THE AEROBIC TREATMENT OF REVERSE OSMOSIS PERMEATE FOR REUSE

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ABSTRACT

The reduction of effluent streams and the demand for freshwater intake in the dairy industry, may be accomplished by the segregation and reuse of streams that can be readily treated. This study assessed the biodegradability and suitability for reuse of reverse osmosis (R/O) permeate from Kiwi Dairies Ltd processing factory (Hawera), using aerobic treatment.

Analysis of the permeate showed that there was a direct relationship between chemical oxygen and lactose concentration. The chemical oxygen demand of R/O permeate from two reverse osmosis membrane plants operating in parallel varied widely during the period of study. This wide variation in permeate chemical oxygen was directly related to the membrane efficiency.

Elemental analysis of the R/O permeate showed that iron and phosphorous would need to be supplemented to ensure balanced microbial growth.

The biodegradability was characterised by a series of batch tests to determine the biokinetic constants μ_m, K_S, $q_{s\,m}$ and Y_t. These tests showed that the biodegradability of reverse osmosis permeate is comparable to general dairy wastes. Batch tests were also performed on permeate from R/O membranes of varying performance efficiency, with different lactose and mineral concentrations. There were no conclusive variations in biokinetic constants between permeates from R/O membranes of varying performance efficiency.

Operation of a model activated sludge pilot plant showed that soluble COD removal

efficiencies of over 90% could be achieved at hydraulic retention times of 10 and 20 hours. The sludge settling characteristics were more favourable at a 10 hour hydraulic retention time. Sudden fluctuations in membrane efficiency caused shock loads resulting in a deterioration in treatment efficiency and sludge settling characteristics. Although the pilot plant achieved satisfactory reductions, soluble COD levels were not decreased to the level of 10 to 15 mg l^{-1} required to enable the reuse of the permeate.

In order to determine if low substrate levels could be achieved when aerobically treating R/O permeate from an efficient membrane plant, a laboratory scale reactor was used to treat permeate with a COD of 200 mg l^{-1}. It was established that R/O permeate could be aerobically treated to levels suitable for reuse, provided the previous membrane processes performed efficiently.

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CHAPTER 1

INTRODUCTION

Within the New Zealand dairy processing industry is there increasing emphasis on waste minimization. This may involve further processing of byproducts to produce a saleable product, or treatment to enable the reuse of byproducts within the manufacturing plant. In the modern dairy industry the majority of milk constituents now end up as saleable products. This compares to the days of the "cream can", when on-farm separators separated only the cream for transportation to the local dairy company for further processing.

The emphasis of this research is the aerobic treatment of reverse osmosis permeate, from a whey processing plant, to such a standard, to enable its reuse as wash water within the factory. The reverse osmosis permeate used in this research, is currently a waste stream from the whey protein concentrate (WPC) plant at the Kiwi Cooperative Dairies Ltd (Hawera). Initial treatment of the raw whey involves ultrafiltration and diafiltration to produce a protein concentrate that is then dried. The UF permeate is then further processed using Reverse Osmosis membranes, that produce a retentate stream of mainly lactose (Figure 1.1), which is sent to the Lactose Company Ltd (Kapuni) for processing into lactose powder.

Theoretically the permeate from a reverse osmosis plant should be almost pure water. In the dairy industry reverse osmosis plants seldom reach this level of performance (*Robinson, 1986*). The main organic substrate constituent of the reverse osmosis permeate in the dairy industry is lactose. The Kiwi Dairy Company has two reverse osmosis plants, the RO1 & RO2 plants. An R/O membrane plant operating without membrane tears or leaks in seals should produce a permeate with a have a low COD

(Typically less than a COD of 300 mg l^{-1}).

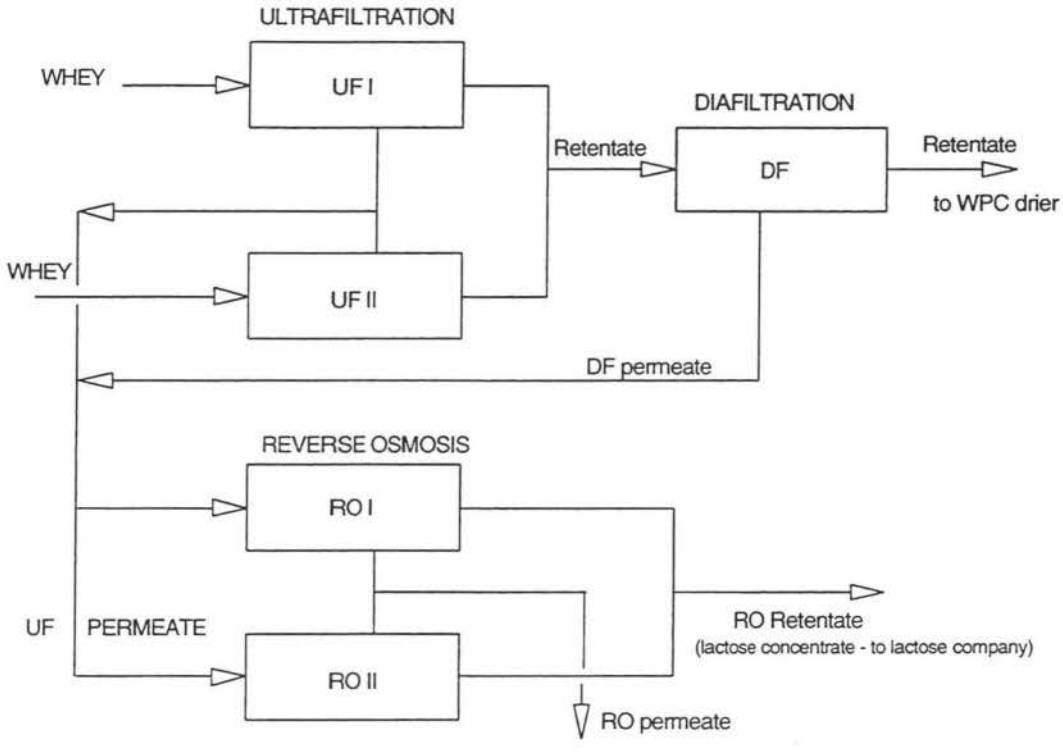

Figure 1.1: Block diagram of Kiwi Dairy Company whey membrane processing plant.

The RO1 plant operated through out the 1994-1995 season with a lower permeate chemical oxygen demand then the RO2 plant which appeared to have substantial leakages. The permeate currently has a wide variation in COD from 150 to over 2000 mg l^{-1} depending on the performance of the membranes. With the intention of decreasing the effluent load, it is anticipated that this low strength stream be treated to enable it to be recycled as wash water. The variation in performance of the membranes is an important factor in any consideration of treatment design.

Flowrates of reverse osmosis permeate at the Kiwi Dairy Company are estimated to be approximately 80 m^3 hr^{-1}. With recent plant expansion hourly flows can reach close to

150 m^3 hr^{-1}. Typically peak flows are in the range 100-120 m^3 hr^{-1}. Including membrane plant down times for washing, daily flows of R/O permeate range up to 2000 m^3 day^{-1}. It is anticipated daily flows may eventually reach 3000 m^3 day^{-1}.

Potentially the treatment of R/O permeate could involve varying options, namely physical or biological treatment. Physical treatment could include polishing using further reverse osmosis membranes. Advantages of this process would be that a retentate of concentrated lactose solution could be added to the retentate from the main R/O plant for further processing by the Lactose Company, and the need for filtering and disinfection of the treated permeate would be minimal. Disadvantages are that membrane performance cannot be guaranteed. and with the pressures required, operating costs can be higher than a biological process. Biological treatment on the other hand is an autocatalytic process operating at ambient temperature and pressure. Consequently such a process is, in general, cost effective for readily biodegradable wastes.

This research focuses on aerobic suspended growth treatment using activated sludge. Advantages of this process, are that it is relatively cheap to operate and that treatment efficiency can usually be guaranteed as process control is easier. In this research a conventional complete-mix activated sludge pilot plant was used to examine the biological treatability of the reverse osmosis permeate.

CHAPTER 2

LITERATURE REVIEW

2.1 DAIRY INDUSTRY WASTES

2.1.1 Characteristics of Dairy Industry Wastes.

Dairy industry wastes are generally dilutions of milk or milk products, together with detergents, sanitizes, lubricants, chemicals from boiler and water treatment, washings from transport tankers and domestic wastes (*Marshall and Harper, 1984*). Dairy wastes are characterized by relatively high organic concentrations, and are highly variable in quantity and composition. Whole milk has a high BOD_5 of about 100,000 mg l^{-1} (COD~ 210,000 mg l^{-1}) (*Marshall and Harper, 1984*). Typical characteristics of New Zealand dairy industry wastes are illustrated in Table 2.1. There is a high variability in waste characteristics as the composition depends on the process operated and the volume of milk handled.

Characteristic	**Concentration (mg/l)**
Biochemical oxygen demand	90 - 12,400
Chemical oxygen demand	180 - 23,000
Suspended Solids	7 - 7,200
Nitrogen	1 - 70
Fat	0 - 2100
Phosphorous (as PO_4)	4 - 150
pH	3 - 13
Temperature (°C)	11 - 72

Table 2.1: Characteristics of dairy plant wastes in New Zealand (*Marshall and Harper, 1984*).

2.1.2 Sources of Dairy Industry Wastes

Large amounts of water are used in the dairy product manufacturing process, where effluent volumes often exceed process volumes (*Blanchard, 1991*). This is particularly true in the dairy processing with reduction functions like evaporation and drying, where these process can be thought of as water producers rather water users. The processes and other sources of waste that have a significant effect on the liquid effluent from dairy processing operations include (*Marshall and Harper, 1984*):

- Washing of outsides of tank trucks.
- Rinsing and washing of collection tankers at milk reception stations.
- Rinsing of residual product remaining in or on surfaces of pipelines, pumps, tanks, separators, evaporators, driers, membrane plants and other processing operations.
- Washing of processing equipment (performed every processing cycle).
- Water-milk solids mixtures discharged during startup, product changeover and shutdown.
- Entrainment of milk droplets into the tailwaters of vacreators, pasteurizers and evaporators.
- Sludge discharged from clarifiers.
- Fines from cheese, powder and casein operations.
- Spills and leaks due to improper equipment operation and maintenance.
- Waste of unwanted byproducts (eg. Whey permeates, buttermilk, evaporate condensate) or spoiled materials and rejected batches of products.
- Loss in packaging operations through equipment failure and broken packages.
- Product returns.
- Lubricants from processing and handling equipment.
- Dust from coal and wood fuel and spills of fuel oil.
- Powder deposits from drier discharges.
- Ash from boilers.

• Water and boiler treatment chemicals and sludges.

2.1.3 Waste Minimization in the Dairy Industry

Waste reduction not only decreases waste water treatment costs, but increases product yield and prevents excessive use of water. The control of waste within the manufacturing process involves monitoring waste levels and initiating steps to reduce the waste to an unavoidable minimum. Despite the importance of waste reduction many plants still have excessive milk losses, frequently without knowing the full extent or realising the economic impact of such losses (*Marshall, 1988*). The following procedure has been proposed to reduce or eliminate losses in the dairy industry (*Creedon, 1988*):

(1) Establish exact data on intrinsic, and possibly unavoidable, losses from each production area.

(2) Elucidate data on small or continuous losses superfluous to the intrinsic losses.

(3) Confirm or define intermittent significant losses (tank overflow, etc.) superfluous to intrinsic losses.

(4) Eliminate losses in (2) by operating in accordance with production routines.

(5) Eliminate losses in (1), if possible, by revised procedures and/or equipment, etc.

(6) Eliminate the significant losses in (3) by automated procedures such as valve closure to retain spillage.

To initiate the above measures, a management strategy must first be established, to obtain managerial commitment, educate staff, set goals and determine the costs of steps to improve yields. To prioritise the areas of the process that require waste reduction steps, product yields must be determined by measuring losses. The product yield can be expressed two ways as follows (*Parkin and Galpin, 1988*):

$$Yield\% = 1 - \left[\frac{\Sigma \text{ of the losses}}{\text{Raw material recieved}}\right] x \frac{100}{1} \quad (2.1)$$

$$Yield\% = 1 - \left[\frac{\Sigma \text{ of the losses}}{\text{Product packed} + \Sigma \text{ of losses}}\right] x \frac{100}{1} \quad (2.2)$$

Using the above equations with loss measurement as a determinant of yield, gives management a more accurate estimate of yield then the traditional method of comparing packed product with quantities credited to the plant as raw materials and identifies the sources of the losses (*Marshall, 1988*). Losses should be measured in the liquid effluent (using the appropriate tests for COD, TN, and milkfat), overweight packaging, variation from minimum specification, and product requiring reprocessing , recycling or disposal.

2.1.4 Waste Stream Recovery in the Dairy Industry

The primary inducement to treat liquid waste streams in New Zealand to an appropriate standard to enable their reuse, is the pressure on intake and discharge permits that increased processing capacity, and the introduction of the Resource Management Act (1991) has caused. Another factor is the influence on biological secondary treatment processes of large variation in hydraulic flows and organic loadings (shock loads). When waste streams are biologically treated, the hydraulic retention times of the treatment processes are critical to successful operation. Significant deviations in influent flow from design capacity will result in reductions in treatment efficiency. The solution to decreasing discharge volumes, is the segregation and reuse of streams that are relatively free of contaminants. This is often a simple and inexpensive way of initiating water conservation efforts and limiting discharge volumes. Streams with low chemical oxygen demand (or biological oxygen demand) can also be reclaimed and treated for re-use in

various applications.

Another contributor to biological treatment problems of dairy waste, are BOD loadings which exceed design capacities of treatment processes. Severe shock loads can adversely effect microbial health by rapidly depleting dissolved oxygen in aerobic systems. Product recovery before and after it enters the effluent stream, for human or animal nutrients, not only boosts yield, reduces treatment costs and but is economically justifiable.

Once both the flow and organic strength problems have been recognized, work needs to be done to define the streams (Table 2.1) and sources of the problem. The first step involves isolating the streams which make significant contributions to the total hydraulic or organic effluent load (*Blanchard, 1991*).

Selection of an appropriate treatment process will vary from case to case but may include biological, chemical or physical treatment methods. Blanchard (*1991*) proposes pretreatment of high BOD_5 streams using flocculation or air floatation with solids recovery. Using these methods, potential fat recovery can be up to 90%, potential protein recovery can be up to 60%, while potential carbohydrate recovery (eg. lactose) is less than 1%. The recovered solids can be used for a variety of uses, including food fillers or as animal feed. The liquid effluent is then most suitable to further treatment using biological methods before discharge. A French Dairy cooperative is currently using a three stage physio-chemical pretreatment phase of flocculation-coagulation, then flotation to recover proteins and fats from waste water (*Ecalard, 1988*). The resulting sludge is then processed for pig feed.

High BOD_5 streams	• Initial Rinse Water • Product Spillage • Centrifugal Separator Ejection
Medium BOD_5 Streams	• Cleaning System Water • Product Wash Water • Wet Scrubber Overflow
Low BOD_5 Streams	• Evaporator Condensate • Reverse Osmosis Permeate • Intermediate Wash Water
Used Water Streams	• Process Transport Water • Condensing Cooling Water • Final Rinse Water

Table 2.2: Defining various waste streams (*Source, Blanchard, 1991*).

For medium BOD_5 strength streams Blanchard (*1991*) suggests ultrafiltration with the solids recovered in the retentate stream (protein recovery 90% and almost total fat recovery). The retentate stream is then further processed using either the flocculation or air floatation step previously mentioned. The UF permeate is further treated using the biological method as for the high strength stream. The potential for water reuse can be exploited in the low strength streams by using a two step reverse osmosis system, with the retentate streams passing to biological treatment and the permeate being used as process water.

While the above water reuse system is primarily based on physical treatment methods, there is a dairy wastewater treatment and reuse process being operated in Cyprus using

activated sludge as the main treatment unit operation (*Hadjivassilis, 1991*). Treated water is used for cooling and irrigation. Dairy wastewater is suitable for reuse for in-plant cooling due to its relatively low salinity and its treatability using activated sludge is good if plant design can prevent filamentous bulking. The plant layout (Figure 2.1) incorporates nutrient addition, pH addition, flow balancing, and two stage activated sludge treatment incorporating an oxic selector for suppression of bulking. This is followed by chlorination, flocculation (using alum and polyelectrolyte) and a two stage high-rate multi-layer granular filtration. Both aeration tanks are of equal volume and operate with a hydraulic retention time of 1.45 days each. The treatment plant design was based on an influent BOD_5 of 1,725 mg l^{-1} and total flow of 200 m^3 day^{-1}. Over a three year period the effluent after biological treatment had an average BOD_5 of 15.5 mg l^{-1} (COD=36 mg l^{-1}) and a suspended solids concentration of 15.2 mg l^{-1}. After tertiary treatment the BOD_5 was 2.7 mg l^{-1} (COD=9.7 mg l^{-1}) and the suspended solids 1.3 mg l^{-1}. No problems with cooling water quality have been encountered during the three years of operation. The operating cost of the plant has ranged from US$0.38-0.42 per m^3. This includes electricity, surplus sludge handling and disposal, maintenance, labour and chemicals.

There has also been research into the use of reverse osmosis membranes to recover the solids from effluent streams from dairy processing waste water in Japan (*Hayashi and Hatanaka, 1988*). Initial tests failed to produce a permeate with a BOD_5 of less than 300 mg l^{-1} to meet the discharge standards. A BOD_5 reduction from a feed of 47,000 mg l^{-1} to only 4620 mg l^{-1} was achieved. A permeate was produced however with zero suspended solids. As a form of pretreatment the application of reverse osmosis is a possibility, with the recovery of the majority of the milk solids, allowing their reuse for either human or animal consumption.

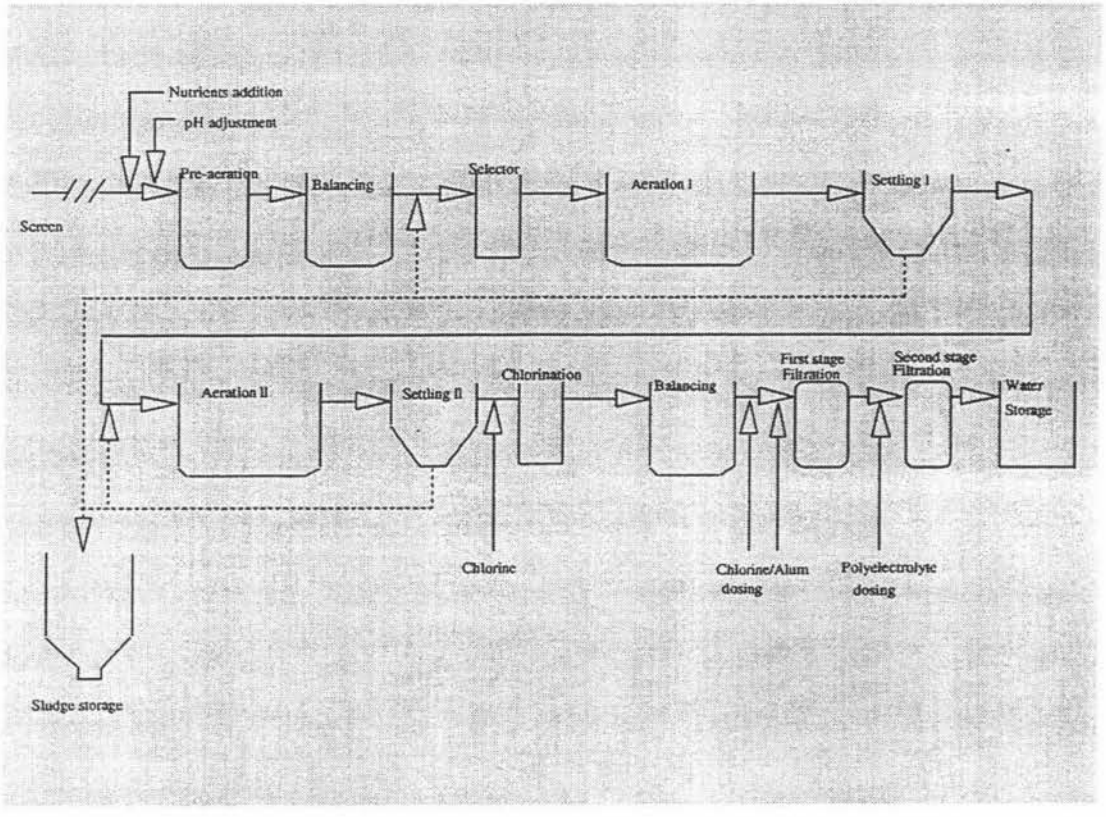

Figure 2.1: Dairy wastewater aerobic treatment plant for water reuse (*source, Hadjivassilis, 1991).*

Another area of potential water reuse in the dairy industry is the reuse of low strength streams such as evaporator condensate and reverse osmosis permeates. The Kiwi Dairy Company currently has a treatment process operating for evaporator condensate treatment and reuse. Evaporator condensate contains certain volatile organics and particulate contaminants due to the carry over of milk, giving the condensate the objectionable odour of burnt milk. The treatment is a physio-chemical process using ozonation, coagulation and filtration producing 350 m^3 day^{-1} of high quality grade demineralised water available for reuse (*McGregor and Bhamidimarri, 1994*). The quality of vapour condensate can vary and depends on the type of product, the type of evaporator and care taken by the operating personnel. The chemical oxygen demand of evaporator condensate varies from 10 - 13 mg l^{-1} at Kiwi Dairy company, while a study

done in Europe found that condensate COD varied from 14 to over 1000 mg l^{-1} during normal operation depending on the product. The evaporation of acidic raw materials such as acid whey and mother liquor, increases the COD value 10 - 100 times the COD value of condensate from the evaporation of skim milk (*Anon, 1988*). The Bulletin lists disinfectants (eg. Ozone, P3 Oxonia), activated carbon, reverse osmosis or ion exchange as possible treatment methods either individually or in combination.

Reverse osmosis membranes in the dairy industry, produce low strength permeates. The amount of organic matter present in the permeate is influenced by the type of membrane used, the raw material concentrated and the degree of concentration required . The flow velocity and corresponding shear forces influence the quality of permeate from tubular systems. Higher velocities improve the BOD and COD of the permeate by reducing the build up of deposits on the membrane. Using sweet whey as the feed, for a continuous R/O process, the COD of the permeate on start up was 508 mg l^{-1} while at the end of the run the COD was 343 mg l^{-1}(*Anon, 1988*).

In the above report, the International Dairy Federation suggested that possible uses of both the vapour condensate and R/O permeates, could be for product washing, product reconstitution, pre and intermediate rinsing, preparation of dilute acid and alkaline solutions, cleaning of buildings, external cleaning of transport vehicles and for use after cooling as pump seal water.

If conventional treatment processes (eg. biological) processes are shown to produce a reclaimed effluent suitable for reuse in food processing plants, then wastewater reclamation and reuse may be implemented on a wide scale in the foreseeable future. If advanced processes such as activated carbon, ultrafiltration or reverse osmosis are required to achieve a satisfactory quality for reclamation and reuse, implementation on

a commercial scale will be less likely in the near future (*Middlebrooks, 1982*).

2.1.5 Water Quality

The Ministry of Health has recently issued revised standards for drinking water in New Zealand (*Ministry of Health, 1995*). The first step was to select the determinands which pose the highest public risk. With these standards the determinands have been divided in to four priority classes. For a treatment plant to demonstrate compliance with the standards, compliance with the determinants that fall into the high risk priorities of 1 and 2 need be monitored. Priority 1 determinands include only determinands of microbiological significance, such as faecal coliforms, giardia and cryptosporidium. Their absence from drinking-water must be demonstrated to comply with the standards. Free chlorine studies may be partially substituted for faecal coliform monitoring. Priority 2 determinants are chemical and radiological determinants that are at levels greater than 50 percent of the maximum allowable value.

Water standards for the dairy industry (*Dairy Division Code of Practice, 1983*), state that potable water must not contain chemical substances or micro-organisms in amounts that could cause a hazard to health. That the water should be free of sediment, turbidity, colour and undesirable taste or odour. The standards state that potable water of an adequate standard can be used for:

(1) All water coming into contact with any dairy product or any dairy processing contact surface and all water used as an ingredient in any dairy product.

(2) The cleaning of all rooms where dairy produce is processed or packed.

(3) All eating rooms and handwashing facilities.

(4) All hoses in processing or packing areas.

(5) Defrosting refrigeration coils in air chillers.

(6) Water seals in product pumps.

One of the most important stages of treatment is the final disinfection, as it must carry protection through the factory distribution pipework to the furthest point of use. For certain uses, such as washing cottage cheese curd, where chlorine would be unacceptable in contact with the product, it may be possible to use ozone (*Hills, J.S., 1978*). Ozone will oxidise and precipitate soluble ferrous and manganous salts and will remove colour from peaty water. It does not give rise to tastes or odours and does not produce potentially toxic chlorinated hydrocarbons.

Non-potable water may not be used in such a way that it comes into contact with any dairy product, or be exposed in a manufacturing or packing area (*Dairy Division Code of Practice, 1983*).

2.2 REVERSE OSMOSIS IN THE DAIRY INDUSTRY

2.2.1 Principles of Reverse Osmosis

Membrane separation is possible due to the fact that surface forces can give rise to concentration gradients at interfaces of aqueous solutions, resulting in a layer of practically pure water at the interface. With membrane technology this interface is removed, by preferential sorption-capillary flow. The surface layer of the R/O membrane must be as thin as possible to minimize resistance to fluid transport through membrane pores, and the preferentially sorbed interfacial fluid layer must be mobile enough to be transported through the membrane pores under the process conditions (*Sourirajan*, 1993). Ultrafiltration is distinguished from R/O by the relatively larger sizes of pores on the membrane surface, and is effectively a sieving process compared to the diffusion process in reverse osmosis. Because of the low porosity of the membrane, a high pressure is required to facilitate an economic rate of water permeation.

Membrane geometry for reverse osmosis can be, tubular, flat or spirally wound. In the New Zealand dairy industry tubular membrane plants are the predominant geometry used. R/O plants typically operate at pressures above 50 bar and temperatures of 30 - 40^{0}C (*Robinson, 1986*).

2.2.2 Reverse Osmosis in the Processing of Whey

Whey is the product obtained by using acids, rennet and/or chemico-physical processes during the production of cheese of casein. (*Sienkiewicz and Riedel, 1990*). Whey is usually differentiated into rennet (sweet) and acid whey. Rennet whey results from the manufacture of products that principally use rennet type enzymes at about pH 5.6. Acid whey occurs as where the coagulum is formed by acidification in a pH range of about 5.1 or below. Whey contains lactose, proteins, minerals and traces of fat and contains approximately 6% total solids of which 70% or more is lactose and about 0.7% whey proteins (*Zadow, 1992*).

At present about half the R/O membranes used in the dairy industry are made of cellulose acetate and half of thin film composite aromatic polyamide (*Sourirajan, 1993*). Long term cleaning with chlorine can reduce membrane life which is typically around 12 to 18 months.

The greatest problem in the concentration of whey by reverse osmosis is the membrane deposition of materials with a high molecular weight (eg. whey proteins) and the boundary films of materials of low molecular weight (eg. lactose and salts). Where calcium salts are the primary foulant, operation at a lower pH of 5 to 6 decreases calcium phosphate precipitation on the membrane surface. Both these phenomena cause a decline in water flux as a function of time known as membrane fouling. The boundary films can be removed by a rinsing with water, but a special cleaning produce is

necessary for removal of the deposits (*Sienkiewicz and Riedel, 1990*).

The permeate from reverse osmosis processing of whey should be almost pure water (*Sourirajan, 1993*), in reality defects in the membrane cause loss of lactose into the permeate (*Robinson, 1986*). Robinson (*1986*) cites one study where the permeate contained 1000 ppm total solids consisting of 250 ppm of lactose. The purity of the R/O permeate is influenced by the type of membrane , raw material concentrated and the concentration required (Section 2.1.4).

2.3 AEROBIC WASTE TREATMENT

2.3.1 The Aerobic Process

There are many types of organisms active in the breakdown of organic matter, these may be broadly classified as aerobic, facultative and anaerobic Aerobic organisms require molecular oxygen for their metabolic process, and utilizes organic carbon as an energy source and as a carbon source for cell synthesis (heterotrophs). Equations 2.1 and 2.2 illustrate the reactions occurring during the aerobic stabilization of organic wastes.

$$\textbf{organic} + O_2 + \textbf{N+ P} \rightarrow \textbf{cells} + H_2O + \textbf{nondegradable soluble residue} \qquad (2.3)$$

$$\textbf{cells} + O_2 \rightarrow CO_2 + H_2O + \textbf{N} + \textbf{P} + \textbf{nondegradable cellular residue} \qquad (2.4)$$

In the stabilization of an organic substrate, a portion of the energy obtained from the reaction is used for biological synthesis and the remainder is used to satisfy the energy requirements for growth. A small amount of the energy is used for cellular maintenance (*Eckenfelder, 1980*). The primary feeders (bacteria) in the population use soluble food,

the secondary feeders are larger microbes (eg. protozoa) which ingest particulate food, mostly bacteria that have grown on the waste molecules. The primary and secondary feeders, along with whatever matter is contained in the waste, or passes in to the aeration tank, are collectively termed "activated sludge".

2.3.2 Nutrient Requirements for the Aerobic Process.

From equations 2.3 and 2.4 it is clear that for balanced microbial growth, the nutrients nitrogen and phosphorous are required in sufficient amounts. In addition to these two nutrients trace levels of other nutrients are required to assure good floc formation, for example addition of small amounts of iron will usually solve the problem (*Eckenfelder and Grau, 1992*).

With nitrogen limiting conditions, the amount of cellular material synthesized per unit of organic matter removed increases due to the accumulation of polysaccharide and restricts the rate of BOD removal and stimulates filamentous growth that can lead to poor floc formation and bulking problems. Nitrogen is available to the biomass in the form of ammonium (NH_4^+) and nitrate (NO_3^-). Ammonia as the available nitrogen source is preferred as the organic removal rate is substantially higher than with nitrate, due to nitrate needing to be reduced to ammonia first. When organic nitrogen is present in the wastewater as protein or amino acids, it must first be biologically hydrolysed to release ammonium (*Eckenfelder and Grau, 1992*).

In order for the biomass to assimilate phosphorous it must be in the form of soluble orthophosphate (PO_4). Complex inorganic and organically bound phosphorus must first be bio-hydrolysed to orthophosphate to be available to the biomass.

To ensure adequate nitrogen and phosphorous supply for BOD removal it is necessary

to provide a nutrient mass ratio of 100:5:1 (BOD:N:P). For industrial where nutrients are limiting, they are commonly added in the form of urea for nitrogen and as phosphorous acid in the case of phosphorous (*Jokinen and Savolainen, 1990*). Where the COD test is used a ratio of (COD) concentration to nitrogen concentration (with nitrogen added as ammonium ion) of 25/1 to 20/1 is needed to ensure that carbon is the nutrient that limits the growth rate (*Gaudy and Gaudy, 1984*).

2.3.3 Growth Characteristics and Kinetics Constants

Bacterial growth can be distinguished by a number a of phases (Figure 2.2). The phases that are of most interest are the logarithmic increasing phase in growth and the autodigestive phase. In these phases the specific growth rate μ and the specific decay rate k_d which are essentially constant can be determined.

The existence of an exponential system is easily determined by plotting the values of X (biomass concentration) against time on a semi-logarithmic scale. The biomass (X) can be determined either directly by measuring suspended solids, or indirectly by using some marker such as optical density (absorbance or turbidity). The specific growth rate is then readily determined using Equation 2.5.

$$\mu = \frac{\ln(X_t/X_o)}{(t-t_o)} \qquad (2.5)$$

A batch culture with substrate limited growth (non inhibitory waste) can be defined by

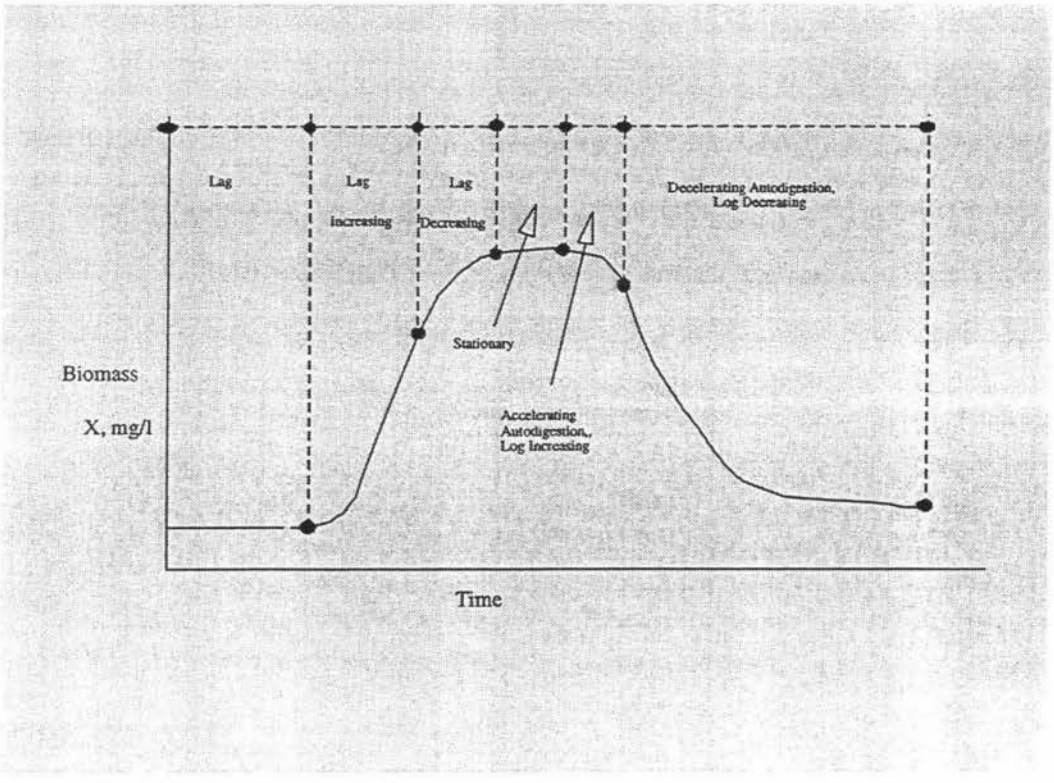

Figure 2.2: Distinguishable portions of biomass growth and decay curve (*Gaudy and Rozich, 1992*)

the well known Monod's expression (Equation 2.3). This expression is substrate specific, and its numerical values are governed by the type of substrate and cells present. This makes μ a powerful tool for characterizing waste/activated sludge systems and predicting effluent quality (*Gaudy and Rozich, 1992*).

$$\mu = \frac{\mu_{max}.S}{K_s + S} \qquad (2.6)$$

The maximum specific growth rate (μ_{MAX}) designates the upper or maximum value of μ regardless of how high the substrate concentration (S_O) is. The value of K_S is numerically equal to the concentration of S which makes μ equal to one half μ_{MAX}, and is term that is related to the sharpness or flatness of the curve in Figure 2.4.

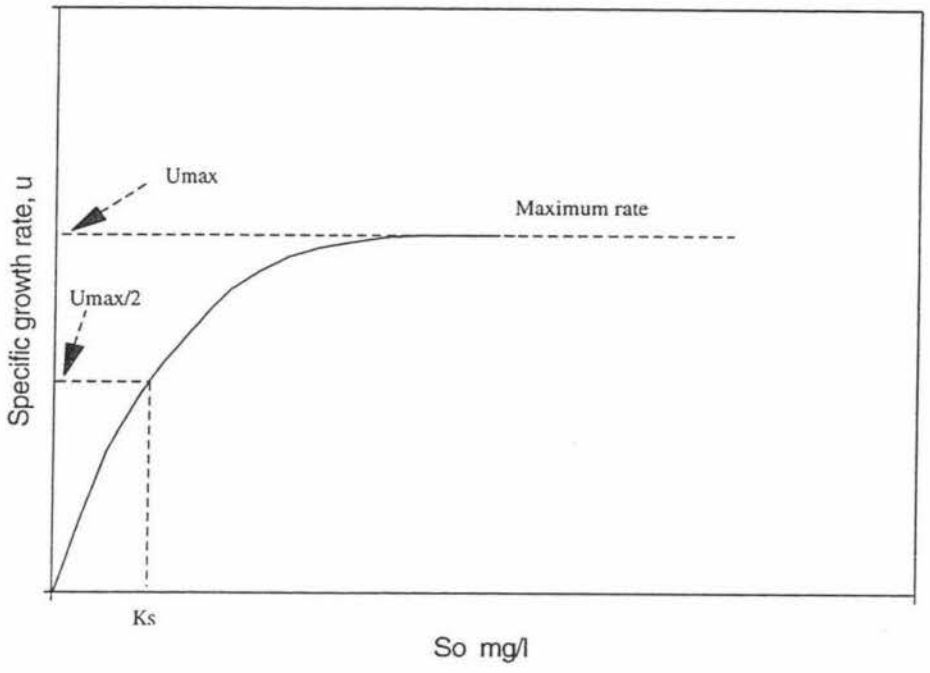

Figure 2.3: Plot of Monod equation, showing effect of substrate concentration on the specific growth rate (μ)

The Monod equation holds for heterogeneous populations and mixed carbon sources, though the constants μ_{MAX} and K_S are dependent upon temperature and pH as are any chemical constants.

Another quantity that can be defined during microbial cell growth is the cell or sludge yield Y_t. This factor is the ratio of the amount of sludge , or biomass, produced per unit of substrate removed when the cells are growing during the log increasing phase. At any time during the substrate removal Y_t remains constant. Erratic values may be obtained if the measurement is made too early in the growth phase. Y_t is called the true or

maximum cell yield (Equation 2.7). When the cell yield is affected by the autodigestion, it is designated by Y_O and is called the observed sludge yield (*Gaudy and Rozich, 1992*).

$$Y_t = \frac{(X_t - X_o)}{(S_o - S_t)} \qquad (2.7)$$

2.3.4 Kinetic Determination using Oxygen Uptake Rates

The determination of μ_{max} and K_S, using the standard techniques of either directly measuring the biomass growth in a batch reactor or indirectly using optical density is time consuming. Recently a method for the determination of these methods using oxygen uptake rates has been established (*Cech et al, 1985*). This method enables more rapid determination of these constants and is especially useful for plant operation in analysing how the activated sludge population will respond to varying feed compositions. In this method a suspension of activated sludge is put into a batch reactor at constant temperature and aerated until all substrate is utilized and endogenous respiration exists. The dissolved oxygen concentrations is then measured with a probe attached to a chart recorder. When a dissolved oxygen concentration of about 8 mg/l is reached the aeration is stopped. A slow decrease in DO will be observed and at this point a known volume of concentrated substrate is injected and this causes a temporary increase in the respiration rate. The respiration rate at this point equals the total respiration rate at the substrate concentration. The oxygen consumption (Equation 2.8) can be readily related back to the growth rate. Multiple respirograms at varying concentrations can be used to evaluate the maximum specific growth rate (*Cech et al, 1985*).

Gaudy and Rozich have also developed a method using respirometry to determine biokinetic constants. The link between oxygen uptake (or respiration) and biomass growth or substrate utilization is based on the assumption that the COD being removed from solution during metabolism is channelled in varying proportions into the synthesis of new cells and to respiration measurable as oxygen uptake (in a closed reactor). This is quantified using Equation 2.8.

$$\Delta COD = O_2\ Uptake + \Delta COD_{cells} \qquad (2.8)$$

If the values for cell yield (Y_t) and the unit COD of the cell mass (O_x) are known Equation 2.8 can be simplified to Equation 2.9, which is used to convert oxygen uptake into biomass growth curves (*Gaudy and Rozich, 1992*).

$$X_t = X_o + \frac{O_2\ Uptake}{\left[\frac{1}{Y_t - O_x}\right]} \qquad (2.9)$$

2.3.5 The Activated Sludge Process

Aerobic waste treatment processes can be either attached growth reactors or suspended growth reactors. Attached growth reactors include trickling filters, packed bed reactors and rotating biological contactors, while suspended growth processes include activated sludge, aerated lagoons and aerobic digesters (*Metcalf and Eddy inc., 1991*). In this study activated sludge will be the process used. Activated sludge processes themselves

come in varying configurations, the flow can be plug, complete-mix or in batch mode. The conventional complete-mix reactor is the most common process in use and will the method considered further. The conventional complete-mix activated sludge process is earlier illustrated in Figure 2.4 showing the respective streams parameters.

Conventional operational parameters for an activated sludge process are the hydraulic residence time $\bar{t}$ and the sludge age θ_c. Typical hydraulic residence times vary from 5 hours to 12 hours, while sludge age for conventional activated sludge operation varies from 5 to 15 days.

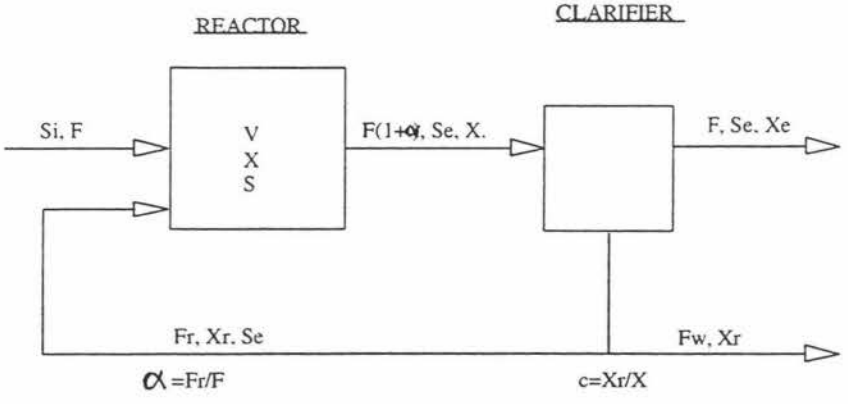

Figure 2.4: Flow diagram used to develop equations for complete-mix activated sludge process (*Gaudy and Rozich, 1992*)

The recycle flow F_R can be controlled at some fraction (α) of the inflowing wastewater ($\alpha=F_R/F$). This recycle flow contains a biomass concentration (X_R), which may be controlled at some ratio c ($c=X_R/X$). The recycle flow may contain some amount of

substrate, and for the purpose of simplification, it will be assumed that there is essentially no chemical or biochemical activity in the cell separator or clarifier so that the clarifier so that the substrate concentration in both the effluent and the effluent and recycle flow are the same as in the reactor (*Gaudy and Rozich, 1992*). Gaudy and Rozich by equating mass balances for biomass (dX/dt) and substrate (dS/dt) with time and assuming that the waste the Monod relationship is applicable derive a relationship for μ for a activated sludge recycle system in Equation 2.10, where D is the dilution rate which is equal to the inverse of the hydraulic retention time in the reactor.

$$\mu = D(1 + \alpha - \alpha c) + k_d \qquad (2.10)$$

Equation 2.10 shows that μ not only falls under hydraulic control of D, but that the recycle flow ratio α and the recycle sludge concentration ratio c also exert controls over the specific growth rate. The effluent quality is also determined by μ, and as μ is influenced by the factor D(1+ α-αc), the recycle has a large effect on the effluent quality. Gaudy and Rozich (*1992*) have derived Equation 2.11 and 2.12 as the model to determine the predictive effluent quality and biomass concentration. It must be noted that this model will only work if 1+α is greater than αc. Typically c will be about 4, and this places a limitation on the recycle ratio (α) of less than 0.32. For a recycle ratio of 1, which is generally the maximum that would be used then this places a limitation of 2 for c.

$$Se = \frac{K_s[D(1 + \alpha - \alpha.c)+k_d]}{\mu_{max} - [D(1 + \alpha - \alpha.c) + k_d]} \qquad (2.11)$$

$$X = \frac{Y_t D(S_i - S_e)}{D(1 + \alpha - \alpha c) + k_d} \qquad (2.12)$$

One conclusion that can be drawn from Equation 2.11 is that the recycle enables the operator to produce a lower value of Se for a lower hydraulic retention time. It can also be seen that S_e can be controlled by the recycle after the plant in is in operation by manipulating the values of α and c, as the only way that the dilution rate can change is by varying the influent flow rate F. It is usually found that c is not a very good engineering control variable and in order to change the equation to engineering reality, X_R, rather than c is used. It must be noted that a highly fluctuating recycle sludge concentration, will result in process upsets unless other compensatory measures are used, for example long reactor detention times.

In determining the amount of sludge that must be wasted (X_w) with the above model Rozich and Gaudy (*1992*) have derived Equation 2.13, which is the difference between the amount of biomass that exits in the reactor and the amount that enters the reactor.

$$X_w = D\left(1 + \alpha - \alpha\frac{X_R}{X}\right)XV \qquad (2.13)$$

Equation 2.13 can be simply converted to an expression involving the net specific growth rate (μ_n) and Equation 2.14 results.

$$X_w = \mu_n XV \qquad (2.14)$$

The design and operational methodology formulated by Rozich and Gaudy (*1992*) is not yet often used to represent an activated sludge system. Typical the conventional method uses food to microorganism ratio (F:M), substrate utilization rate (U) and mean cell residence time θ_c. These conventional control parameters, F:M, U, θ_c are expressed in terms of activated sludge parameters in Equations 2.15, 2.16 and 2.17 respectively (*Metcalf and Eddy, 1991*).

$$F{:}M = \frac{S_i}{\bar{X}t} \tag{2.15}$$

$$U = \frac{(S_i - S)}{\bar{X}t} \tag{2.16}$$

$$\theta_c = \frac{VX}{F_w X_R + FX_e} \tag{2.17}$$

If the units for sludge wastage are expressed as in Equation 2.13 then F_wX_R factor in the denominator can be expressed as X_w, the sludge wastage rate. If it is assumed that the biomass in the treated effluent is negligible then FX_e can be removed from Equation 2.17. Then by simple manipulation of Equations 2.13, 2.14 and 2.17 the following expression (Equation 2.18) can be derived that illustrates the relationship between the conventional model for cell residence time and that presented by Gaudy and Rozich (*1992*).

$$\mu_n = \frac{X_w}{VX} = \frac{\left(1 + \alpha - \frac{\alpha X_R}{X}\right)}{\bar{t}} = \frac{1}{\theta_c} \qquad (2.18)$$

Equation 2.18 shows that there are two ways to control θ_c , a feed forward model that utilizes the recycle parameters or a feed back that utilizes the wasting rate. The hydraulic detention time is usually fixed, so the parameters μ and X may be used to control μ_n and θ_c. The relationship of the substrate utilization rate (U) can be related to both μ_n and θ_c as shown in Equation 2.19 (*Metcalf and Eddy, 1991*).

$$\mu_n = Y_t U - k_d = \frac{1}{\theta_c} \qquad (2.19)$$

Influent waste strength increases can have significant effects on the effluent quality and the conventional approach does not adequately determine the combination of values of engineering parameters needed for insuring good treatment. The modelling approach however allows the engineer to determine the optimum parameters for achieving target F:M or θ_c values at higher influent concentrations (*Gaudy and Rozich, 1992*).

2.3.6 The Aerobic Treatment of Dairy Waste

Conventional activated sludge treatment systems used in the treatment of dairy wastes generally produce good quality effluents, with a treatment of over 90%. Difficulties in biological aerobic treatment systems treating dairy waste relate mainly to the large variation in hydraulic flows, organic loads, temperatures and pH. Due to the daily and seasonal variations, care must be taken when formulating treatment operations. Low strength or clean processing effluent should be diverted or reused to prevent hydraulic overloads, while waste minimization and pretreatment can even the organic fluctuations in biologically treated effluent streams. Filamentous bulking problems in the secondary clarifier commonly occur with long term operation of conventional activated sludge treating dairy wastes. Aerobic selector configurations have been found to cure bulking that occur, producing reactor biomass sludge volume index as low as 100 (*Leonard, 1994*).

Previous studies of activated sludge pilot plants treating dairy wastes by Fang (*Fang, 1990 and Fang,1991*) have used a three stage activated sludge pilot plant to treat general waste and wastewater from a whey processing plant. Treatment of the whey processing plant waste water resulted in a 99% reduction in BOD_5 after a total retention time of 19.8 hours. A reduction of 86% in BOD_5 was achieved in the first stage with a retention time of 3.8 hours and 97% after another 8 hours in the second stage. The same pilot plant treating general dairy wastewater achieved the same reductions at each stage as with the whey plant waste water, indicating similar wastewater characteristics for both effluent streams. As mentioned in Section 2.14 a full scale activated sludge dairy wastewater plant in Cyprus (*Hadjivassilis, 1991*) using two stage aeration with a total hydraulic retention time of 3 day has an average BOD_5 reduction of 99.99%.

There have not been any previous studies of R/O permeate aerobic treatment, however microbial growth rate constants for dairy waste, typically average 1.0 d^{-1}, but vary within the range 0.6 - 2.0 d^{-1} with K_s averaging 18.5 mg/l but varying between 5 - 33 mg/l (*Leonard, 1993*). Leonard (*1993*) found that the yield coefficient Y_t varied from 0.48 - 0.67 mg cell COD/mg COD removed, depending on the composition of the dairy waste being treated. Other kinetic studies for dairy waste (*Orhon et al, 1993*) resulted in similar values for the yield coefficient but slightly higher values for K_s and μ_{max} of 74 - 257 mg cell COD/mg COD removed and 3.1 - 3.74 d^{-1} respectively depending on the composition and source of the waste being treated. These higher values obtained by Orhon et al (*1993*), compared favourably to those determined by Leonard when using similar methods.

CHAPTER 3

MATERIALS AND METHODS

3.1 ACTIVATED SLUDGE PILOT PLANT

A pilot scale activated sludge plant (Figure 3.1) was operated on-site at Kiwi Cooperative Dairies Ltd (Hawera). The balance tank, aerated reactor, and clarifier were constructed from stainless steel farm milk storage vats. The reactor had a working volume of 1700 litres, and aeration was provided by two fine bubble air diffusers using site compressed air. Optimum *p*H conditions were maintained between 6.5 and 8 using an industrial *p*H controller. A 50% sodium hydroxide solution was to used to maintain the *p*H above the set point of 6.5. The nutrients nitrogen and phosphorous were added using a peristaltic pump (Cole-Parmer model 7553-75). A 200 litre stirred plastic drum was filled with site water and 2 kg of fertilizer (Taranaki Farmers Ltd Fertilizer, 12% wt N and 14% wt P) and added to the reactor at a rate of 50 ml per minute to maintain an appropriate nutrient balance (Section 2.24).

Sludge recycle was via a 5 cm flexible hose using an air operated Wilden (California, USA) diaphragm pump and the flowrate controlled via a valve in the compressed air line. Due to difficulty in controlling low recycle flows, the recycle ratio was operated between 1 and 2. Reverse osmosis permeate was pumped from an tee-join in the reverse osmosis permeate discharge pipe, to a 2000 litre balance tank positioned beside the pilot plant using a Wilden diaphragm pump. Pump operation was controlled by a level sensor in the balance tank. The pump was also controlled by a PLC, and was turned off when the reverse osmosis membranes were not operating or in cleaning cycles. Permeate was pumped from the balance tank to the aeration tank using another Wilden diaphragm pump with flow control.

The clarifier consisted of an 800 litre reconfigured farm vat with a rubber scrapper rotating at 2 rpm. The outlet from the reactor was positioned above the clarifier inlet so flow was maintained by static head. The clarifier outlet was a single 2 cm stainless pipe with the effluent then pumped to a pilot scale dual medium sand filter (Silicon Industries Ltd, Hamilton). Manual back-washing of the sand filter was done daily.

The reactor was seeded with activated sludge microorganisms from the Anchor Milk Ltd, (Waitoa) aerated lagoon. The reactor was operated at two hydraulic retention times of 10 and 20 hours. Solids retention time was controlled at approximately 10 days by wasting biomass directly from the reactor using a peristaltic pump (Cole-Parmer, Model 7553-75).

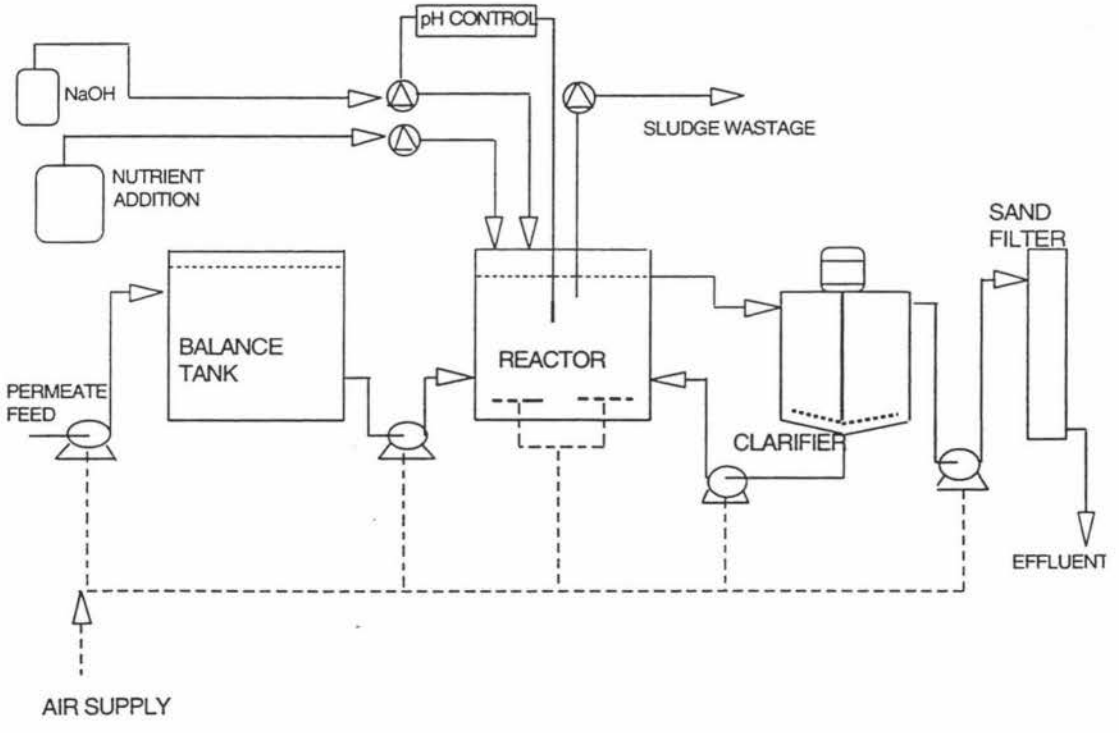

Figure 3.1: Process flow diagram of activated sludge pilot plant

3.2 LABORATORY SCALE ACTIVATED SLUDGE SYSTEM

A laboratory scale activated sludge system was operated at a constant temperature of 25^{0}C. The reactor consisted of a seven litre Pyrex glass vessel (New Brunswick Scientific Co., New Jersey, USA) with temperature and *p*H control. The working volume of the reactor was kept constant at 5 litres. The *p*H of the reactor was maintained between 6.5 - 7.5 using a *p*H controller (Chemtrix Inc, Oregon, USA, Type 5997-20) using a 50% sodium hydroxide solution. The dissolved oxygen of the reactor was kept above 4 mg l^{-1} and the stirrer speed set at 60 rpm.

The reactor was initially seeded with sludge from the pilot plant. Refrigerated reverse osmosis permeate from the Kiwi Dairy Company was feed to the reactor at two different rates to give hydraulic retention times (HRT) in the reactor of 10 and 20 hours.

A laboratory scale clarifier (1.8 litres) with a 1 rpm scraper was used to settle to the sludge. Sludge recycle ratio was kept constant at 0.25. All pumps used were Masterflex peristaltic laboratory pumps (Cole-Parmer, model 7553-75), and were used for feed, recycle, and sludge wastage.

3.3 BATCH REACTOR TESTS

3.3.1 Substrate Removal Rate and Yield Coefficient Determination

For biokinetic constant determination, two methods of batch tests were performed. In the determination of yield coefficients and substrate removal rate, a five litre reactor, with temperature control and aeration (New Brunswick) was used. Temperature was controlled at 20^{0}C with stirring and aeration to maintain the dissolved oxygen concentration at 5-6 mg/l. The permeate was brought to constant temperature and seeded

with 100 ml of sludge from the pilot plant treating R/O permeate, and then immediately sampled for TSS and soluble COD. Sampling was done every 30 minutes until the logarithmic growth phase ceased.

3.3.2 Specific Growth Rate Determination

For specific growth rate determination, simultaneous batch tests were performed at constant temperature. Various dilutions of R/O permeate were put into 1 litre perspex reactors and immersed in a water bath at 20^0C. Aeration was provided using laboratory compressed air via air frits to each reactor. Once the reactors reached 20^0C, each reactor was seeded with 10ml of acclimated sludge and the change in absorbance measured with a spectrophotometer (HACH, USA) at 540nm each 30 minutes. Periodically total suspended solids was measured and a calibration curve constructed to relate TSS to absorbance.

3.3.3 Oxygen Uptake Rate Tests

One litre of acclimated activated sludge was placed into four perspex reactors and placed into a water bath at 20^0C and aerated for 1 hour to ensure that the mixed liquor was in the endogenous phase. Total suspended solids measurements of the reactor contents were then taken.

The reactors were then removed one at a time and placed on a magnetic stirrer, and a DO probe immersed in the mixed liquor. To measure the oxygen uptake rate (OUR) the dissolved oxygen probe (YSI, USA) was connected to a continuous chart recorder. Once a constant OUR line was established, a known volume of concentrated R/O permeate was injected into the reactor. The change in the OUR rate was measured and μ calculated for each substrate volume injected using the method proposed by Cech et al (*1985*).

The permeate was concentrated using a freeze dryer (Virtis, Model 10-020, Newark, USA), with small volumes concentrated over three days.

3.4 ANALYTICAL METHODS

3.4.1 Biomass Concentration

The mixed liquor suspended solids (MLSS) and total suspended solids (TSS) were measured by the method given in Standard Methods (*APHA, 1992*). Whatman GF/C filter paper (4 cm diameter) was used for filtering. Solids in the reactor were taken directly from the reactor while the recycled solids and effluent solids were withdrawn from the recycle line and the clarifier outlet respectively.

3.4.2 Chemical Oxygen Demand (COD)

Chemical oxygen demand was measured using the closed reflux colorimetric method as given in Standard Methods (*APHA, 1992*). The soluble COD was measured by filtering the sample through GF/C filter paper. The samples were digested by closed reflux in a COD reactor (*HACH, USA*). Absorbance was measured at 600 nm with a spectrophotometer (*HACH, USA*).

3.4.3 Sludge Volume Index (SVI)

The SVI was calculated as given in Standard Methods (*APHA, 1992*). One litre of the mixed liquor was placed in a measuring cylinder and the sludge volume read after 30 minutes. The SVI was then calculated using the equation given below.

$$\text{SVI} = \frac{\text{settled sludge volume (30 min) (ml/l) x 1000 (mg/g)}}{\text{Suspended solids (mg/l)}}$$

3.4.4 Lactose Determination

A liquid chromatograph (Waters Associates, Model 590, Massachusetts,USA) with a sugarpak column was used and calibrated with lactose standards of 0.1 and 1 mg l^{-1} for all lactose determination.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 REVERSE OSMOSIS PERMEATE CHARACTERISTICS

Whey is not a product of defined composition, and varies considerably, with the product from which it is derived and the manufacturing process used. It follows, that the composition of the feed stream to the R/O membrane plant will vary accordingly. This feed stream is know as whey permeate, and is the permeate stream from the preceding ultrafiltration and diafiltration stages and consists predominantly of lactose. The higher molecular weight compounds (greater than 10,000), such as proteins, casein micelles and fat globules are practically all retained by the UF membrane. Retention coefficients of the non-protein nitrogen compounds are generally 20 to 40 per cent, of the initial whey non-protein nitrogen of 0.02 to 0.04 per cent w/w. The losses through the membrane are mainly urea and amino acids (*Robinson, 1986*). Retention of lactose by the UF membrane can be up to 10%. Unbound minerals will pass through the membrane, but some are partly bound to the protein (calcium, magnesium, phosphate and citrate) and will be retained by the membrane. The permeate from the ultrafiltration is a solution of mainly lactose, with a concentration of similar to that of the initial whey solution of 4.4 to 5.2 per cent (*Kiwi Dairies Ltd, internal laboratory data*).

With reverse osmosis, retention of the mineral content of whole milk and whey exceeds 99 per cent, and only a small proportion of the smallest ions escape into the permeate. Due to the high operating pressures of the R/O membrane process (~5MPa) membrane defects are common in the dairy industry. Robinson (*1986*) reports an analysis of a R/O permeate with a lactose concentration of 250 mg l^{-1}. The substrate composition of the R/O permeate will vary depending on the performance of the

reverse osmosis membranes and whether there are leaking seals or tears in the membranes.

In the aerobic treatment of the permeate, the elements of interest, are the nutrients necessary for balanced microbial growth. These elements are nitrogen, phosphorous and trace elements such as iron (*Eckenfelder, 1980*).

4.1.1 Permeate Elemental Analysis

The reverse osmosis membrane plant at the Kiwi Dairy Company, concentrates the lactose in the ultrafiltration permeate stream, for transport to the Lactose Company (Kapuni) for further processing. The R/O process consists of two reverse osmosis membrane plants, RO1 and RO2. Both the RO1 and RO2 membrane plants can be operated individually or in parallel. If one plant is operating more efficiently then the other, the permeate composition may vary within one processing run, depending on whether one or both plants are operating. Table 4.1 shows the elemental analysis of three permeate samples. Sample 1 is of a permeate with a COD of less than 200 mg l^{-1}), while sample 2 is a permeate with a COD of 450 mg l^{-1}, and sample 3 is of a permeate with a COD greater than 1000 mg l^{-1}.

	Sample 1 COD ≈200 mg l^{-1}	Sample 2 COD ≈450 mg l^{-1}	Sample 3 COD≈1000 mgl^{-1}
Al	< 0.02	< 0.02	< 0.02
As	< 0.01	< 0.01	< 0.01
B	0.04	0.02	0.05
Ca	0.93	2.4	20.5
Cd	< 0.001	< 0.001	< 0.001
Co	< 0.002	< 0.002	< 0.002
Cr	< 0.001	< 0.001	< 0.001
Cu	< 0.003	< 0.003	< 0.003
Fe	0.005	0.01	0.007
K	28.5	16.6	263.0
Mg	0.15	0.42	3.4
Mn	0.001	< 0.0003	0.001
Mo	< 0.001	< 0.001	< 0.001
Na	25.0	4.6	248.0
Ni	< 0.002	< 0.002	< 0.002
P	1.1	1.9	21.0
Pb	< 0.02	< 0.02	< 0.02
S	0.56	0.52	3.0
Se	< 0.03	< 0.03	< 0.03
Sn	< 0.003	< 0.003	< 0.003
Sr	< 0.0002	0.001	0.008
Zn	< 0.001	0.02	0.003

Table 4.1: Reverse Osmosis permeate elemental analysis (ICP analysis, AgResearch Ltd.). All concentrations are in mg l^{-1}.

From Table 4.1 it can be seen, that with poorly performing membranes the elements that increase substantially in the R/O permeate are calcium, potassium, sodium and phosphorus, as the mineral content of the whey is not retained by the previous ultrafiltration step. The elements in highest concentration are sodium and potassium. In sample 1 the concentrations were potassium 28.5 mg l^{-1} and sodium 25.0 mg l^{-1} whereas in sample 2 the concentrations were 16.6 mg l^{-1} and 4.6 mg l^{-1} respectively. This compares to sample 3 which had sodium concentration of 248 mg l^{-1} and potassium concentration of 263 mg l^{-1}. In raw whey these elements are in concentrations in the region of 500 mg l^{-1} for sodium and 1400 mg l^{-1} for potassium. Robinson (*1986*) gives the retention of Na^+ and K^+ by reverse osmosis membranes as 95 per cent and 98 percent respectively, lower than the retention of other minerals which exceeds 99 per cent. In terms of sodium and potassium retention the approximate values for these samples they are: sample 1; 95 % for Na ,98 % for K, sample 2; 99 % for Na, 99 % for K, sample 3; 50 % for Na and 81 % for K. This shows that the membrane, when sample 1 and 2 were taken, was performing within expectations, were as for sample 3 the membrane was operating below specifications.

Iron is present in all three permeates at a concentration ranging from 0.005 to 0.01 mg l^{-1}. Eckenfelder and Grau (*1992*) list the iron requirement for balanced microbial growth in the activated sludge process as 12 x 10^{-3} mg/mg BOD. For a low strength permeate with a BOD removal of 100 mg l^{-1} this would require an iron concentration of 1.2 mg l^{-1}. A deficiency of iron may cause poor floc formation during aerobic treatment.

Due to their toxicity certain cations are of great importance in the aerobic treatment of wastewaters. Copper, lead, silver, chromium, arsenic, and boron are toxic in varying degrees to microorganisms and therefore must be taken into consideration in

the design of a biological treatment plant. Apart from silver, which was not present, of these potentially toxic elements boron has the highest concentration in the permeate of 0.05 mg l^{-1}, well below toxic levels of 1 mg l^{-1} (*Eckenfelder, 1980*).

Of all the elements listed in Table 4.1, phosphorus is the most important for balanced microbial growth. The general rule for phosphorus requirements is a BOD to phosphorus ratio of 100 to 1. The phosphorous concentration of sample 1 was 1.1 mg l^{-1}, for sample 2 it was 1.9 mg l^{-1}, and for sample 3 it was 21.0 mg l^{-1}. For sample 1 with a COD of 200 mg l^{-1} (assuming a BOD/COD ratio of 0.5), and a phosphorus concentration of 1 mg $^{-1}$ this concentration would be adequate, however for sample 2 with a COD of 450 mg l^{-1}, the concentration of 1.9 mg l^{-1} would be inadequate. For sample 3 the phosphorus concentration of 21.0 mg l^{-1} is sufficient.

4.1.2 Permeate Nitrogen Analysis

For balanced microbial growth nitrogen needs to be present in a COD to nitrogen ratio of 20 - 25 to 1. Ammonia and TKN tests were performed on both the R/O permeate from membrane plant 1 and plant 2. R/O plant 1 was operating to requirements and produced a low strength permeate of 200 mg l^{-1} COD or less. The ammonia concentration ranged from 6.9 to 7.6 mg l^{-1} and the TKN ranged from 82.6 to 92.7 mg l^{-1}. The presence of organic nitrogen would be as non-protein nitrogen, such as urea and amino acids. Previous tests by the Kiwi Dairy company confirm that no protein was detectable in the permeate. Previous non-protein nitrogen analysis showed concentrations of 50 to 60 mg l^{-1} were present, lower than the concentrations shown in this study. There is sufficient nitrogen present to provide a COD:N ratio greater than required. Organic nitrogen present in the permeate as amino acids, must first be biologically hydrolysed to release ammonia in order to be available to the biomass, therefore the organic removal rate with ammonia as the nitrogen source is

higher. The permeate from R/O membrane plant 2 had an ammonia concentration of 17.5 mg l^{-1} and a TKN of 136 mg l^{-1}. For this permeate no supplementary nitrogen would be required.

4.1.3 Permeate Lactose Concentration.

The main organic substrate in R/O permeate is lactose. Previous analysis done by the Kiwi Dairy Company showed lactose concentrations of 470 to 730 mg l^{-1}.

In this research lactose concentrations of the low strength permeate from plant 1, ranged from 41.7 mg l^{-1} to 59.4 mg l^{-1}. The permeate from R/O plant 2 when operated with leaking membranes, had a lactose concentration of 282 to 961 mg l^{-1} over a period of one month. Figure 4.2 shows the relationship between lactose concentration and chemical oxygen demand. The COD increased linearly with lactose concentration, over the range investigated.

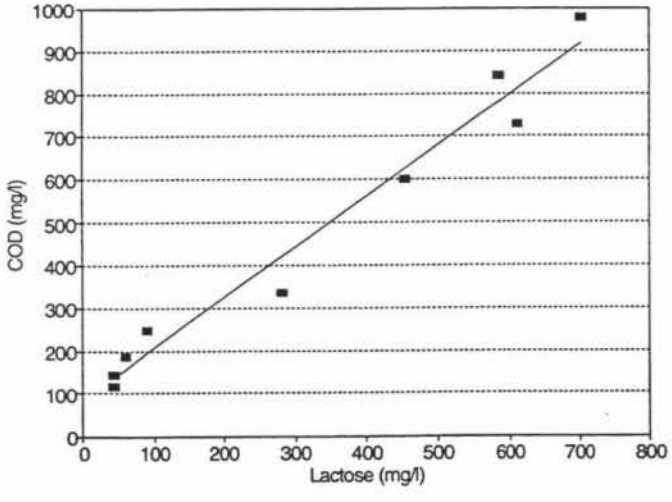

Figure 4.1: Relationship between R/O permeate lactose concentration and COD

4.1.4 Permeate Conductivity

At Kiwi Dairies conductivity is the only continuous online measurement of the R/O permeate stream before discharge to the drain. It would therefore be useful to find the conductivity variation over the research period, and its relationship to chemical oxygen demand, and lactose concentration. Potentially conductivity may be used as a control parameter for organic loading to any future biological treatment process if it can be related to COD. The variation of both R/O membrane plant 1 and 2 for a period of 141 days (1/9/94 to 14/1/95) is shown in Figure 4.2. The conductivity meters have a maximum value of 2000 microsiemens, so values equal or greater than this are shown as 2000 ms on Figure 4.2.

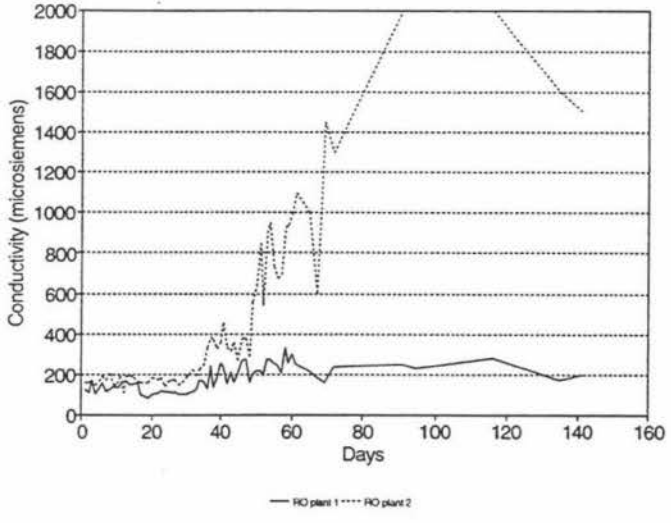

Figure 4.2:Variation of R/O permeate conductivity for membrane plants 1 and 2

The conductivity for R/O plant 1 remained relatively constant throughout this period, but R/O plant 2 had a noticeable deterioration in performance at 40 to 50 days and this corresponded to an increase in permeate COD. Conductivity is a measure of the

permeates ability to conduct electricity, and adding electrolytes such as salts will increase conductance. An increase in lactose by itself will not cause an increase in conductivity, but this will usually be accompanied by an increase in the mineral content of the permeate, causing an increase in conductivity. This is also illustrated in Table 4.1 where plant 2 (sample 3) had a large increase in minerals present in solution as cations.

The relationship between conductivity and chemical oxygen demand is shown in Figure 4.3. It is a semi-logarithmic relationship and the regression analysis for the line of best fit did not include conductivity values of 2000. The equation for the line of best fit is;

COD= exp(0.00128*conductivity + 4.81213)

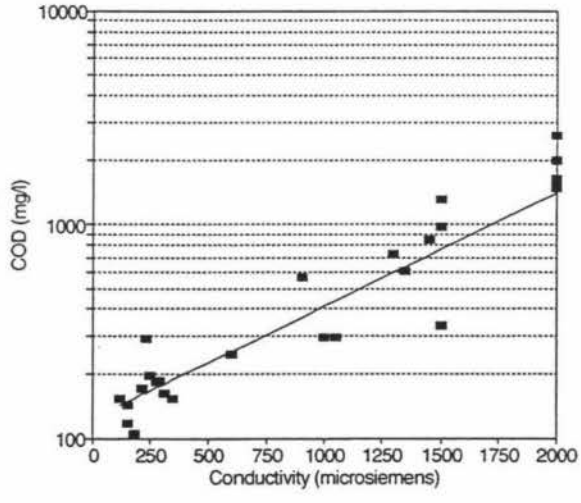

Figure 4.3:Semi-log plot of relationship between permeate conductivity and COD

Figure 4.4 shows the semi-logarithmic plot of the relationship between conductivity

and lactose concentration for R/O permeate. As with Figure 4.3 the regression analysis did not include conductivity values of 2000 microsiemens. The equation for the line of best fit is;

Lactose= exp(0.00192*conductivity + 3.51726)

It is well documented that conductivity decreases at high ion concentrations after reaching a peak (*Omega Engineering INC, 1992*). Both Figure 4.3 and 4.4 show a decrease in the rate of conductivity increase with substrate concentration, at higher values of conductivity.

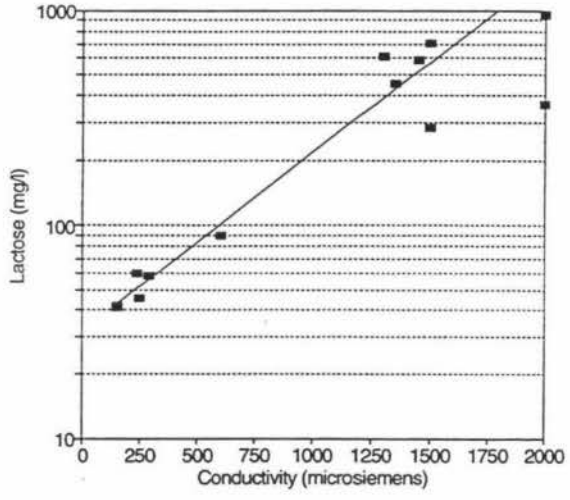

Figure 4.4:Semi-log plot of relationship between permeate conductivity and lactose concentration

4.2 BATCH TESTS

Batch tests are an easy and relatively quick method to determine the kinetic constants of aerobic growth. Microbial growth can be measured directly (plate count or suspended solids analysis), or measured indirectly (oxygen uptake rates or optical density measurement). The methods used in this research are optical density, oxygen uptake and the direct measurement of TSS. Determination of the specific growth rate (μ) at varying concentrations, will allow determination of the maximum specific growth rate (μ_m) and the half saturation constant K_S. Measurement of the soluble COD with time will give the specific substrate removal rate (q_s) and the true cell yield (Y_t).

4.2.1 Biokinetic Constants using Optical Density

The maximum specific growth rates were determined for both a low strength permeate and a high strength permeate by measuring optical density. One litre perspex reactors were filled with 500 ml of permeate and seeded with 10 ml of activated sludge from a continuous reactor treating R/O permeate. A water bath at 20°C was used to maintain constant temperature, and laboratory air diffusers used to provide aeration. Concentration of low strength permeate from membrane plant 1 was not possible using a rotovac, due to the high temperature required for concentration (80 - 90 ^{0}C). At this temperature the composition of the permeate may alter, so for the low strength permeate growth rates were measured only at concentrations less than or equal to the original concentration.

Figures 4.5 shows the graphical method used to determine μ_m and K_S, from the growth rate data for the low strength permeate. The slope of the regression line equals the inverse of μ_m and the y axis intercept is equal to K_S/μ_m. Figure 4.6 displays

the same data as a hyperbolic plot of specific growth rate versus substrate concentration, with the continuous line being the Monod's plot using the values for μ and K_S determined from Figure 4.5. The values of μ_m and K_S for the low strength permeate were 2.1 d^{-1} and 32 mg l^{-1} respectively.

Batch growth rate tests where also performed on a permeate from membrane plant 2 which had a COD of 940 mg l^{-1}. Figure 4.7 is the plot for biokinetic determination and Figure 4.8 shows a plot of the raw data and the Monod's plot using the constants.

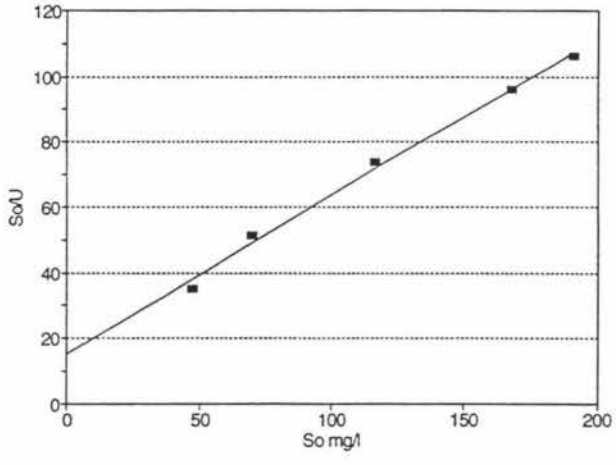

Figure 4.5:Plot for determination of biokinetic constants for permeate from plant 1

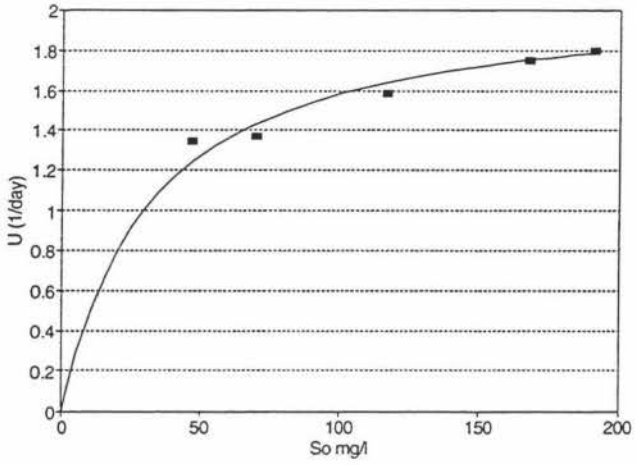

Figure 4.6:Hyperbolic plot of specific growth rate and substrate concentration for permeate from plant 1

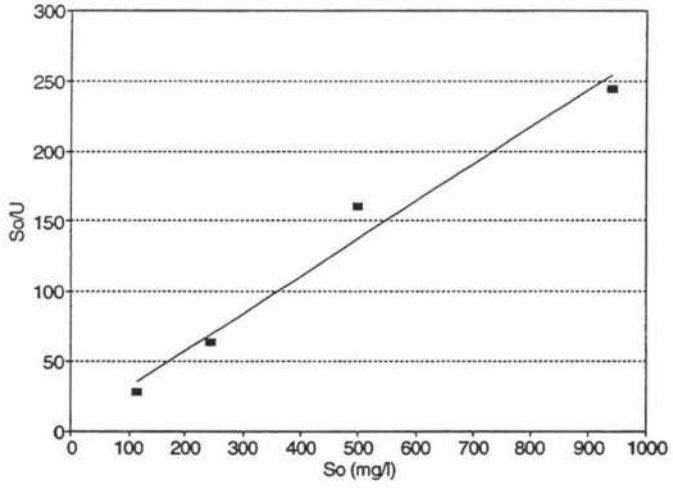

Figure 4.7:Plot for determination of biokinetic constants for permeate from plant 2

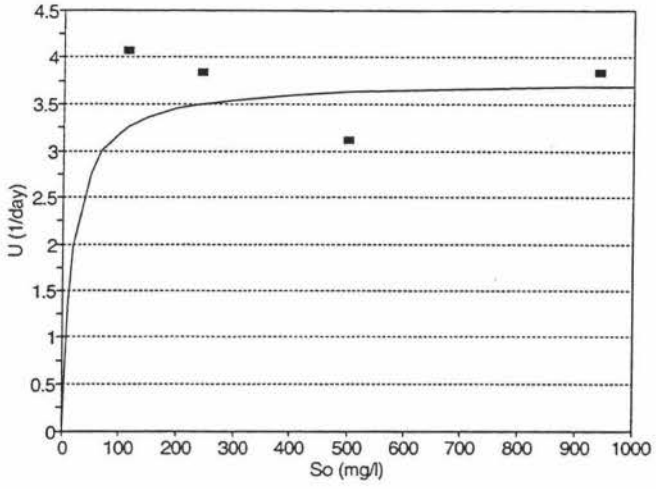

Figure 4.8:Hyperbolic plot of specific growth rate and substrate concentration for permeate from plant 2

The values of μ_m and K_S determined for a high strength permeate from plant 2 were 3.76 d^{-1} and 18 mg l^{-1} respectively. The maximum specific growth rate for permeate from plant 2 was 55% greater than for permeate from plant 1. Both batch tests were done without supplementary nutrients. A reason for the variation in constants, may be the initial substrate to biomass ratio S_o/X_0. In test 1, the S_o/X_0 ratio ranged from 4.7 to 14.7 and for test 2 the ratio ranged from 55.4 to 122. Chudoba *et al* (*1992*) proposes that the S_o/X_0 ratio is one of the most important factors in batch cultivation of mixed cultures. When this ratio is low no cell multiplication takes place during the substrate removal, and under these conditions , biomass increase is mostly due to the synthesis of storage polymers. They concluded that for studies to obtain kinetic constants it is necessary to use low S_o/X_o ratios to prevent biomass from substantial multiplication, so the proportion of slow and fast growers in the original mixed culture does not change. The results of batch tests by Chudoba *et al* (*1992*), show

that the value of μ_m for high S_o/X_o ratios was higher than for low ratios, while the same applied for K_S. This was also the case in these two batch tests were the value for μ_m was greater for a higher S_O/X_o.

4.2.2 Substrate Removal Rates

A series of batch tests was performed on permeate from plant 1 to determine soluble COD removal rates and yield coefficients. From this data values for μ and μ_m were also calculated. Four tests at varying substrate concentrations were performed over a period of four days, using a temperature controlled fermentation vessel. Five litres of R/O permeate were seeded with 100 mls of sludge from a continuous reactor treating R/O permeate, and aerated and completely mixed. Biomass and soluble COD were measured hourly until the soluble COD remained constant.

Figure 4.9 shows the substrate removal curves at varying concentrations of permeate. Because the substrate removal rate batch tests were performed over a period of 4 days, the biological population of the sludge may have changed accordingly (*Leonard, 1993*).

The specific substrate removal rate (q_s) was calculated from the maximum slope of the removal curves shown in Figure 4.9. For all four concentrations this generally occurred during the first 3 hours of the test. For these batch studies the S_o/X_o ratio ranged between 0.4 and 1.1, giving a linear maximum removal rate. Chudoba *et al* (*1992*) showed that a S_o/X_o ratio of less than 3 is required for linear removal curves and zero lag times, however the threshold between low and high values of the S_o/X_o ratio is not strictly defined and depends on various factors.

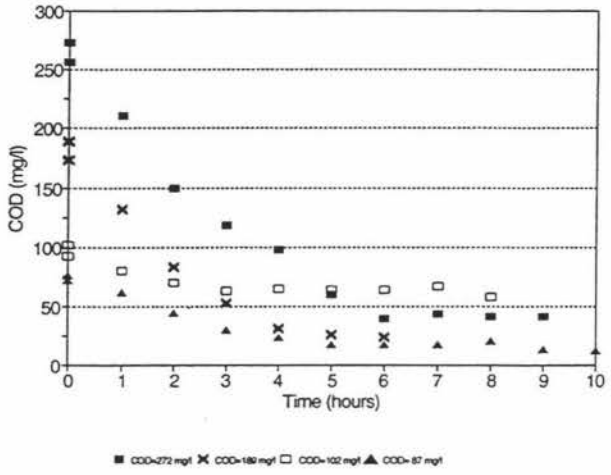

Figure 4.9: Substrate removal curves for R/O permeate

Part of the substrate during the removal period is used for maintenance, and the total rate of substrate consumption is defined by Equation 4.1.

$$\left(\frac{ds}{dt}\right)_{total} = \left(\frac{ds}{dt}\right)_{growth} + \left(\frac{ds}{dt}\right)_{maintenance} \qquad (4.1)$$

The specific substrate removal rate during the growth phase is readily calculated from Figure 4.9. Once q_s is determined, μ can be calculated for each initial substrate concentration using Equation 4.2 and μ_m calculated using the methods previously described.

$$\frac{1}{x}\cdot\left(\frac{ds}{dt}\right)_{growth} = q_s = \frac{\mu}{y_t} \qquad (4.2)$$

Equation 4.2 shows that q_s is proportional to μ, and therefore would be expected to increase to a maximum $q_{s\,m}$ as with the specific growth rate. This presents another method to determine μ_m, as shown by Equation 4.3.

$$q_{s\,m} = \frac{\mu_m}{y_t} \qquad (4.3)$$

S_o (mg l^{-1})	Y_t (mgTSS/mgCOD)	q_s (mgCOD/mgTSS.d)	μ (d^{-1}) q_s	μ (d^{-1}) TSS
87	0.5	2.23	1.12	0.77
102	0.41	2.43	1.00	0.91
189	0.37	2.93	1.08	1.10
272	0.62	2.87	1.78	2.02

Table 4.2:Biokinetic constants determined from substrate removal curves

The average yield coefficient of the values listed in Table 4.2, is 0.48 mg TSS/mg COD. The value for μ_m ,as determined from the values of μ in Table 4.2 is 2.37 d^{-1} and K_S is 138 mg l^{-1}. The maximum substrate removal rate $q_{s\,m}$ is calculated as 3.34 mg COD/mg TSS.d. Using Equation 4.3 the value of μ_m calculated is 1.60 mg l^{-1},

while K_S is 38 mg l^{-1}. During each of the batch tests, TSS was measured hourly and μ calculated for each S_o.

The value of y_t used in the calculation of μ_m (Equation 4.3) is the average value from Table 4.2. The main source of experimental error during the batch tests was the measurement of TSS, as it is easier to determine soluble COD with more accuracy than TSS. When measuring TSS directly and pipetting a volume of the reactor MLSS, there is an inherent difficulty in obtaining a completely representative sample of the MLSS.

There are no literature values of biokinetic constants for R/O permeate, though the values determined for other dairy wastes are of similar magnitude. Orhon *et al* (*1992*) found values of μ_m ranged from 3.1 to 3.74 d^{-1}, K_S ranged from 74 to 257 mg l^{-1} and the values of y_t ranged from 0.41 to 0.54. Leonard (*1993*) determined values of μ_m from 0.6 to 5.1 d^{-1}, K_S from 5 to 600 mg l^{-1} and y_t averaged 0.42.

Due to the mixed substrate of typical dairy wastes it is difficult to compare the values of q_s from these tests to those for other dairy wastes. Leonard (*1993*) gives values of q_s for lactose solution, and because the substrate in R/O permeate is predominantly lactose these values should be comparable. Leonard (*1993*) found that q_s ranged from 1.0 to 1.4 mg lactose/mg TSS.d for lactose concentrations from 200 to 800 mg l^{-1}, these are in the same order of magnitude as those in Table 4.2 (2.23 - 2.87 mg COD/ mg TSS.d).

4.2.3 Batch Tests using R/O Permeate from Different Sources.

A series of three batch tests were performed on permeate from membrane plant 1, membrane plant 2 and from the balance tank which is a composite of both permeates.

In test 1, batch tests were performed using the same method as the substrate removal tests in the previous section. Tests 2 and 3 were performed using 2 litres of permeate in 2.5 litre flasks and then agitating in a shaker at a constant temperature of 20°C. Batch tests 3 were performed using additional nutrients (tests 1 and 2 had no additional nutrients).

Figure 4.10 shows the values of μ determined from the direct measurement of TSS for permeate from plant 1, plant 2 and from the balance tank. As stated previously the permeate from plant 2 had a high COD. The COD for each test is shown in Table 4.3. The S_o/X_o ratio of all batch tests ranged from 0.8 to 5.7.

	Batch Test 1	Batch Test 2	Batch Test 3
RO1	201	143	159
RO2	993	938	921
BT	742	623	629

Table 4.3: Initial substrate concentrations for permeate batch tests.

The specific growth rates in Figure 4.10 were all measured by direct TSS measurement and ranged from 1.2 to 2.7 d^{-1}. These are less than or within the range of μ_m values calculated in the previous sections. The values of μ calculated for the permeate from the balance tank (composite of RO1 and RO2) were lower than those for RO1 and RO2. Additional nutrients had no apparent effect on the specific growth rates calculated. Gaudy and Gaudy (*1984*) cite previous studies which found that μ_m values obtained for nitrogen as the limiting nutrient, are essentially the same for as when carbon is the limiting nutrient, since the same non-limiting case is approached

in either study. The values of nitrogen present in the permeate given in Section 4.1 suggest that nitrogen is in sufficient quantities to be not a major factor in batch tests.

Specific growth rates were also calculated from substrate removal rates and are shown in Figure 4.11. These μ values are lower than those in Figure 4.10 and ranged from 0.7 to 2.7 d^{-1}. The values of μ for RO2 permeate are higher than those for either RO1 or BT. The range of μ values calculated in Figure 4.13 is slightly greater than in Figure 4.10. Some of this variation may be due to experimental error because when μ is determined from q_s it includes both the experimental error of soluble COD and TSS determination. Again nutrient addition had no apparent effect on μ.

Substrate removal rates in Figure 4.12 range from 1.44 to 7.96 mg COD/ mg TSS.d. The values of q_s in Figure 4.12 are larger for RO2 than either RO1 and BT for all three batch tests.

Because the substrate concentrations for RO2 and BT are higher than those for RO1, it would be expected that both μ and q_s will be largest with for RO2, and BT would in turn be larger than RO1. Figures 4.11 and 4.12 show that this was in fact the case. The exception is Figure 4.10, which possibly indicates a small K_S value, as μ does not change significantly with substrate concentration.

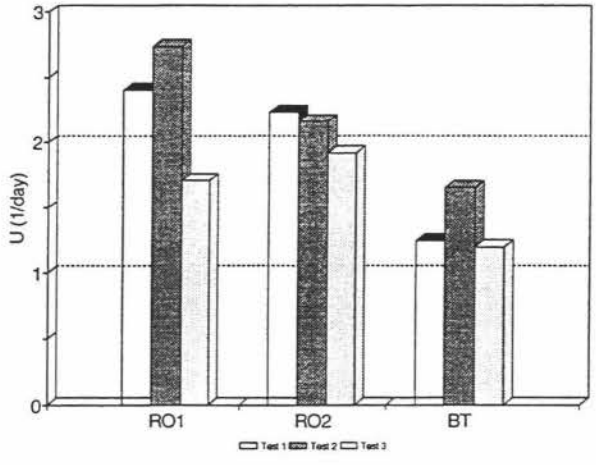

Figure 4.10: Specific growth rates from direct biomass measurement.

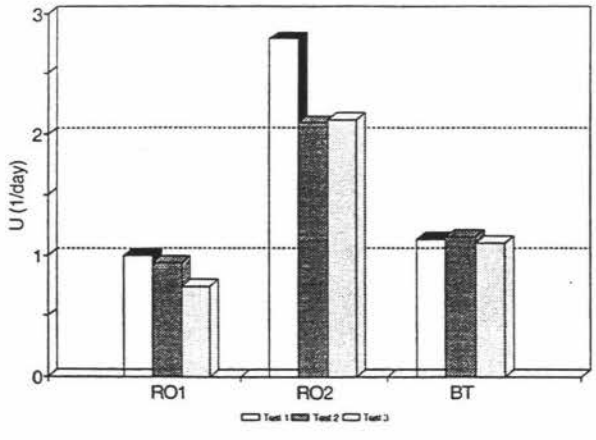

Figure 4.11: Specific growth rates determined from substrate removal rates

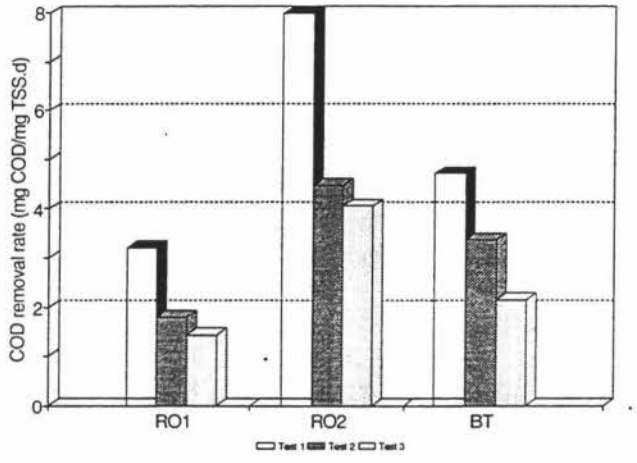

Figure 4.12: COD removal rates for different permeates

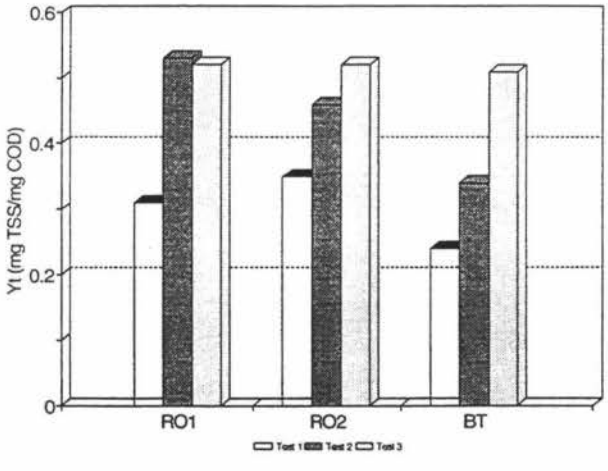

Figure 4.13: Maximum yield coefficients for permeates from varying sources.

The maximum yield coefficients for all batch tests in Figure 4.13 vary from 0.24 to 0.53, and average 0.42 mg TSS/mg COD, similar to literature values for other dairy wastes. Yield coefficients for test 1 are lower than those for tests 2 and 3, although there appears to be no variation of Y_t for test 3 with nutrient addition.

In summary there is no conclusive trend in biokinetic constants for permeate from R/O membranes of varying performance. Supplementary nutrient addition also had no obvious effect on the biokinetic constants.

4.2.4 Biokinetic Constants using Oxygen Uptake Rates

Two batch tests using the respirometric method developed by Cech *et al* (*1985*) were performed. This method involves injecting small volumes of concentrated feed into a volume of mixed liquor and measuring the change in OUR. R/O permeate was concentrated using freeze drying. Only small volumes of permeate could be concentrated at any one time. In the first test a low strength permeate (plant 1) was concentrated to a COD of 800 mg l^{-1} over a period of three days, and for the second test, permeate from plant 2 was concentrated to a COD of 4770 mg l^{-1}.

Figure 4.14 shows the Monod plot for the test using the first concentrate, and Figure 4.15 is the plot for the test using the second concentrate. The values of μ_m obtained were 1.7 and 2.8 d^{-1} respectively, and are in the range of values given in Sections 4.2.1 and 4.2.2. The half saturation constants from these OUR tests are 1.23 and 2.95 respectively, much lower than those previously determined. Leonard (*1993*) also found that using the injection method, the K_S values were on average 18 times smaller then those obtained using traditional batch methods with dairy wastes.

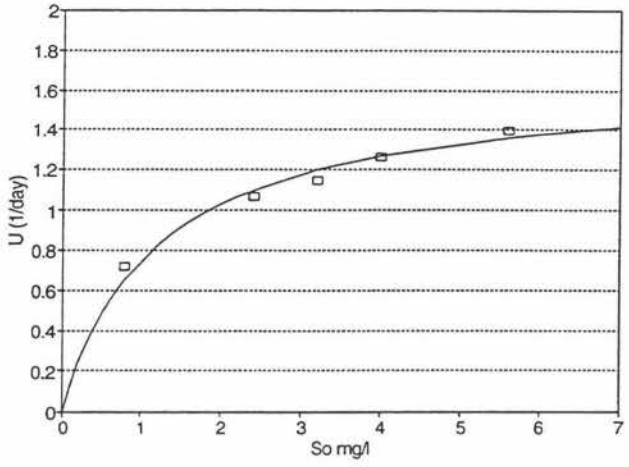

Figure 4.14: Hyperbolic plot using oxygen uptake rates (Permeate from plant 1)

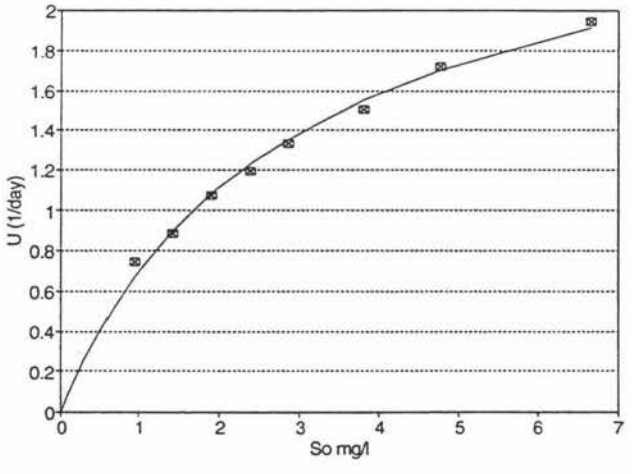

Figure 4.15: Monod hyperbolic plot using oxygen uptake rates (Permeate from plant 2)

4.2.5 Summary

For the design of continuous reactors it is necessary to use appropriate values for the biokinetic constants. The average maximum specific growth rate μ_m for the six values determined is 2.4 d^{-1}. As all values of μ_m lie within the expected range for a dairy waste, all values were included in the calculation of the average. The average half saturation coefficient K_S was calculated from all six values is 38 mg l^{-1}. It is generally accepted that readily biodegradable substrates, such as dairy wastes, have low K_S values. The average yield coefficient y_t of the 17 values determined is 0.45 mg TSS/mg COD.

It must be realised that the evaluation of these constants presents a challenge as the history of the biomass will dictate the value of the coefficients. The biokinetic constants determined for R/O permeate are summarized in Table 4.4 and compared to literature values for other dairy wastes.

Author	**Waste**	**μ_m (d^{-1})**	**K_S (mg l^{-1})**	**Y_t (mgTSS/mgCOD)**
Orhon *et al* (1993)	Whey-washwater	3.1	100	0.44
Orhon *et al* (1993)	General Discharge	3.3	74	0.41
Leonard (1993)	Butter-powder mixture	1.0	18.5	0.42
This Study	R/O permeate	2.4	38	0.45

Table 4.4: Comparison of biokinetic constants from this study with literature values for other dairy wastes.

4.3 ACTIVATED SLUDGE PILOT PLANT STUDIES

4.3.1 Introduction

To determine the viability of a continuous aerobic process to treat R/O permeate, and the level of performance achievable, a 1.7 m^3 completely mixed activated sludge pilot plant was continuously operated for a period of 54 days. The reactor was initially seeded with activated sludge from an aerated lagoon treating dairy wastewater. The pilot plant was operated on a semi-continuous basis once seeded, for a period of 50 days before true continuous operation. This initial 50 day period was for sludge acclamation and to allow the completion of an automated feed supply to be installed. Because of the variability of the feed, steady state operation was not anticipated. A pilot scale sand filter was installed after the clarifier to determine the level of biomass removal achievable without previous coagulation.

4.3.2 Hydraulic Retention Time (HRT)

An HRT of 10 hours was set initially for a period of twenty days and then changed to 20 hours. Due to biomass carryover in the final effluent it was decided not to use a shorter HRT than 10 hours, as excessive biomass may have been washed out. Once the HRT was set at 20 hours, it was left at that time for the remainder of the study.

4.3.3 Substrate Removal Efficiency

The level of substrate removal can be difficult to quantify with a fluctuating influent concentration. In some cases the influent COD may not of the same strength as the influent treated one HRT earlier, yet it is this figure that is used in the calculation of substrate removal. Figure 4.16 shows the COD of the feed and the soluble effluent COD and the total COD of the effluent. Soluble COD reduction ranged from 85 to 95 % except when there were significant perturbations. These lower reductions

coincided with organic shock loads. The COD of the feed varied from 379 to 1949 mg/l, and was essentially soluble substrate. The HRT had no effect on the substrate removal achieved. Fang (*1990 & 1991*) treated whey wastewater in a pilot plant with three stages and achieved substrate removals of, 90 % using an HRT of 10 hours and 99 % for an HRT of 20 hours.

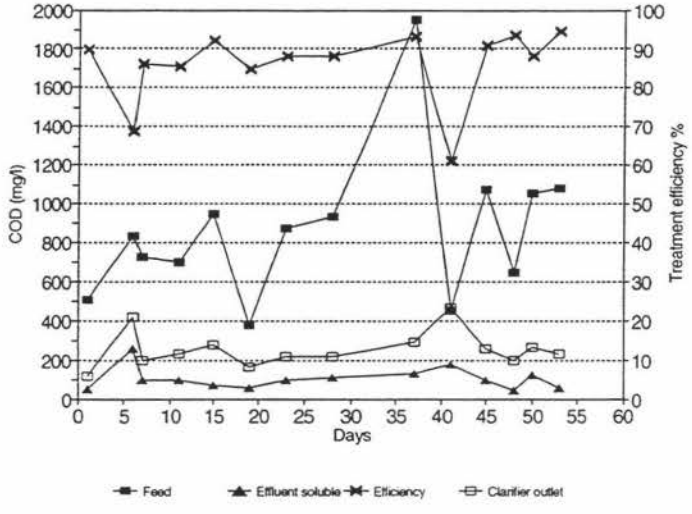

Figure 4.16: Plot of feed, soluble effluent and effluent COD and treatment efficiency achieved

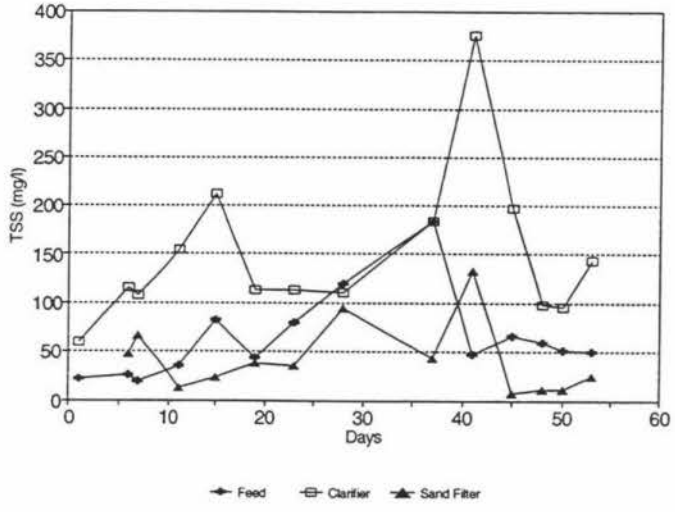

Figure 4.17: Total solids of feed, clarifier outlet and effluent after sand filter

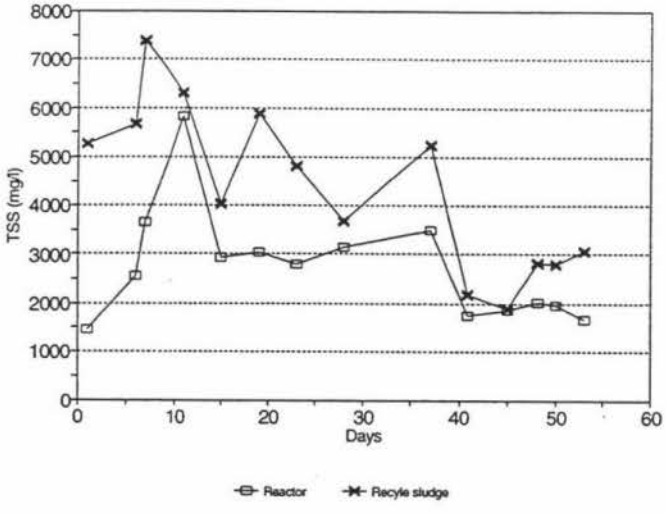

Figure 4.18: Total solids of reactor biomass and recycle sludge

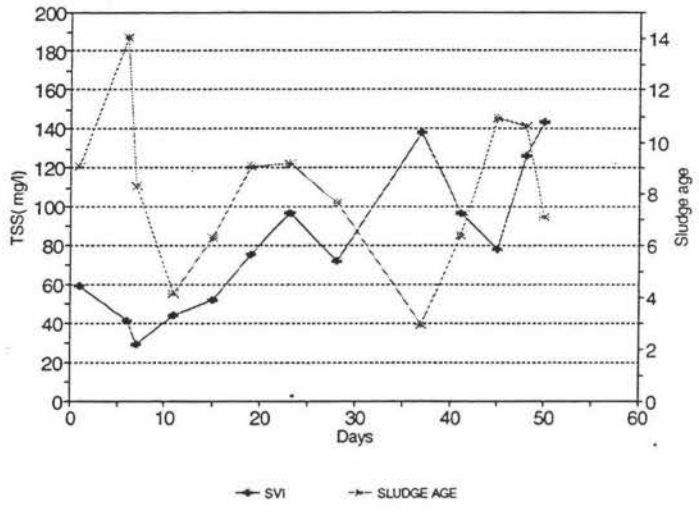

Figure 4.19: Plot of SVI and sludge age variation

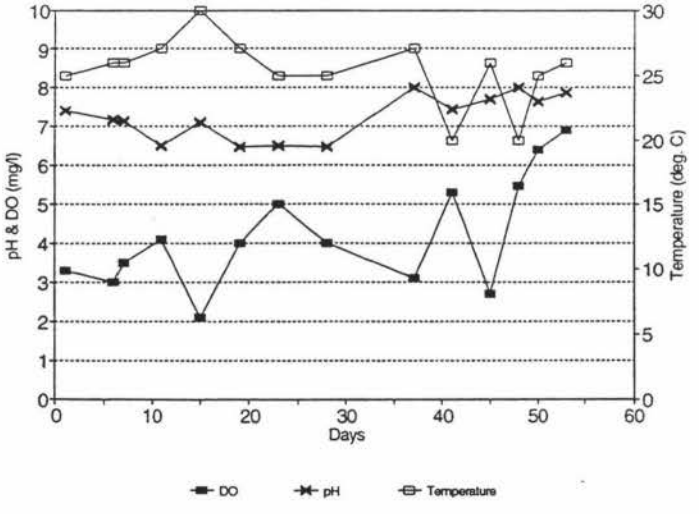

Figure 4.20: Plot of DO, pH and temperature variation

The effluent soluble COD varied from 49 to 259 mg/l. The leakage of soluble COD occurred due to two reasons. Firstly due to organic shock loads, and also because the recycle pump occasionally failed. The total effluent COD from the clarifier varied considerably due to poor settling in the clarifier which also coincided with organic shock loads and recycle pump failures. The total COD of the effluent from the clarifier ranged from 164 to 463 mg/l, depending on the performance of the clarifier. The main concern in this study was the soluble COD removal and the levels of reduction are based on this. This is because as the treated permeate is to be reused within the plant, the effluent from aerobic treatment will be further treated by coagulation and filtration.

4.3.4 Feed Total Suspended Solids

Fresh R/O permeate has no suspended solids, however this changes when stored due to mineral precipitation. Prior to being pumped to the reactor a 2000 litre balance tank was used to hold the permeate. With a 10 hour HRT in the reactor this equated to an 11 hour retention time in the balance tank, and at a 20 hour HRT in the reactor this equated to a 22 hour retention time in the balance tank. From Figure 4.17 it can be seen that solids in the feed tank increased with time and were generally higher during the 20 hour HRT.

4.3.5 Effluent Total Suspended Solids

The effluent TSS ranged from 59 to 376 mg/l. Figure 4.17 shows that generally the effluent suspended solids concentration was 100 to 150 mg/l. High effluent suspended solids coincided with either recycle pump problems or organic shock loads.

Improved sludge recycle rate control and the ability to keep the recycle rate (α) < 1 would decrease the solids flux loading on the clarifier and possibly decrease the

TSS in the effluent. The overflow rate for the clarifier ranged between 1.11 and 2.22 $m^3/m^2.d$ and is much lower than the typical design values of 15 to 32 $m^3/m^2.d$ used for sewage treatment. The largest solids loading rate for the clarifier during pilot plant operation was 28 $kg/m^2.d$, and is again lower than the typical values of 70 to 140 $kg/m^2.d$ used in domestic sewage treatment systems (*Tchobanoglous, 1985*). The pilot scale clarifier effluent outlet was 30 mm diameter and the depth of the clarifier was 0.4 m. It is likely that with an increase in side water depth and the use of a weir rather than a single outlet, the effluent TSS would also improve.

A pilot scale dual medium sand filter was tested for its effectiveness in reducing the TSS of the effluent. Generally a solids reduction of 70 to 90 % was obtained. In this study, the sand filter was only backwashed daily and occasionally every second day. With coagulation and regular backwashing every 4 to 6 hours, higher solids removals would be obtained.

4.3.6 Mixed Liquor Suspended Solids

For a typical activated sludge process the MLSS of the reactor should be 2000 to 4000 mg l^{-1}. Figure 4.18 shows that there were no problems in maintaining a viable biomass. With the exception of a sudden increase in MLSS at 11 days the biomass concentration was maintained at 2000 to 3000 mg l^{-1} without much difficulty. The main difficulty in controlling a the reactor MLSS was the variability of the recycle rate.

The recycle TSS is commonly used as a method for plant control to obtain a suitable effluent COD. The recycle sludge concentration was maintained between 4000 to 8000 mg l^{-1} for the first 20 days. During this period the recycle ratio was close to 1, and was then increased to approximately 2.5 for the 20 hour HRT. The recycle

ratio was increased as it was found that pump failures occurred less frequently at the higher flow rate. The effect of the higher recycle ratio was to decrease the TSS of the recycle stream as shown in Figure 4.18. The recycle TSS is typically maintained at 10,000 mg l^{-1} for complete-mix activated sludge plants (*Metcalf and Eddy inc., 1991*).

4.3.7 Sludge Volume Index

An SVI of less than 100 signifies a sludge with good settling properties. At an HRT of 10 hours the biomass had an SVI of 29 to 75 while at a HRT of 20 hours the SVI ranged from 97 to 138. Generally a good settling biomass was maintained, any difficulty with high effluent suspended solids was due to poor recycle sludge control and short circuiting in the clarifier. Figure 4.19 shows the variation of SVI during the period of operation.

Low food to microorganism (F:M) ratios can result in bulking of the sludge. In this study the F:M ratio was maintained in the range 0.29 to 0.79 mg COD/mg TSS.d, within the range for a completely mixed activated sludge plant treating industrial wastes (*Eckenfelder & Grau, 1992*).

4.3.8 Sludge Age

Figure 4.19 also shows the variation of sludge age. Difficulty was encountered in controlling this variable, again due to control problems with the sludge recycle pump as previously mentioned. In this operation the sludge age varied from 3 to 14 days, again within the typical range for an activated sludge process without the need for nitrification.

4.3.9 Physical Variables

Aeration was provided by dome air diffusers, and the DO level maintained between 2 and 7 mg l^{-1} (Figure 4.20).

The *p*H was controlled using a *p*H controller with a low level set point of 6.5. Any tendency for *p*H to vary outside the optimum range of 6 to 8 was towards more acidic values. In an full scale plant it would also be advisable to have an upper limit on the *p*H control as well. The *p*H of untreated R/O permeate is typically 6 to 6.5.

The pilot plant was operated during the summer period, with the temperature varying between 20 and 30 ^{0}C and there were no problems with temperature affecting the pilot plant operation.

4.3.10 Summary

The operation of the pilot plant showed that regular substrate reductions of 90% could be achieved over a prolonged period. While the pilot plant achieved satisfactory reductions, effluent soluble COD levels were not sufficiently low to enable the reuse of the permeate. With improved R/O membrane performance and a lower strength feed, the aerobic reactor would produce effluent substrate levels sufficiently low for permeate reuse.

Attempts were made to use only RO1 for the pilot plant feed stream, however due to solids loss in the effluent, a biomass of sufficient concentration in the aeration tank could not be maintained over sustained periods. This was due to the COD of the permeate being less than 200 mg l^{-1}, and the amount of biomass produced from this substrate being less than the biomass lost in the effluent.

4.4 LABORATORY SCALE MODEL ACTIVATED SLUDGE SYSTEM

4.4.1 Introduction

A 5 litre laboratory scale activated sludge system was operated to determine the levels of effluent soluble COD achievable with a low substrate R/O permeate such as that produced by membrane plant 1.

The reactor was seeded with sludge from the pilot plant and operated at HRT's of 10 and 20 hours.The laboratory reactor was operated with a recycle ratio of 0.3. No sludge was wasted due to effluent TSS levels. The reactor was operated for a period of 20 days until the biomass in the reactor decreased to 320 mg l^{-1}.

4.4.2 Soluble Substrate Reductions

Soluble COD reduction averaged 91 %, and ranged from 84 to 95 % for both HRTs. The COD of the influent ranged from 106 to 191 mg l^{-1}. The soluble COD of the effluent ranged from 10 to 18 mg l^{-1}, and averaged 14 mg l^{-1}. This demonstrates that R/O permeate can be aerobically treated to substrate levels low enough for reuse, provided further tertiary treatment is used. For example the activated sludge plant treating dairy wastewater for reuse studied by Hadjivassilis (*1991*), had a COD of 9.7 mg l^{-1} after tertiary treatment. The reductions in soluble substrate achieved during the period of reactor operation are displayed in Figure 4.21.

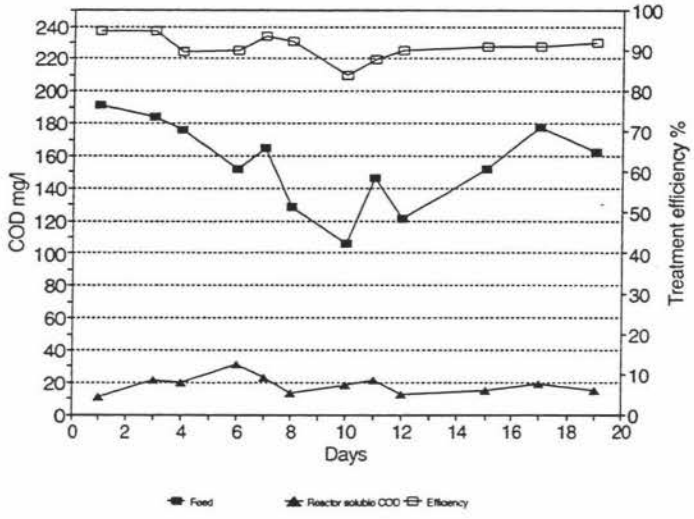

Figure 4.21: Plot of feed COD, effluent soluble COD, and substrate reductions achieved with a laboratory reactor.

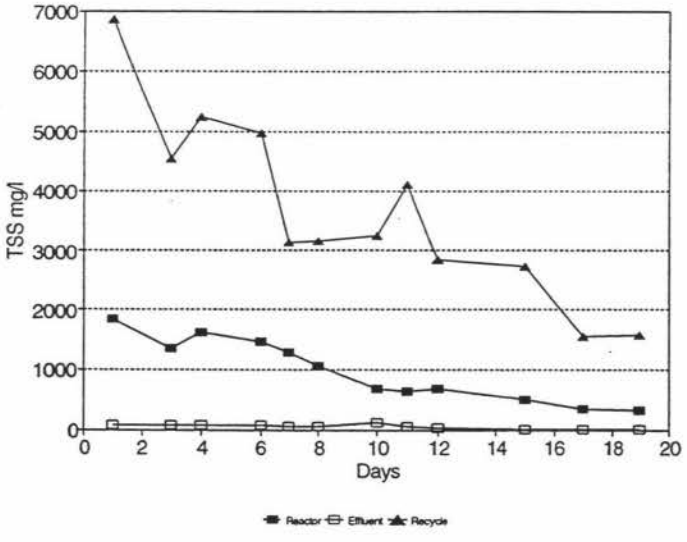

Figure 4.22: Plot of reactor MLSS, recycle TSS and effluent TSS during laboratory reactor operation

4.4.3 Mixed Liquor Suspended Solids (MLSS)

Both the reactor and recycle biomass concentration decreased significantly during the operation of the laboratory reactor. As seen in Figure 4.22 the MLSS of the reactor decreased to 320 mg l^{-1} from the initial 1860 mg l^{-1} concentration over the 20 day period. Even with this significant MLSS reduction the soluble substrate removal remained over 90 %. The TSS of the effluent ranged from 22 to 82, although 118 mg l^{-1} was recorded 10th day. This high level was primarily due to a pump malfunction on this particular day. During HRT's of both 20 and 10 hours MLSS levels in the reactor decreased with out any obvious differences. It is anticipated that the installation of a selector will reduce the levels of TSS in the effluent.

4.4.2 Summary

Permeate from a properly functioning R/O membrane can be treated to substrate levels suitable for reuse following tertiary treatment as demonstrated by the use of a laboratory scale activated sludge process.

4.5 FULL SCALE APPLICATION OF AEROBIC TREATMENT

4.5.1 Activated Sludge Model

Application of the activated sludge model introduced in Section 2.34 (*Gaudy and Rozich, 1992*), using the biokinetic constants found in this research, can be used to predict the dilute-out behaviour for full scale aerobic treatment of R/O permeate. Figure 4.25 shows the predicted curves, for the effluent COD (Se) and the biomass concentration (X) using Equations 2.11 and 2.12. Typical full scale values of α and c of 0.25 and 4, were used as representative of full scale application (*Gaudy and Rozich, 1992*). A decay rate of 0.19 d^{-1} was also used as representative of a whey dairy waste (*Orhon et al, 1993*).

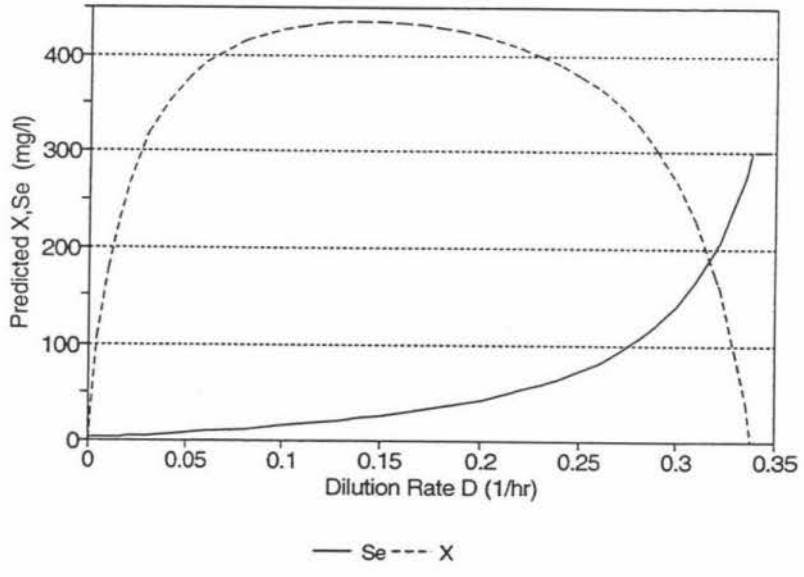

Figure 4.23: Predicted curves for effluent quality and biomass concentration using Gaudy and Rozich model (*1992*).

It is estimated that a final effluent COD of 10 mg l^{-1} or less is required for permeate reuse (*Hills, 1978*). Assuming an influent COD of 300 mg l^{-1} a dilution rate of 0.077

(HRT = 13 hours) or less is required to achieve an effluent COD of 10 mg l^{-1} as shown in Figure 4.25. A steady state biomass concentration of 400 mg l^{-1} is necessary to achieve this reduction. This is a lower level than usual for activated sludge bioreactors, were biomass concentrations of 2000 - 3000 mg l^{-1} are common. The low level of biomass concentration displayed needed for treatment was also evident in the laboratory scale reactor used were the biomass concentration (X) decreased to 300 to 400 mg l^{-1} after initially being seeded with sludge at a concentration of 2000. The required treatment efficiency was still achieved with the laboratory reactor at biomass concentrations of 300 mg l^{-1}.

Because the biomass concentration (X) required to achieve specified effluent concentrations, is a function of the influent COD, then it follows that leaking R/O membranes, resulting in permeate with a high COD, will cause the effluent quality to deteriorate. This is because higher permeate influent COD concentrations, require higher concentrations of biomass to achieve the required effluent levels for reuse. For operation of a full scale plant a diversion of the R/O permeate streams to general effluent discharge streams will be required for significant increases in permeate COD.

4.5.2 Options

It has been established that biological aerobic treatment of reverse osmosis permeate is feasible. Soluble substrate levels can be reduced to levels sufficiently low to enable to reuse of the treated permeate with further tertiary treatment. A completely mixed activated sludge process can be operated, provided adequate process control is used to maintain appropriate operating variables.

There are other possible options such as batch or semi batch aerobic treatment. The use of an Sequencing Batch Reactor (SBR) would minimize the bulking operating problems

encountered with a conventional activated sludge process. A batch process would also be advantageous when there are prolonged periods that R/O permeate is not being produced, due to plant maintenance or cleaning. Also because the membrane plant relies on downstream processes for its feed stock, there will be times when the reverse osmosis plant is operating for a low percentage of the day especially near the end of the season.

It has been shown that the permeate composition relies greatly on the performance and operation of the membranes. Sudden organic shock loads may lower the quality of the final effluent substantially. With batch operation the effect of shock loads is greatly reduced, and with suitable process control the aeration time of a sequencing batch reactor could be increased or decreased relative to the conductivity of the permeate.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The main organic substrate in reverse osmosis permeate is lactose. The lactose concentration of R/O permeate from the Kiwi Dairy company during the period investigated, varied from 41.7 to 59.4 mg l^{-1} for R/O plant 1 and from 282 to 961 mg l^{-1} for R/O plant 2. A approximate linear relationship exists between permeate COD and lactose concentration. The COD of the R/O permeate streams varied from 120 to 2000 mg l^{-1}. The wide variation in COD is due to fluctuating membrane performance.

Elemental analysis of three different strength permeates ranging from less than 200 mg l^{-1} to over 1000 mg l^{-1} showed that the calcium, potassium, sodium and phosphorous concentrations varied with membrane efficiency. This is due to the fact that the mineral content of whey not being retained by the previous ultrafiltration. Iron was present in all three permeate samples ranging from 0.005 to 0.01 mg l^{-1} less than the required concentration for balanced aerobic growth There were no elements present at concentrations toxic to microbial growth. Phosphorous was present at the required concentrations.

Nitrogen analysis of the permeate showed that nitrogen was present as ammonia and non-protein nitrogen such as amino acids. TKN ranged from 82 to 136 mg l^{-1}, suggesting that sufficient nitrogen was present in the permeate to sustain balanced microbial growth. A more detailed nitrogen analysis would be required before it could be conclusively stated that supplementary nitrogen is not required.

An exponential relationship exists between conductivity and permeate COD and lactose concentration, which could be useful as a control parameter in full scale application.

The maximum specific growth rate (μ_m) from six batch tests averaged 2.4 d^{-1} and the half saturation constant (K_S) averaged 38 mg l^{-1}. The true yield coefficient y_t averaged 0.45 mg TSS/mg COD. These biokinetic constants are consistent with previous constants determined for dairy wastes. The specific substrate removal rates for R/O permeate ranged from 2.23 to 2.87 mg COD/mg TSS.d and were in the order of magnitude as previous studies for lactose solutions.

There are were no conclusive variations in biokinetic constants for permeates from R/O membranes of varying efficiency. Supplementary nutrient addition had no obvious effect on the biokinetic constants.

Pilot plant operation showed that regular substrate reductions of 90% could be achieved over a prolonged period. Although the pilot plant achieved satisfactory reductions, effluent soluble COD levels were not sufficiently low to enable the reuse of the permeate. With improved membrane performance resulting in a low strength permeate, an aerobic reactor would produce soluble effluent substrate levels sufficiently low for reuse.

A laboratory scale activated sludge system treating permeate of COD 200 mg l^{-1} or less, produced soluble effluent COD suitable for reuse. It can be concluded that permeate from a properly functioning R/O membrane can be treated to substrate levels suitable for reuse following aerobic and tertiary treatment.

Models for a full scale activated sludge model show that permeate with a COD of 300 mg l^{-1} can achieve soluble effluent COD levels of 10 mg l^{-1} provided an HRT of 13 hours or greater is used and a biomass concentration of at least 400 mg l^{-1} is maintained.

An aerobic treatment process based upon the SBR process, would most likely be more flexible in its operation and more suited as a treatment system for reverse osmosis permeate. Also a batch process would be more resistant to shock loads and less affected by membrane plant start-up and shut-down.

5.2 RECOMMENDATIONS FOR FURTHER WORK

Further work should be carried out to assess the variation of the nitrogen content of the permeate, both with substrate concentration, and with time. It could then be determined accurately if at what levels supplementary nutrient addition is required.

For design of an aerobic process calculations should be performed to determine the maximum permeate COD acceptable for treatment by the reactor, and how the aeration time will vary with permeate COD.

Tertiary treatment while not covered by this study, should be investigated especially the individual processes required and the concentration of coagulant and biocide required.

CHAPTER 6

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APPENDIX

Appendix A1
Conductivity, Lactose and COD relationships of R/O permeate Streams

		Conductivity (umhos)	
Day	date	RO1	RO2
1	1/9	125	159
2	2/9	105	156
3	3/9	173	174
4	4/9	100	149
5	5/9	128	164
6	6/9	154	186
7	7/9	114	168
8	8/8	126	203
9	9/9	140	146
10	10/9	133	152
11	11/9	148	189
12	12/9	163	103
13	13/9	161	190
14	14/9	145	188
15	15/9	150	181
16	16/9	153	162
17	17/9	97	160
19	19/9	82	155
20	20/9	100	183
22	22/9	106	174
23	23/9	121	181
24	24/9	115	140
25	25/9	112	161
26	26/9	108	172
27	27/9	116	170
28	28/9	99	143
29	29/9	97	157
30	30/9	100	181
31	1/10	102	197
32	2/10	110	221
33	3/10	126	190
34	4/10	170	220
35	5/10	167	242
36	6/10	125	334
37	7/10	240	380
38	8/10	130	373
39	9/10	180	325
40	10/10	255	359
41	11/10	233	455
42	12/10	152	328
43	13/10	210	315
44	14/10	159	357
45	15/10	203	262
46	16/10	264	376
47	17/10	276	375
48	18/10	160	285
49	19/10	195	555
50	20/10	216	634
51	21/10	213	850
52	22/10	190	535
53	23/10	270	896
54	24/10	271	950
55	25/10	254	728
56	26/10	241	670
57	27/10	202	690
58	28/10	328	922
59	29/10	253	936
60	30/10	296	994
61	31/10	245	1100
65	4/11	212	1000
67	6/11	180	603
69	8/11	155	1450
72	11/11	234	1300
91	30/11	250	2000
95	4/12	230	2000
116	21/12	280	2000
135	8/1	170	1600
141	14/1	200	1500

PLANT	DATE	Conductivity umhos	COD mg/l
RO1	14/11	120	154
RO1	8/11	155	117
RO1	11/11	155	143
RO1	6/11	180	105
RO1	29/10	220	170
RO1	4/12	230	293
RO1	30/11	250	197
RO1	21/12	280	185
RO1	31/10	290	186
RO1	16/12	310	163
RO1	15/1	350	154
RO2	21/10	600	248
RO2	29/10	900	570
RO2	4/11	1000	295
RO2	31/10	1050	298
RO2	11/11	1300	728
RO2	6/11	1350	603
RO2	8/11	1450	841
RO2	11/11	1500	978
RO2	31/10	1500	338
RO2	14/11	1500	1305
RO1	8/12	2000	1571
RO2	30/11	2000	2000
RO2	4/12	2000	2597
RO2	16/12	2000	1637
RO2	21/12	2000	1476

PLANT	DATE	Conductivity umhos	Lactose mg/l
RO2	21/10	600	89.9
RO1	31/10	290	58.2
RO2	31/10	1050	
RO2	31/10	1500	282.5
RO2	6/11	1350	454.4
RO1	6/11	180	
RO1	8/11	155	41.7
RO2	8/11	1450	584.5
RO1	11/11	155	42.2
RO2	11/11	1500	702.2
RO2	11/11	1300	612.9
RO1	20/11	250	45.5
RO2	20/11	2000	361.3
RO1	16/11	240	59.4
RO2	16/11	2000	961.1

COD mg/l	Lactose mg/l
248	89.9
186	58.2
338	282.5
603	454.4
117	41.7
841	584.5
143	42.2
978	702.2
728	612.9

Appendix A2
Batch test data for determination of μ_m and Ks using optical density

REVERSE OSMOSIS GROWTH RATE BATCH TESTS (RO1)

	So= 168		u=1.752	So= 47		u=1.344	So= 191		u=1.80	So= 117		u=1.584	So= 70		u=1.368
Time (hrs)	Absorbance	Biomass	LN(Biomass)	Absorbance	Biomass	LN(Biomass)	Absorbance	Biomass	LN(Biomass)	Absorbance	Biomass	LN(Biomass)	Absorbance	Biomass	LN(Biomass)
0	0.0132	15.73	2.76	0.0035	11.88	2.47	0.0089	13.32	2.59	0.0153	14.34228053	2.66	0.0184	14.83651384	2.70
0.25	0.0138	15.97	2.77	0.0033	11.80	2.47	0.0085	13.26	2.58	0.0187	14.88434287	2.70	0.0179	14.75679879	2.69
0.5	0.0143	16.17	2.78	0.0026	11.52	2.44	0.0095	13.42	2.60	0.0186	14.86839986	2.70	0.0176	14.70896976	2.69
0.75	0.0144	16.21	2.79	0.0034	11.84	2.47	0.0098	13.47	2.60	0.0198	15.05971598	2.71	0.0167	14.56548267	2.68
1	0.0144	16.21	2.79	0.0032	11.76	2.46	0.0105	13.58	2.61	0.022	15.4104622	2.74	0.022	15.4104622	2.74
1.5	0.0152	16.53	2.81	0.0031	11.72	2.46	0.0126	13.91	2.63	0.0222	15.44234822	2.74	0.0229	15.55394929	2.74
2	0.0162	16.93	2.83	0.004	12.08	2.49	0.0143	14.18	2.65	0.0281	16.38296581	2.80	0.0228	15.53800628	2.74
2.5	0.0172	17.32	2.85	0.0057	12.75	2.55	0.014	14.14	2.65	0.0381	17.97728681	2.89	0.0289	16.51052989	2.80
3	0.0186	17.88	2.88	0.0063	12.99	2.56	0.0177	14.72	2.69	0.032	17.0047632	2.83	0.0261	16.06412561	2.78
3.5	0.0206	18.68	2.93	0.0088	13.99	2.64	0.0146	14.23	2.66	0.0291	16.54241591	2.81	0.038	17.9613438	2.89
4	0.0256	20.66	3.03	0.0067	13.15	2.58	0.025	15.89	2.77	0.04	18.280204	2.91	0.0415	18.51934915	2.92
4.5	0.0237	19.91	2.99	0.0077	13.55	2.61	0.0232	15.60	2.75	0.0393	18.16860293	2.90	0.0441	18.93386741	2.94
5	0.023	19.63	2.98	0.0073	13.39	2.59	0.0291	16.54	2.81	0.0485	19.63535985	2.98	0.0485	19.63535985	2.98
5.5	0.0227	19.51	2.97	0.0096	14.30	2.66	0.0247	15.84	2.76	0.0472	19.42810072	2.97	0.043	18.7584943	2.93
6	0.0239	19.99	3.00	0.0104	14.62	2.68	0.0277	16.32	2.79	0.0487	19.66724587	2.98	0.0453	19.12518353	2.95
6.5				0.0122	15.34	2.73	0.0283	16.41	2.80	0.0547	20.62382647	3.03	0.0527	20.30496627	3.01
7				0.0128	15.58	2.75	0.0386	18.06	2.89	0.0698	23.03122098	3.14	0.0608	21.59635008	3.07
7.5				0.0154	16.61	2.81	0.0421	18.62	2.92	0.0774	24.24288974	3.19	0.064	22.1065264	3.10
8				0.0157	16.73	2.82	0.0417	18.55	2.92	0.0765	24.09940265	3.18	0.0634	22.01086834	3.09
8.5				0.0189	18.00	2.89	0.0458	19.20	2.96	0.0813	24.86467	3.21	0.0658	22.3935	3.11
9				0.0190	18.04	2.89	0.0564	20.89	3.04	0.0986	27.62281	3.32	0.0791	24.51392	3.20
9.5				0.0199	18.40	2.91	0.0587	21.26	3.06	0.0961	27.22423	3.30	0.081	24.81684	3.21

Regression Output:		Regression Output:		Regression Output:		Regression Output:		Regression Output:	
Constant	2.689701404	Constant	2.3755043	Constant	2.339835334	Constant	2.651333756	Constant	2.653711
Std Err of Y Est	0.028739556	Std Err of Y Est	0.0309369	Std Err of Y Est	0.022966029	Std Err of Y Est	0.041381045	Std Err of Y Est	0.030151
R Squared	0.901125598	R Squared	0.9650935	R Squared	0.958419129	R Squared	0.962086744	R Squared	0.967563
No. of Observations	7.075321721	No. of Observations	19.066049	No. of Observations	9	No. of Observations	22	No. of Observations	19
Degrees of Freedom	5.005929603	Degrees of Freedom	17.002932	Degrees of Freedom	7	Degrees of Freedom	20	Degrees of Freedom	17
X Coefficient(s)	1.759859545	X Coefficient(s)	1.348455719	X Coefficient(s)	1.807721	X Coefficient(s)	1.5851752	X Coefficient(s)	1.3756725
Std Err of Coef.	0.010862531	Std Err of Coef.	0.00259161	Std Err of Coef.	0.00593	Std Err of Coef.	0.0029318	Std Err of Coef.	0.0025454

Batch Data: Absorbance vs Biomass TSS for RO1 calibration curve

For So= 168 and 47 mg/l only

Absorbance	TSS	best fit
0.0088	20	14
0.0925	44	47
0.0791	40	42
0.0983	56	50
0.0323	16	23

Regression Output:		
Constant		10.48506
Std Err of Y Est		6.967371
R Squared		0.87144
No. of Observations		5
Degrees of Freedom		3
X Coefficient(s)	397.3463	
Std Err of Coef.	88.11356	

Batch Data: Absorbance vs Biomass TSS for RO1 calibration curve

For RO1 So=191, 117 & 70 mg/l only

Absorbance	TSS	best fit
0.1583	36	37
0.0421	16	19
0.0774	28	24

Regression Output:		
Constant		11.90344
Std Err of Y Est		4.717577
R Squared		0.890187
No. of Observations		3
Degrees of Freedom		1
X Coefficient(s)	159.4301	
Std Err of Coef.	55.99609	

REVERSE OSMOSIS GROWTH RATE BATCH TESTS (RO2)

Time (hrs)	So=940mg/l Absorbance	Biomass	u=3.84 LN(Biomass)	So=499mg/l Absorbance	Biomass	u=3.12 Ln(Biomass)	So=244mg/l Absorbance	Biomass	u=3.84 Ln(Biomass)	So=115mg/l Absorbance	Biomass	u=4.08 Ln(Biomass)
0	0.0206	9.0	2.20	0.0206	9.0	2.20	0.005	1.96	0.67	0.005	1.96	0.67
1	0.0287	12.7	2.54	0.0222	9.8	2.28	0.006	2.41	0.88	0.006	2.41	0.88
2	0.023	10.1	2.32	0.0294	13.0	2.57	0.0108	4.59	1.52	0.0106	4.50	1.50
3	0.0428	19.1	2.95	0.0304	13.5	2.60	0.0069	2.82	1.04	0.0063	2.55	0.94
5	0.0456	20.4	3.01	0.0383	17.1	2.84	0.0175	7.63	2.03	0.0117	5.00	1.61
7	0.0652	29.3	3.38	0.0362	16.1	2.78	0.0169	7.36	2.00	0.0138	5.95	1.78
8	0.0508	22.7	3.12	0.0486	21.8	3.08	0.0199	8.72	2.17	0.0208	9.13	2.21
9	0.0995	44.9	3.80	0.0678	30.5	3.42	0.0227	9.99	2.30	0.0233	10.27	2.33
10	0.1115	50.3	3.92	0.0811	36.5	3.60	0.0251	11.08	2.41	0.0227	9.99	2.30
11	0.1263	57.0	4.04	0.0996	44.9	3.80	0.0366	16.30	2.79	0.023	10.13	2.32
12	0.1471	66.5	4.20	0.1036	46.7	3.84	0.047	21.02	3.05	0.0217	9.54	2.26
14	0.1664	75.2	4.32	0.118	53.3	3.98	0.0612	27.47	3.31	0.0216	9.50	2.25
15	0.1788	80.8	4.39	0.1427	64.5	4.17	0.0671	30.15	3.41	0.0301	13.35	2.59
17	0.1994	90.2	4.50	0.1557	70.4	4.25	0.0938	42.27	3.74	0.0218	9.59	2.26
18	0.2105	95.2	4.56	0.1814	82.0	4.41	0.1024	46.17	3.83	0.0217	9.54	2.26
20	0.2185	98.9	4.59	0.2414	109.3	4.69	0.1374	62.06	4.13	0.0222	9.77	2.28
21	0.2375	107.5	4.68	0.2423	109.7	4.70	0.1662	75.13	4.32	0.026	11.49	2.44
23	0.2575	116.6	4.76	0.2451	110.9	4.71	0.1963	88.79	4.49	0.0289	12.81	2.55
24	0.2973	134.6	4.90	0.2327	105.3	4.66	0.2586	117.07	4.76	0.0304	13.49	2.60

Regression Output:	
Constant	2.231073126
Std Err of Y Est	0.187512072
R Squared	0.93568619
No. of Observations	11
Degrees of Freedom	9
X Coefficient(s)	3.863747901
Std Err of Coef.	0.014069002

Regression Output:	
Constant	2.210130749
Std Err of Y Est	0.12852506
R Squared	0.975805851
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	3.02274105
Std Err of Coef.	0.005300284

Regression Output:	
Constant	0.877512523
Std Err of Y Est	0.174913038
R Squared	0.981677923
No. of Observations	19
Degrees of Freedom	17
X Coefficient(s)	3.946420217
Std Err of Coef.	0.005448419

Regression Output:	
Constant	0.74094295
Std Err of Y Est	0.23129391
R Squared	0.87979165
No. of Observations	8
Degrees of Freedom	6
X Coefficient(s)	4.115932213
Std Err of Coef.	0.025879671

Batch Data: Absorbance vs Biomass TSS for RO2 calibration curve

For optical density tests on RO2 permeate

Absorbance	TSS	best fit
0.0919	36	41
0.0267	10	12
0.0189	6	8
0.0748	44	34
0.2141	96	97

Regression Output:		
Constant		-0.30921
Std Err of Y Est		6.968206
R Squared		0.972047
No. of Observations		5
Degrees of Freedom		3
X Coefficient(s)	453.9073	
Std Err of Coef.	44.44015	

PERMEATE SUBSTRATE REMOVAL CURVES

BATCH REACTOR So=87mg/l

	total COD		coeff=	0.000342	filtered COD				SUSPENDED SOLIDS (samples 25ml)			
	sample1	sample2	sample3	average	sample1	sample2	sample3	average	FP before	FP after	difference	SS
time	87	87	98	87					0.0876	0.0876	0	0
0	322	313	300	311	73	70	72	72	0.0866	0.0921	0.0055	220
1	330	307	352	330	62	65	58	62	0.0875	0.0933	0.0058	232
2	317	328	340	328	46	44	44	44	0.0859	0.0919	0.006	240
3	306	309	317	311	31	144	29	30	0.0866	0.0927	0.0061	244
4	364	329	302	315	26	21	23	23	0.0868	0.0931	0.0063	252
5	287	299	345	310	18	14	17	18	0.0869	0.093	0.0061	244
6	318	392	344	351	23	16	18	17	0.087	0.0932	0.0062	248
7	221	395	279	298	21	18	18	18	0.0863	0.0925	0.0062	248
8	291	363	328	327	21	27	24		0.087	0.093	0.006	240
9	272	304	356	311	26	14	12	13	0.0863	0.0925	0.0062	248
10	245	227	263	245	13	12	9	12	0.0856	0.093	0.0074	296

Regression Output:

Constant	71.79337
Std Err of Y Est	3.136474
R Squared	0.982456
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	-12.8558
Std Err of Coef.	0.99184
COD removal rate=	2.230437
u=	1.115219

Regression Output: 0-4hrs

Constant	5.405113
Std Err of Y Est	0.011333
R Squared	0.964179
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	0.772881 =u
Std Err of Coef.	0.003584

Calculating Y

Biomass growth due to soluble COD removal:=252-220=32

Soluble COD removed:=87-23=64

Biomass cell yield=32/64=0.50

PERMEATE SUBSTRATE REMOVAL CURVES

BATCH REACTOR So= 102mg/l

	total COD		coeff=	0.000342	filtered COD				SUSPENDED SOLIDS (samples 25ml)			
	sample1	sample2	sample3	average	sample1	sample2	sample3	average	FP before	FP after	difference	SS
Time(hr)					101	106	101	102	0.0857	0.0863	0.0006	24
0	286	313	275	280	97	92	89	93	0.0869	0.0920	0.0051	204
1	280	273	287	280	81	80	83	81	0.0862	0.0915	0.0053	212
2	275	292	287	285	72	71	68	70	0.0849	0.0901	0.0052	220
3	293	336	321	317	62	65	63	63	0.0866	0.0913	0.0047	210
4	254	269	273	265	63	65	68	65	0.0872	0.0923	0.0051	204
5	265	263	254	261	60	68	63	64	0.0870	0.0919	0.0049	196
6	252	280	273	268	66	65	60	64	0.0869	0.0918	0.0049	196
7	258	288	282	276	67	67	68	67	0.0864	0.0912	0.0048	192
8	263	246	252	254	56	181	61	58	0.0868	0.0915	0.0047	188

Regression Output:	0-3hrs
Constant	91.77388
Std Err of Y Est	1.594394
R Squared	0.989697
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-19.7661
Std Err of Coef.	1.426069
COD removal rate=	2.24296
u=	1.003528

Regression Output:	0-2hrs	Y=0.41
Constant	5	
Std Err of Y Est	0	
R Squared	1	
No. of Observations	3	
Degrees of Freedom	1	
X Coefficient(s)	0.906091	=u
Std Err of Coef.	0.000411	

SUBSTRATE REMOVAL CURVES

BATCH REACTOR So=189mg/l

	total COD		coeff=	0.000342	filtered COD				SUSPENDED SOLIDS (samples 25ml)			
	sample1	sample2	sample3	average	sample1	sample2	sample3	average	FP before	FP after	difference	SS
time	194	188	185	189					0.0867	0.0868	0.0001	4
0	570	597	370	370	176	178	165	173	0.0872	0.0951	0.0079	316
1	429	424	527	424	134	130		132	0.0875	0.0957	0.0082	328
2	318	312	332	332	88	82	79	83	0.0865	0.095	0.0085	340
3	368	380	370	373	45	65	47	52	0.0867	0.0958	0.0091	364
4	418	347	475	413	27	35	30	31	0.0869	0.096	0.0091	364
5	440	440	424	435	26	28	24	26	0.087	0.0964	0.0094	376
6	432	440	427	433	27	21	22	23	0.0869	0.0962	0.0093	372

Regression Output:	0-3hrs
Constant	171.7641
Std Err of Y Est	5.404602
R Squared	0.993123
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-41.077
Std Err of Coef.	2.417012
COD removal rate=	2.925365
u=	1.082385

Regression Output:	0-3hrs
Constant	5.749689
Std Err of Y Est	0.012161
R Squared	0.972824
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	1.104 =u
Std Err of Coef.	0.005438

Calculating Y

Biomass growth due to soluble COD removal:=376-316=60

Soluble COD removed:=189-26=163

Biomass cell yield=60/163=0.37

SUBSTRATE REMOVAL CURVES

BATCH REACTOR So=272mg/l

	total COD			coeff= 0.000342	filtered COD				SUSPENDED SOLIDS (samples 25ml)			
	sample1	sample2	sample3	average	sample1	sample2	sample3	average	FP before	FP after	difference	SS
Time					270	272	275	272	0.0872	0.0879	0.0007	28
0	521	515	526	521	253	256	259	256	0.0871	0.0933	0.0062	248
1	487	515	606	501	208	212	209	211	0.0868	0.0938	0.007	280
2	517	484	542	514	147	152	150	150	0.0858	0.0941	0.0083	332
3	508	500	507	505	123	117	115	119	0.0854	0.0936	0.0082	328
4	433	396	676	501	123	87	84	98	0.0863	0.0955	0.0092	368
5	326	339	553	553	60	56	61	59	0.0859	0.0954	0.0095	380
6	464	469	462	465	39	41	39	39	0.0866	0.0956	0.009	360
7	450	462	443	452	46	41	43	43	0.0865	0.0956	0.0091	364
8	466	435	469	457	51	42	31	41	0.0873	0.0958	0.0085	340
9	439	443	432	438	42	39	43	41	0.0869	0.0972	0.0103	412

Regression Output:	0-5hrs
Constant	5.555665
Std Err of Y Est	0.05047
R Squared	0.923845
No. of Observations	6
Degrees of Freedom	4
X Coefficient(s)	2.017009 =u
Std Err of Coef.	0.012065

Regression Output:	0-5hrs
Constant	245.3773
Std Err of Y Est	12.95999
R Squared	0.974904
No. of Observations	6
Degrees of Freedom	4
X Coefficient(s)	-38.6188
Std Err of Coef.	3.098031
COD removal rate=	2.872174
u=	1.780748

Calculating Y

Biomass growth due to soluble COD removal:=380-248=132

Soluble COD removed:=272-59=213

Biomass cell yeild=132/213=0.62

Appendix A4
Batch test data for R/O permeate from membranes of varying efficiency

BATCH TEST 1

RO1 BATCH TEST 21/11
5 LITRES FEED 201mg/l
@ 20C SS sample size=25ml
SEED 100ML

	Tare		Tare + SS		SS			TOTAL COD MG/L				FILTERED COD mg/l			MEAN
Time (hrs)	1	2	1	2	1	2	Mean	1	2	3	Mean	1	2	3	201
0	0.0885	0.0877	0.0916	0.0914	124	148	131	314	308	332	318	129	123	124	121
0.5															
1	0.0885	0.0895	0.0924	0.0929	156	136	146	346	300	294	314	102	105	100	100
1.5															
2	0.089	0.0886	0.0934	0.0926	176	160	168	326	300	296	307	84	78	83	82
2.5															
3	0.0903	0.0885	0.0934	0.0918	124	132	128	290	286	283	286	77	91		77
3.5															
4	0.0885	0.0883	0.0915	0.0915	120	128	124	284	278	285	283	79	75	77	75
4.5															
5	0.0866	0.0876	0.0898	0.0909	128	132	130	270	279	272	274	66	67	69	68

Regression Output: 0-2hrs

Constant	4.878004
Std Err of Y Est	0.006876
R Squared	0.997641
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	2.399718 =u
Std Err of Coef.	0.004862

Regression Output:

Constant	120.5
Std Err of Y Est	1.224745
R Squared	0.998031
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-19.5
Std Err of Coef.	0.866025
COD removal rate=	3.21208
u=	0.995745

Calculating Y
Biomass growth due to soluble COD removal=168-131=37
Soluble COD removed=201-82=119
Biomass Cell Yield (Y)=37/119=0.31

BATCH TEST 1

RO2 BATCH TEST 29/11

5 LITRES FEED 993 mg/l

@ 20C SS sample size=25ml

SEED 100ML sludge

	Tare		Tare + SS		TSS			TOTAL COD MG/L				FILTERED COD mg/l			MEAN
Time (hrs)	1	2	1	2	1	2	Mean	1	2	3	Mean	1	2	3	993
0	0.0944	0.0933	0.099	0.0973	184	160	172		991	1007	999				993
1	0.0944	0.0927	0.0992	0.0977	192	260	192	1000	1002	997	1000	962	953	954	957
2	0.0936	0.0934	0.0983	0.0979	188	180	184	997	1001	995	998	937	914	923	925
3	0.0951	0.0932	0.1	0.0981	196	196	196	1005	999	1002	1002	847	851	845	847
4	0.0922	0.0932	0.0974	0.0987	208	220	214	995	1012	990	999	798	802	812	804
5	0.0935	0.0947	0.097	0.1001	140	216	216	1012	1002	991	1002	762	749	748	753
6	0.0939	0.0931	0.1004	0.0992	260	244	252	1005	1006	1023	1006	700	716	711	709
7	0.091	0.0911	0.098	0.0979	280	272	276	982	990	983	985	612	634	629	632
8	0.0935	0.0932	0.0998	0.1002	252	280	266	999	981	981	987	557	540	545	547
9	0.0926	0.0926	0.1001	0.1002	300	304	302	1000	983	987	985	469	447	451	456
10	0.0915	0.0924	0.1001	0.1005	344	324	334	980	979	1000	980	319	326	304	324

Regression Output: 4-11hrs

Constant	4.940573
Std Err of Y Est	0.082945
R Squared	0.897545
No. of Observations	8
Degrees of Freedom	6
X Coefficient(s)	2.226955 =u
Std Err of Coef.	0.012799

Calculating Y

Biomass growth due to soluble COD removal=444-160=284

Soluble COD removed=993-187=806

Biomass cell yield(Y)=284/806=0.35

Regression Output: 6-11hrs

Constant	1356.392
Std Err of Y Est	27.21953
R Squared	0.984468
No. of Observations	6
Degrees of Freedom	4
X Coefficient(s)	-103.606
Std Err of Coef.	6.506712
COD removal rate=	7.962015
u=	2.786705

BATCH TEST 1

BALANCE TANK BATCH TEST 29/11
5 LITRES FEED 742 mg/l
@ 20C SS sample size=22ml
SEED 100ML sludge

	Tare		Tare + SS		TSS			TOTAL COD MG/L				FILTERED COD mg/l			MEAN
Time (hrs)	1	2	1	2	1	2	Mean	1	2	3	Mean	1	2	3	742
0	0.0925	0.0917	0.096	0.0953	159	164	161	840	847		843	647	617	622	620
1	0.0921	0.0917	0.0961	0.0958	182		182	854	845		850	536	548	538	541
2	0.0919	0.0926	0.0961	0.0968	191	191	191	838	819		828	502	498	502	501
3	0.0896	0.094	0.0938	0.0979	191		191	815	799		807	474	474	473	474
4	0.0933	0.0915	0.0979	0.0961	209	209	209	804	804		804	444	450	444	446
5	0.0934	0.0914	0.0982	0.0963	218	223	220	764	770		767	401	399	407	402
6	0.093	0.0945	0.0981	0.0993	232	218	225	776	785		780	367	369	364	367
7	0.0951	0.0936	0.1	0.0989	223	241	232	754	750		752	317	321	322	320
8	0.0922	0.0925	0.0976	0.0979	245	245	245	747	747		747	263	264		264
9	0.092	0.0934	0.0977	0.099	259	255	257	711	717		714	211	213	222	215

Regression Output:	0-5hrs
Constant	5.131557
Std Err of Y Est	0.046818
R Squared	0.845302
No. of Observations	6
Degrees of Freedom	4
X Coefficient(s)	1.255747 =u
Std Err of Coef.	0.011192

Regression Output:	0-9hrs
Constant	602
Std Err of Y Est	14
R Squared	0.988319
No. of Observations	10
Degrees of Freedom	8
X Coefficient(s)	-41.4978
Std Err of Coef.	1.595023
COD removal rate=	4.713429
u=	1.131223

Calculating Y
Biomass growth due to soluble COD removal:=257-161=96
Soluble COD removed:=620-215=405
Biomass cell yield(Y)=96/405=0.24

BATCH TESTS 2

	TSS TARE			TSS Tare+SS			Suspended Solids		
TIME	RO1	RO2	BT	RO1	RO2	BT	RO1	RO2	BT
0	0.0939	0,095	0.0935	0.1013	0.101	0.1029	370	300	470
2	0.0922	0.0912	0.0945	0.1015	0.1006	0.106	465	470	575
4	0.0919	0.0928	0.0914	0.1005	0.1036	0.1038	430	540	620
6	0.0937	0.0922	0.0924	0.103	0.1037	0.1041	465	575	585
8	0.0915	0.0918	0.0926	0.1014	0.1051	0.1051	495	665	625

Soluble COD removal

	RO1			RO2			BT		
Time	1	2	Avg	1	2	Avg	BT		Avg
0	147	142	145	948	951	950	631	631	631
0	176	187	181			950	492	513	503
2	121	117	119	744	697	720	334	333	334
4	116	114	115	517	521	519	192	191	192
6	68	68	68	355	358	357	140	134	137
8	49	49	49	158	171	165	121	123	122

RO1 0-2hr

u= 2.7432

COD removal rate= 1.779904
u= 0.943349

Y= 0.53

RO2

Regression Output:

Constant	5.841719
Std Err of Y Est	0.127587
R Squared	0.868209
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	2.152376 =u
Std Err of Coef.	0.020173

Regression Output: RO2

Constant	928.9688
Std Err of Y Est	21.3546
R Squared	0.996358
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	-96.7344
Std Err of Coef.	3.376459

COD removal rate= 4.552206
u= 2.094015

Y= 0.46

BT

Regression Output:

Constant	6.173781
Std Err of Y Est	0.051557
R Squared	0.935198
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	1.661921 =u
Std Err of Coef.	0.018228

Regression Output: BT

Constant	498.0208
Std Err of Y Est	10.97167
R Squared	0.997516
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-77.7344
Std Err of Coef.	3.879072

COD removal rate= 3.361486
u= 1.142905

Y= 0.34

BATCH TESTS 3

Batch tests with nutrients 10/12/94

	So=159mg/l			So=921 mg/l			So=629mg/l		
	RO1			RO2			BT		
Time (hrs)	Tare	Tare +SS	SS	Tare	Tare+SS	SS	Tare	Tare+SS	SS
0	0.0934	0.0973	195	0.0924	0.0969	225	0.093	0.0997	335
1	0.0931	0.0972	205	0.0913	0.0964	255	0.0919	0.0988	345
2	0.0915	0.0957	210	0.0916	0.0969	265	0.0934	0.0972	
3	0.0917	0.0964	235	0.0929	0.0982	265	0.0907	0.0983	380
4	0.0932	0.0984	260	0.0938	0.0994	280	0.0917	0.0998	405
6	0.0919	0.0971	260	0.0918	0.0982	320	0.0918	0.1004	430
8	0.0916	0.097	270	0.0935	0.1005	350	0.0917	0.1006	445
11	0.0929	0.0979	250	0.0927	0.1007	400	0.092	0.1013	465
14	0.0935	0.0986	255	0.091	0.1017	535	0.0908	0.102	560
17	0.0911	0.0963	260	0.0937	0.1066	645	0.0922	0.1028	530
23	0.0919	0.0966	235	0.0938	0.1061	615	0.0927	0.1035	540

Soluble COD removal

Time (hrs)	RO1			RO2/2				BT			
	1	2	AVG	1	2	3	AVG	1	2	3	AVG
0			159				921				629
0			152	864	867		866	605	612		609
1	138	145	142	866	868		867	601	599		600
2	133	148	133	847	848		848	576	566		571
3	109	114	112	789	811		800	531	533		532
4	94	97	96	795	795		795	526	528		527
6	76	72	74	748	752	757	752	415			415
8	74	65	65	716	712		714	425	426		360
11	73	86	73	590	592	601	594	271	269	268	269
14	45	42	44	349	337	347	344	77	60		69
17	41	39	40	60	64		62	51	53		52
23	34	35	35	62	52		57	55			55

RO1		RO2		BT	
Regression Output:	time 0-4hrs	Regression Output:	time 11-17hrs	Regression Output:	time 0-4hrs
Constant	5.250289	Constant	5.132827	Constant	5.805205
Std Err of Y Est	0.033011	Std Err of Y Est	0.042384	Std Err of Y Est	0.012153
R Squared	0.939408	R Squared	0.984505	R Squared	0.987139
No. of Observations	5	No. of Observations	3	No. of Observations	4
Degrees of Freedom	3	Degrees of Freedom	1	Degrees of Freedom	2
X Coefficient(s)	1.708655 =u	X Coefficient(s)	1.911143 =u	X Coefficient(s)	1.142736 =u
Std Err of Coef.	0.010439	Std Err of Coef.	0.00999	Std Err of Coef.	0.003843

RO1		RO2		BT	
Regression Output:	0-6hrs	Regression Output:	11-17	Regression Output:	0-8hrs
Constant	154.3429	Constant	897	Constant	327.6643
Std Err of Y Est	3.924738	Std Err of Y Est	18.69678	Std Err of Y Est	5.852503
R Squared	0.985982	R Squared	0.964744	R Squared	0.99334
No. of Observations	6	No. of Observations	6	No. of Observations	6
Degrees of Freedom	4	Degrees of Freedom	4	Degrees of Freedom	4
X Coefficient(s)	-13.6286	X Coefficient(s)	-25.8333	X Coefficient(s)	-29.5929
Std Err of Coef.	0.812498	Std Err of Coef.	2.469239	Std Err of Coef.	1.211583
COD removal rate=	1.437739	COD removal rate=	4.04237	COD removal rate=	1.967392
u=	0.747624	u=	2.213427	u=	1.141087
Y=0.52		Y=0.52		Y=0.58	

Appendix A5
Oxygen uptake rates data

Biokinetic Constant Determination using Oxygen Uptake Rates

MLSS=308mg/l
VSS=266mg/l

Using Ox=1.42

RO2 ml	So mg/l	OURt	OURe	dO2	1-Y	Y	YH	d OUR	SpOUR	u (1/d)	So/u
1.4	6.67	5.33	0.69	0.88	0.13	0.87	0.61	4.64	0.012	0.08	82.43
1	4.77	5.03	0.69	0.66	0.14	0.86	0.61	4.34	0.011	0.07	66.66
0.8	3.81	3.93	0.69	0.46	0.12	0.88	0.62	3.24	0.009	0.06	60.93
0.6	2.86	3.72	0.69	0.36	0.13	0.87	0.62	3.03	0.008	0.06	51.41
0.5	2.38	3.72	0.69	0.33	0.14	0.86	0.61	3.03	0.008	0.05	47.81
0.4	1.91	3.97	0.69	0.31	0.16	0.84	0.59	3.28	0.009	0.04	42.62
0.3	1.43	2.09	0.69	0.13	0.09	0.91	0.64	1.40	0.004	0.04	38.62
0.2	0.95	2.03	0.69	0.10	0.10	0.90	0.63	1.34	0.004	0.03	30.79

RO1 ml	So mg/l	OURt	OURe	dO2	1-Y	Y	YH	d OUR	SpOUR	u (1/d)	So/u
7	5.60	3.16	1.29	0.44	0.08	0.92	0.65	1.87	0.005	0.06	96.27
5	4.00	3.07	1.29	0.33	0.08	0.92	0.65	1.79	0.005	0.05	76.08
4	3.20	2.69	1.29	0.23	0.07	0.93	0.65	1.40	0.004	0.05	66.72
3	2.40	2.25	1.29	0.13	0.05	0.95	0.67	0.96	0.003	0.04	54.07
1	0.80	2.87	1.29	0.10	0.12	0.88	0.62	1.58	0.004	0.03	26.69

OURt=oxygen uptake rate (mg O2/l/hr)
OURe=endogenous oxygen uptake rate (mg O2/l/hr)
dO2=oxygen consumed after substrate addition (mg/l)
1-Y= oxygen used per mg of substrate added (mg O2/ mg COD)
Y=mg cells produced per mg substrate removed
YH = growth yield in COD units (mg cell COD/mg substrate COD)
d OUR = increse in OUR due to substrate addition (OURe - OURt)
SpOUR = specific change in OUR (mg O2/l per mg cell COD per d)

Regression Output:	RO2	
Constant	25.66119	Ks= 70.68
Std Err of Y Est	1.797996	
R Squared	0.990062	
No. of Observations	8	
Degrees of Freedom	6	
X Coefficient(s)	8.713431	u= 2.754
Std Err of Coef.	0.356397	

Regression Output:	RO1	
Constant	17.81076	Ks= 29.64
Std Err of Y Est	2.77134	
R Squared	0.991421	
No. of Observations	5	
Degrees of Freedom	3	
X Coefficient(s)	14.42313	u= 1.664
Std Err of Coef.	0.774613	

Kiwi Dairies Ltd: R/O Permeate Activated Sludge Pilot Plant

Day	Date	Feed Flow litres/hr	Recyle Flow litres/hr	Waste rate litres/hr	Chemical Oxygen Demand mg/l									Suspended Solids				
					RO1	RO2	Bal Tank	Feed	Aerated T.	Filt. AT	Clarifier	Filtered Clar	Sand Filt.	Filt S.F	Clar Return	Feed	Aerated T.	Clarif. Out	Clar. Return	Sand Filt.
1	24/11							507	630	213	115	51			998	22	1467	59	5260	
6	29/11	173	91	0	143	1690		834	1939	356	421	259	293	219	2229	26	2565	116	5670	47
7	30/11	171	108	0	197	1772		725	1981	406	193	99	159	95	2445	20	3657	108	7373	67
11	4/12	171	189	4	293	2597		696	1902	102	230	100	117	93	2624	36	5827	155	6320	13
15	8/12	169	185	4.8	162	1571	898	948	1817	55	279	73	90	72	3915	82	2930	212	4047	24
19	12/12	173	150	4.8	163			379	3258	67	164	57	104	78	4674	44	3050	114	5870	38
23	16/12	85	225	4.4	162	1637	468	874	2972	103	219	102	134	95	4356	80	2807	113	4800	35
28	21/12	86	257	4.7	185	1476	880	931	2898	75	222	109	175	98	3142	120	3160	111	3687	95
37	30/12	86	189	4.7	166			1949	5048	112	288	134	137	119	3132	184	3500	184	5220	44
42	4/1	88	276	4.9	130			453	1578	309	463	177	160	74	1963	48	1740	376	2180	133
46	8/1	85	240	2	137	1236	656	1070	2057	291	257	97	41	28	1949	66	1860	198	1893	8
49	11/1	87.3	240	2.3				649	2223	46	197	42	49	38	2929	60	2040	98	2827	12
52	14/1	83.7	225	2.6	154	1305	757	1053	2505	104	263	125	87	61	3359	52	1979	96	2783	12
55	17/1	85.5	240	2.58				1080	1989	48	234	59	125	51	3837	50	1667	144	3080	25
62	24/1	88.2	257	0				63	436	30	443	31	106	26	548	20	747	365	980	56
64	26/1	169	240	0				119	366	25	261	44	38	38	547	70	720	235	1090	0
70	1/2	169	257	0	172	1576		175	141	14	97	33	45	40	181	10	120	80	380	8

Clarfier=800litres diam=153cm, hieght 40cm
Aerator=1700 litres, diam.=167cm, hieght=80cm

Day	Date	% Removal soluble.	Sludge SVI	Sludge Age days	HRT hours.	F/M mg COD/mg TSS.d	DO mg/l	Reactor pH	Reactor Temp.	Comments
1	24/11	90					3.3	7.4	25	Sand blocked so no s.f. sample. Control system for feed installed.
6	29/11	69	59	9	10	0.79	3	7.2	26	HRT=10hours. recycle pipe burst emptied contents of clarifier
7	30/11	86	41	14	10	0.48	3.5	7.15	26	RO1=197uS, RO2=2000uS
11	4/12	86	29	8	10	0.29	4.1	6.51	27	RO1=230uS, RO2=2000uS, new waste line from reactor
15	8/12	92	44	4	10	0.77	2.1	7.12	30	RO1=210uS, RO2=2000uS
19	12/12	85	52	6	10	0.30	4	6.5	27	RO1 running only
23	16/12	88	75	9	20	0.37	5	6.52	25	RO1=310uS, RO2=2000uS
28	21/12	88	97	9	20	0.36	4	6.49	25	RO1=280uS, RO2=2000uS. Recycle stopped 20th.
37	30/12	93	72	8	20	0.68	3.1	8.01	27	
42	4/1	61	138	3	19	0.32	5.3	7.44	20	RO1 operating only during sampling
46	8/1	91	97	6	20	0.69	2.7	7.72	26	RO1=170uS, RO2=1600uS, reduced sludge wastage.
49	11/1	94	78	11	19	0.39	5.5	8.02	20	no RO plant operating at time of sample.
52	14/1	88	126	11	20	0.63	6.4	7.66	25	RO1=120Us, RO2=1500uS,
55	17/1	95	144	7	20	0.78	6.9	7.88	26	RO plant not operating at time of sample
62	24/1	51	134	2	19	0.11	10.7	8.48	24	RO1 only going to feed tank as from23/1
64	26/1	63	125	1	10	0.39	7.1	8.29	27	
70	1/2	81	167	1	10	3.48	8	8.32	30	TSS decreasing noticably

Appendix A6
R/O Pilot Plant operational data

Appendix A7
Laboratory scale activated sludge data

Laboratory Scale Activated Sludge System

Day	HRT	Recycle	Chemical Oxygen Demand mg/l				Suspended Solids mg/l			Sludge	% soluble COD
	hours	ml/hr	Feed	Filt. React	Effluent	Filt. Efflu.	Reactor	Effluent	Recycle	Age	Removal
1	20	85	191	11	108	10	1860	74	6860	12	95
3	"	"	184	21	106	10	1370	82	4535	8	95
4	"	"	176	20	92	18	1620	64	5240	12	90
6	"	"	152	31	70	15	1470	64	4960	11	90
7	"	"	165	23	50	11	1305	48	3150	13	93
8	"	"	128	13	47	10	1070	44	3180	12	92
10	10	"	106	18	114	17	700	118	3270	3	84
11	"	"	146	21	86	18	640	62	4120	5	88
12	"	"	121	12	51	12	680	36	2850	9	90
15	"	"	152	15	25	14	515	22	2730	11	91
17	"	"	177	19	25	16	340	24	1560	7	91
19	"	"	162	15	23	13	320	22	1600	7	92