. It emerged that the problem was caused by the air trapped inside the haircatcher. To eliminate this problem, a 32 mm PVC pipe fitted with a ball valve was inserted on the lid of the tank to serve as a venting system.

Runs were thereafter initiated on the main unit. Shortly after this, another problem was experienced. A significant decrease of the flowrate in the system was observed. The reject flowrate on top of the digester was almost a quarter of its normal flow. This problem was related to the amount of sieving material in the haircatcher. To reduce the total resistance offered by the screens on the feed, the number of plastic mesh rolls were reduced to two but the steel gratings were left as they were. After this, the flowrate returned to normal. Runs on the extension manifold were reconducted to ensure that the haircatcher was still effective.

In summary, numerous blockages were experienced on the unit. Investigations indicated that these stemmed from hair accumulating in the inlet manifold, and not from blockages within the tubes themselves. A detailed investigation into the manifold blockages indicated that the problem was complex, and could not be easily correlated with geometric or operating factors. A theory of how blockages form has been proposed, together with a proposal for improving the manifold design. Due to time constraints this could not be developed further. To enable progress on the rest of the project, a simple "hair catcher" was designed and installed before the CFMF unit.

C 4.4. Sundry Mechanical and Operational Problems

There were sundry mechanical and operational problems that beset the project. While these were resolved without much difficulty, they contributed to the excessive downtime on the project. Most of these were not related to the process, but were probably specific to the unit at NWWTW. Hence they have been relegated to the Appendix.

C 4.5. Performance of the Coupled System

Once the problems concerning the cleaning system and tube blockages had been satisfactorily addressed, experiments commenced to evaluate the coupled CFMF/digestor system in September 1996. Due to the short time available on the project, the objectives of these runs was changed to the following :

(i) to demonstrate that blockage free operation was possible

(ii) to determine the correlation between fluxes on the full-scale unit with that on the pilot unit previously used

(iii) to determine the repeatibility of the system

(iv) to determine the effeciency of the pulse and spray cleaning strategy

The unit was run on a single curtain consisting of 30 tubes of 25 mm diameter. The plant was operated for an average of 5 hours per run. Due to the lack of safety controls on the plant, long continuous evaluation was not possible. However, on the 15th of November the plant was run overnight for a period of 18 hours. As a result of problems encountered during runs, some had to be abandoned.

Determination of operating point

The setpoint for the experiments on the pilot unit was a velocity of 2 m/s and a pressure of 2 bar. Ideally, the full-scale unit should be operated at this point to enable correlation with the pilot unit.

As noted in the Appendix, it was not possible to set the flowrate accurately, or to set the flowrate independant of the pressure. Pressure drop calculations on the reject line indicated that for a tube velocity of 2 m/s, the pressure at the *outlet* of the curtain would be approximately *2 bar*, and that at the inlet approximately 3 bar. This was selected as the most appropriate operating point for the system.

In December 1996, after numerous experiments had been executed, it was discovered that there had been an operator error in implementing the above operating point. Due to a mixup, the unit had been set to operate at an *inlet* pressure of 2 bar. In this instance the outlet pressure was close to 1 bar. Calculations indicated that the tube velocity would have been approximately 0,9 m/s. This drastically effected the fluxes achieved, and meant that a correlation with the pilot scale results could not be performed. This is discussed further in

Section C 4.5.3.

Operating Cycle

A single run was made up of three stages, vix. Precoat, filtration and the cleaning cycle.

Precoating :

The operating procedure for each run started with preparing the limestone suspension, of 5 g/ℓ, in the precoat tank. Kulu-brite 5 was used as the precoat. The precoat cycle lasted for 15 minutes, at the velocity and pressure discussed in Section C 3.5.1.

A material balance on the precoat was done on a daily basis. Samples were taken at the beginning and end of the precoat cycle. By determining the total solids content of these sample, the amount of lime consumed during the precoat cycle was calculated, (between 3 and 5 kg of lime). A new limestone suspension was prepared once after two weeks.

Filtration :

At the end of the precoat stage, valves are changed over to enable the feed to be drawn from the digestor, and the reject to be returned to the digestor, taking care not to depressurise the system. This cycle was run under operating conditions which are similar to those of the precoat cycle. At a beginning of the filtration stage a reading on the permeate flowmeter was taken.

The time and permeate flowmeter readings were noted regularly through the run. In addition the temperature of the feed and of the permeate were measured during the runs. The feed temperature varied between 35 and 37 degrees centigrade.

The total solids content of the feed sludge was evaluated at least once in three runs to ensure that the composition of the sludge did not change drastically during the period of evaluation. The feed had an average concentration of 20 g/ℓ.

Cleaning :

For the whole period of the evaluation, pulsing and hosing were used as cleaning strategies. The drain valve that opened to the atmosphere on the reject line was opened. The pump suction was directed to draw from the clean water tank. The pump was switched on and was left to run at full velocity until almost clean water appeared at the reject side. The gate valve between the pump delivery and the inlet manifold was then shut completely for 5 seconds. During this time, whatever the pump was delivering was re-circulated back to the suction line. The gate valve was then opened for 30 seconds and closed again. The same procedure was then repeated for about ten times. This pulsing effect caused the tubes to collapse when the valve was closed. The filtration cake was destabilised by this and was the flushed out by the clean water. After pulsing, the gate valve was set at about 25% opened which gave a flowrate that did pressurize the tubes. By using a hose pipe whose outlet had been fitted with a small nozzle, the curtain was flushed on the outside. The small nozzle effected a high pressure spray which destabilised the slimy remaining foulants, and these were removed by the flush.

Permeate Flux

Due to the relatively low permeate flux, the permeate pump was not actuated very often. Hence, the permeate flowmeter could not be used to infer permeate production rates. Instead, the permeate flux was calculated by measuring the change in level in the permeate tank, and hence inferring the permeate production rates. This figure was then divided by the filtering area to express fluxes in LMH.

The permeate temperature was measured at twice during the day so as to obtain an indication of how much evaporation had occurred. There was a difference of approximately 3 degrees between the fed and the permeate temperatures. This difference was mainly due to the weather conditions during the time of the runs.

The point fluxes approximately two hours after the commencement of the filtration cycle are shown in Figure C 6.

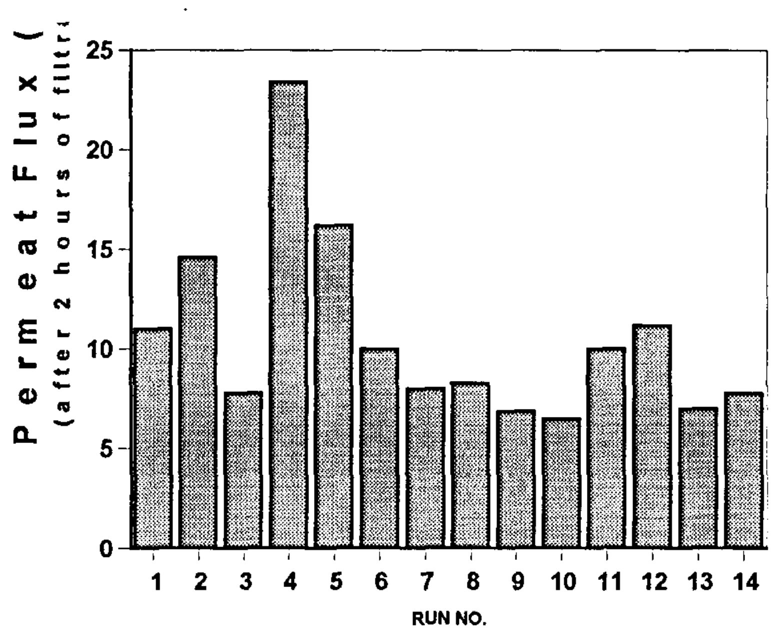

Figure 6 - Permeate Fluxes Obtained on Full-scale Microfilter

The fluxes range from 6 LMH to 22 LMH, well below the average value of approximately 40 LMH obtained in pilot trials at a concentration of 20 g/ℓ. Possible reasons for this are :

(i) evaporation :
The permeate is at an elevated temperature and travels down the curtain in a thin film. Further, the curtain was exposed to the atmosphere and not covered. These are ideal conditions for evaporation, which will have reduced the measured flux.

(ii) In the pilot trials the tube velocity was 2 m/s. In the trials on the full-scale unit, the tube velocity was approxiately 0,9 m/s. It is known that the flux increases significantly with increases in velocity. Hence, the fluxes obtained at the lower tube velocity are expected to be lower than that of the pilot unit.

It is also seen that the flux is relatively repeatible, with no indication of a drastic long term decline. This would indicate that the system is fairly repeatible, and that the pulse and spray cleaning system was being effective.

Since permission for the extension of the project past December 1996 could not be obtained, trials on the fullscale unit were stopped in early December 1996, and the rig dismantled for relocation.

C 5 SUMMARY

The on-site engineering of the coupled CFMF/digestor system proved to be significantly more difficult, and protracted, than was planned for. This was primarily due to problems with two aspects, viz. development of an effective cleaning system, and engineering a blockage-free operation.

The system was originally designed for a brush cleaning system. This proved to be ineffective, and prompted the installation of squeegees that would have a similar cleaning action as rollers. However, significant mechanical problems were experienced with the engineering of the squeegee system. When these mechanical aspects were eventually overcome, it was found that the squeegees had a limited effectivness in removing foulants from the tube wall. Following experiences from other woven fibre microfiltration projects, a simple pulse cleaning technique was subsequently investigated. This proved to be at least as effective as the squeegee system. Combining the pulse cleaning with spraying water onto the outside of the tubes proved to be the most effective cleaning technique, and was subsequently implemented on the unit.

From the initiation of experiments on the digestor sludge, numerous blockages were experienced on the unit. Investigations indicated that these stemmed from hair accumulating in the inlet manifold, and not from blockages within the tubes themselves. A detailed investigation into the manifold blockages indicated that the problem was complex, and could not be easily correlated with geometric or operating factors. A theory of how blockages form was proposed, together with a proposal for improving the manifold design. Due to time constraints, however, this could not be developed further. Options to reduce the blockage potential of the fibres were investigated. This involved, inter alia, investigation the installation of a macerator just upstream of the microfiltration unit. However, discussions with vendors and NWWTW personnel indicated that this was unlikely to be successful. Eventually, to enable progress on the rest of the project, a simple "hair catcher" was designed and installed before the CFMF unit. In the few successful runs performed before the project was terminated, the hair catcher devise proved successful in preventing blockages. The hair catcher device is not, however, regarded as a viable practical solution to the problem of blockages. The issue of blockages remains the greatest process problem associated with the technology, and needs to be resolved if the technology is to be viable (see Recommendations).

Due to the setbacks experienced with the on-site engineering of the system, only a limited number of runs were performed with the microfilter coupled to the digestor. These runs were performed with the hair catcher device installed, and indicated that the process could operate stabily when the problem of blockages was obviated. The permeate fluxes obtained over 14 sucessful runs ranged from 6 LMH to 22 LMH, with an average of about 10 LMH. This is well below the average value of 40 LMH obtained in pilot plant trials, at similar solids concentrations. This significant difference could be ascribed to high evaporation rates from the curtains, reducing the permeate flow, as well as a difference in operating point. The pilot plant trials were performed with a tube velocity of about 2 m/s, whereas the full-scale trials were performed at a tube velocity of about 0,9 m/s. This was due to difficulties with setting operating points on the full-scale unit, as well as partially to operator error. The full-scale runs did however also indicate that there was no significant irreversible fouling of the membranes over the two month test period. This indicated that the pulse-spray cleaning strategy was effective in removing foulants from the curtains.

CONCLUSION AND RECOMMENDATIONS

The objective of the project was to develop and evaluate a combined crossflow microfiltration/digestor system for the improvement of anaerobic digestors at waste water treatment works. The project was divided into three sections : an economic evaluation of the coupled process; an investigation into the microbiological aspects o the combined system; and the on-site engineering and evaluation of a full-scale system.

The basis of the economic evaluation was to compare the cost of the coupled system with that of a conventional digestor to treat 15 000 kg/day of sludge, at a solids concentration of 5,6 %. The capital cost of the coupled system was 27 % lower than that of the conventional system. The operating costs of the coupled system were higher than that of the conventional system. Over a project of 20 years, however, the total (capital and operating) cost of the coupled system was 12 % less than the conventional system. This evaluation indicated that the coupled system was economically viable, and hence that investigations on scale-up should continue.

The aims of the microbiological study were to determine the biodegradability of NWWTW sludge, and to assess whether operation at elevated solids concentrations would be advantageous or detrimental to the biodegradation process. It was found that the ultimate degradability was 50 %, i.e. 50 % of VS could be destroyed by anaerobic digestion. Investigations on flask cultures indicated the rate of digestion increased as biomass concentration was increased, and that no detrimental effect was observed as the biomass concentrations were increased from 2 % to 6 %. Experiments on a semi-continuous system, replicating the coupled microfilter/digestor system, also indicated no significant negative effect as the solids concentration was increased from 2 % to 4,7 %. It was concluded that operating at increased concentrations up to 5 % TS would enhance anaerobic digestor performence, with no observable negative effects.

The on-site engineering of the full-scale system proved to be significantly more problematic and time consuming than expected. This was mainly due to problems experienced with the engineering of an effective cleaning system, and the engineering of a blockage free system. As a result the project was terminated with very few runs being performed on the full-scale coupled system. In the runs that were performed it was shown that the system could operate reliably when the problem of blockages was obviated. They also showed that the pulse-spray cleaning system was effective, in that no long term irreversible fouling was detected. The permeate fluxes obtained on the full-scale system did not correlate with those obtained in pilot plant trials, mainly due to evaporation of the permeate and differences in operating points.

At the end of the day, the project has failed to demonstrate to potential users that the coupled CFMF/digestor system is reliable, robust and easily operable. It could be argued that most of the problems with the coupled process have been ironed out, and that the above demonstration could have been met if the project had been extended. The reality however is that various unexpected problems did arise during the project, resulting in a decrease in process confidence, and this warrants a re-evaluation of the potential applicability of this technology.

Most of the problems experienced could be described as "engineering" problems, and hence can be easily avoided in future designs. However, the problem of blockages is an inherent "process" problem. While this was obviated in the current project by the installation of a hair catcher device, this is not regarded as a permanent solution to the problem. The hair catcher itself is prone to blockages, depending on the nature of the sludge. It would require regular cleaning, and is thus labour intensive. It also introduces the additional problem of disposal of the hair together with unstabilised solids that are trapped with the hair. It is thus an added unit process to what operators at NWWTW regarded as an already complex process, and is unlikely to find favour with end users.

On site experiences at NWWTW during the course of this project also enlightened project personnel to the "nature of the monster" that we have to deal with. On one occasion a 60 cm outlet pipe from the digestor had become completely blocked up with hair. It took operators approximately a day to clear this out. They were extremely sceptical of whether the CFMF unit, with tubes and pipes ranging from 2,5 cm to 25 cm, would handle the sludge.

The project team is forced to conclude that coupling an anaerobic digestor to an external microfilter is not likely to be viable in instances where there is a significant amount of hair/fibres in the digestor sludge. This would preclude operation at most waste water treament works. The coupled process could however be viable when the sludge does not contain fibrous material. The process could thus be applicable in digestors treating industrial effluents.

It is recommended that :

(i) No further work should be performed at waste water treatment works, unless an innovative solution to the blockage problem can be found. Immersed membrane systems could be more suited to digestors at waste water treatment works, since they obviate the problem of hair blockages.

(ii) Application of the coupled CFMF/digestor system to industrial effluent treatment should be investigated.

(iii) For completeness, the microbiological study should be extended to include the aspects of control, stability, and resistance to toxicity at elevated concentrations.

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APPENDIX I

Sundry Problems Experienced During On-site Engineering

Difficulty in Setting Operating Points

The feed pump was sized to feed four modules. However, in the first phase only two modules were installed and the remainder were to be installed as the project progressed. To enable the flow to be reduced appropriately to feed two modules, a recycle line had been installed across the pump. Shortly after commissioning the unit, it was found that it was not possible to reduce the flowrate by activating the recycle line. When the recycle valve was opened, the pump cavitated, with associated vibrations that shook the whole frame.

The next option was to install a restricting valve downstream of the feed pump. While this did reduce the flowrate, it was very difficult to set a flowrate repeatibly. The force of the fluid onto the ball of the valve was substantial. As a result, it was very difficult to adjust the valve while fluid flowed through it, and attempts to do so resulted in the valve seals being blown out. Accordingly, the valve had to be opened to a preset position before the pump was switched on, but this position altered slightly when the surge of the delivery fluid reached it.

The net effect was that it was very difficult to set a constant flowrate for all runs.

A further problem was that there was no flow measuring device on the feed or reject lines. Accordingly flowrate had to be estimated from the pressure drop across the reject line. This yielded a very approximate flowrate, due to the various unknowns in the pressure drop equation. This also meant that the pressure and flwrate could not be set independanty.

Failure of Air Lines

In February 1995, numerous failures were experienced in the airlines that connect the solenoid valve actuators to the pneumatically actuated valves. These occurred randomly and made the unit difficult and dangerous to operate. Investigations indicated that the installed airlines were not appropriate for the investigations. They were designed for a maximum pressure of about 7 bar at 25^{C}. This pressure rating would be greatly reduced in the harsh, direct sunlight conditions experienced at NWWTW. Following discussions with various suppliers, a new type of line was obtained which was designed for use in sunlight and which had a significantly greater pressure rating. All the old airlines were removed and replaced with the new material, and no failures were experienced subsequently.

Failure of Storage Tanks

Leaks developed at the outlet of the permeate and waste storage tanks. The probable reason was that the tank had 'settled' when full, placing a stress on the flange which in turn caused a stress at the point where the flange entered the tank. The suppliers were hired to repair the tank and the flagstones below the flanges below each tank were removed. Thus, even when full, the tank does not place a stress on the flange.

Valve Failures

Various valves failed to function in early 1995, i.e. they did not respond to PLC instructions to open or close. This was partially solved by increasing the pressure of the air supply to the pneumatic actuators. However, there were various valves in which the problem persisted, especially the main feed valve from the digestor. This necessitated the operator opening these valves manually with a spanner.

The cause of the failures was not investigated, but it is suspected that the valves may not be the appropriate type for operation on a fibrous suspension.

Thefts

The project was plagued with numerous thefts, which were a major irritation as well as contributed to unscheduled downtime. The major item stolen was the air compressor used to supply air to the solenoid valves. At one point all the valve actuators were removed for servicing. When they were being replaced, it was found that all the solid metal pieces that connect the valve stems to the actuators had been stolen. We were extremely puzzled at this until it was pointed out that they would make ideal "sinkers" for fishing ! This particular theft set the project back about two weeks, since the connecting pieces were not available off the shelf and had to be individually fabricated.