AEROBIC TREATMENT OF A CTMP WASTEWATER USING A ROTATING BIOLOGICAL CONTACTOR

by

Renata Gabriela Mathys

B.A.Sc.(Bio-Resource Engineering) University of British Columbia

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Department of _Chemical Engineering_

The University of British Columbia
Vancouver, Canada

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ABSTRACT

Effluents from high-yield TMP and CTMP mills contain biochemical oxygen demand and toxicity levels that are much higher than the effluents from low-yield kraft mills and if not properly treated before disposal can impose environmental threats to water bodies. Therefore, this study was undertaken to demonstrate the ability of a rotating biological contactor to remove organic matter from such a CTMP wastewater when operated at different flowrates and temperatures.

An apparatus was constructed to allow for temperature control of the wastewater and the flexibility to change flowrates and disc rotational speed. Parameters studied included BOD_5, COD, suspended solids, dissolved oxygen, sulfur compounds, acetic acid and nutrient uptake. Because the lab device exposes a thin film of liquid to the air over an extensive surface, evaporation from the RBC as high as 87% at temperatures of ~ 30°C were experienced during the experiment.

Results of this study showed that for hydraulic residence times (HRT) of 1 to 2 days the BOD_5 removal ranged from 77 to 86% with a corresponding COD removal of 63 to 72%. Increases in flowrate (decreases in HRT) resulted in a slight decrease in percent BOD (COD) removed and an increase in loading rate and BOD (COD) removal rate. An increase in temperature from 20 to 30°C increased BOD removal from 70.1 to 85% and COD removal from 45.8 to 71.4% at HRT=1.5 days. Dissolved oxygen, pH and MLVSS had no distinct effects on the removal of BOD_5 and COD. Losses due to evaporation of major volatile compounds tested were minimal at the pH of operation. Start-up time of the RBC was of the order of 1 day during the experiment.

An attempt to do a run without microorganism activity by adding 50 mg/l $HgCl_2$ failed to eliminate all the organisms present in the wastewater and RBC.

Tracer studies revealed that the RBC was close to being perfectly mixed.

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CHAPTER 1

INTRODUCTION

Mechanical pulping processes produce higher yields than chemical pulping processes; however mechanical pulping produces lower quality fibres than those from chemical pulping. Recent advances in thermomechanical pulp (TMP) and chemi-thermomechanical pulp (CTMP) processing technology have improved pulp strength properties such that they are suitable for the production of paper and other products. Since the 1980's there has been a significant increase in the utilization of refiner mechanical pulps (TMP and CTMP). The effluent flow from such high-yield TMP and CTMP mills contains biochemical oxygen demand (BOD_5) and toxicity levels that are much higher than in the effluent from the low yield kraft mills. These increased loads in the TMP and CTMP effluents are mainly due to the absence of chemical recovery systems in TMP/CTMP mills, as well as modifications of the TMP/CTMP process which minimize water usage by internal recirculation of process water.

The high oxygen demand and the biological degradability of TMP/CTMP wastewaters suggest biological treatment. Many biological systems have been investigated for this purpose. In general, wastewater treatment practised in this component of the pulp and paper industry includes one or more of the following:

1) Primary treatment for suspended solids removal;

2) Aerobic treatment such as aerated lagoons or activated sludge systems;

3) Anaerobic treatment consisting mostly of high rate processes.

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Aerobic treatment has traditionally been the treatment of choice at most Canadian pulp mills where secondary treatment is practised. Anaerobic treatment has generated extensive interest on the part of governmental agencies, private enterprise and academia because of its ability to treat these high concentration effluents generated from the TMP/CTMP pulping processes. The major disadvantage of aerobic treatment processes are substantial costs associated with power requirements for mixing and aeration, whereas the major limitation for anaerobic treatment processes have been long start up times and process instability leading to system failures. These disadvantages led to the consideration of a process not among those mentioned above, the rotating biological contactor (RBC) which, taking these factors into account, would appear to be an effluent treatment system worth studying. While operating under aerobic conditions, the RBC has low power requirements for aeration with energy needed only for turning the discs and moving wastewater through the system.

The purpose of this research was to demonstrate the ability of an RBC to remove organic matter from a CTMP wastewater when operated at different flowrates and different temperatures.

Mechanical pulp is produced either by grinding logs into separate fibres with rotating stones (stone groundwood), which is the oldest form of mechanical pulping, or by forcing chips between grooved rotating steel plates in refiners (refiner groundwood). The advantage of refiner mechanical pulp over the stone groundwood process is that chips as well as sawmill wastes can be used as a raw material instead of logs. TMP was introduced in the 1970's as a modification of the refiner groundwood pulping process. In TMP pulping, the wood chips are presteamed in a pressurized vessel before fiberization under pressure in a disc refiner. The thermal pretreatment results in a higher strength pulp by softening the lignin to reduce damage of the long fibre component during mechanical fiberization. CTMP refers to a process which utilizes a combination of chemical, thermal and mechanical pulping stages. The impregnation of wood chips with sodium sulfite under alkaline conditions prior to preheating and refining results in pulp, which after washing, exhibits a low extractive content. Consequently, chemical pretreatment improves the quality of the final pulp by

increasing the flexibility of the long fibre fraction (McCubbin, 1983) resulting in an increase in overall

strength of about 10% over that produced by a TMP process (Jackson and Akerlund, 1984). The

improved quality and increase in overall strength makes CTMP more suitable for products typically

made from chemical pulps such as fluff, tissue, printing and writing grades (Jackson and Akerlund,

1984). The bleaching of CTMP is technically a brightening process which uses hydrogen peroxide or

hydrosulfite as a brightening agent. Often chelating agents are also added to deactivate heavy metal

ions which originate in the wood or from system corrosion and which accelerate the decomposition

of the brightening agents. Finally, a further removal of extractives can be achieved by the introduction

of surface active agents into the CTMP process, this leads to a additional improvement in water

absorption properties and brightness of the pulp. Therefore, the quality of CTMP over TMP pulp

is improved at the expense of lower yield and higher effluent load. Typical pulp yield values for the

CTMP process vary from 80-90% as compared to about 91-95% yield for TMP and 43-48% yield for

kraft pulp (Cornacchio and Hall, 1988).

In this project, the CTMP wastewater came from the Quesnel River Pulp (QRP) Mill located on

the Fraser River at Quesnel, B.C. The mill normally operates 24 hours per day, 7 days per week

subject to market demand for pulp. Both TMP and CTMP are produced. The overall toxicity of the

raw mill effluent is quite high. Servizi and Gordon (1986) report a mean 96 hours LC_{50} toxicity of

1.27% for TMP and 0.83% for CTMP effluents. Work done in the UBC Pulp and Paper Centre on

this CTMP wastewater indicated an LC_{50} of 0.55%. Of the wood extractives, resin acids are a major

toxicity problem. Up to 70% of the toxicity of whole effluent from pulp and paper mills has been

attributed to resin acids (Environment Ontario, 1988). Other contributors to the total toxicity of the

wastewater are suspended solids, fatty acids, phenols, tannin-lignins, sulphites, and sulphonated lignins.

The chelating and surface agents may also contribute to the CTMP toxicity (Cornacchio and Hall,

1988).

The RBC process was conceived and commercialized in 1960 in West Germany (Brenner et al.,

1984). The device consists of a series of discs which are mounted on a shaft and rotated while partially submerged in the wastewater to be treated. A microbial film develops on the surface of the discs shortly after seeding with an appropriate source of microorganisms, and provides the microbial population necessary to oxidize the biodegradable materials in the waste. The rotation of the discs leads to continuous growth of the microorganisms, as well as a continuous sloughing of biomass when the innermost layer loses its ability to adhere. The discs further serve as a mixing device for effective treatment. During immersion of the discs the BOD is removed while after emersion, the aeration of the culture is accomplished. The rotating disc is, therefore, utilized as support for the bacteria, an aeration mechanism, and a means of contacting the organism with the wastewater to be treated. Operation in this manner gives this wastewater treatment device the name the "Rotating Biological Contactor" or "RBC".

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of previous work that has been done in areas relevant to the present study. It begins with a review of the characteristics of wastewater from thermomechanical type pulping (TMP) processes, including a brief summary of the environmental inpact of such wastewaters if they were to be discharged without treatment.

2.1 CHARACTERISTICS OF CTMP EFFLUENT

There is quite a variety of thermomechanical pulping processes, many of these are described in Leask (1987). Of the various pulping options this thesis is mostly concerned with chemithermomechanical pulping (CTMP) and bleached CTMP (BCTMP).

In TMP processes wood chips are reduced to pulp by mechanical forces which act on the chips as they pass through a narrow gap between rotating, barred discs. The chips are in water suspension. The refining process generates a lot of heat which raises the temperature inside the refiners hence the "thermo" in TMP, CTMP etc. Some of the wood constituents are solubilized in the process. In the CTMP process sodium sulfite is added to soften the chips and make freeing of the fibres from one another easier. This results in more wood derived chemicals being solubilized along with the residual sulfite. Bleaching is often accomplished with hydrogen peroxide, aided by the addition of chelating agents, which introduces more material into solution.

Figure 2.1 is a flowsheet of a possible CTMP mill configuration put together from information provided in Miotti (1990) and Wearing et al. (1985). It illustrates the prinicipal sources of wastewater
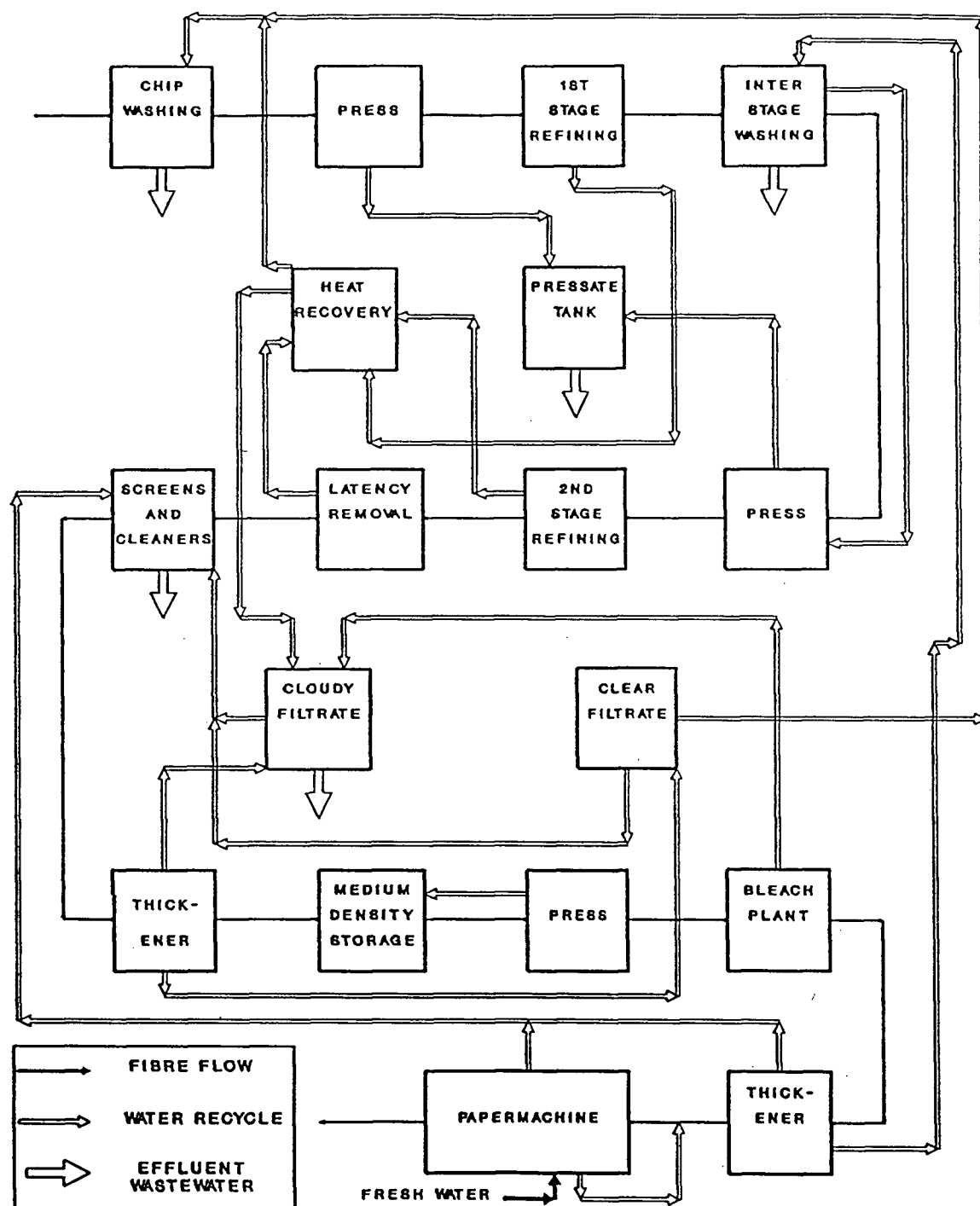
Figure 2.1 TMP/CTMP flowsheet showing water recycle loops and effluent discharge from process.

from various subprocesses and also shows how recycling mixes the various streams.

In the past water use in TMP/CTMP mills has been in the range 16 ~ 150 m³/oven dry tonne of pulp (Novatec Consultants, 1987). More recently water use in such mills is approaching 10 m³/tonne/ADT. Mills are currently under construction in which no liquid effluent is planned (Castagne, 1990 and HPDE Inc). These latter have little or no involvement with biological treatment.

The composition of the organics in CTMP effluents has not been well documented. Pichon et al. (1986) reported that the data from a CTMP pilot plant indicated that the organic material in the effluent was composed of

- carbohydrates (10-15%)

- organic acids (35-40%)

- lignins (30-40%).

The release of carbohydrates and simple wood sugars, extractive composition, as well as the low and high molecular weight lignin compounds varies between wood species.

Environmental regulations control the amounts of suspended solids, biochemical oxygen demand, and toxicity that can be discharged to receiving waters. pH of discharged water is also subject to regulations. In some circumstances wastewater colour and temperature may be subject to discharge limits (Bonsor et al., 1989; Environment Ontario, 1989; Sinclair, 1990).

2.1.1 SUSPENDED SOLIDS

Suspended solids can be classified as settleable and nonsettleable, the two together being total suspended solids (TSS). Discharge of TSS can cause blanketing of the bottom of the receiving water leading to interference with the growth of aquatic plants and benthic fauna. They can also subject fish exposed to them to excessive levels of stress and can interfere with light transmission through the receiving water.

Suspended solids in TMP/CTMP type mill wastewaters consist mostly of fibres or fibre debris that

is generated during the pulping process. Some sand and dirt particles are present in the chip washer effluent stream.

TSS levels in TMP/CTMP wastewater have been reported to be 4.4 to 72 kg/t (Novatec Consultants et al., 1987), 10 to 50 kg/t (Virkola and Honkanen, 1985), 600 to 1000 mg/l (Welander, 1989), 4.8 kg/adt at a concentration of 220 to 300 mg/l (Beak Consultants, 1986), 2.7 to 17 kg/ adt at concentrations ranging from 200 -2000 mg/l (Cornacchio and Hall, 1988). TSS loadings and concentrations in various process streams in an integrated CTMP/paper mill have been measured (Lo et al., 1991). TSS concentrations in streams ranged from 200 to 2600 mg/l. The highest concentrations were observed in a stream called CTMP washing but it is not clear if this refers to chip washing, interstage washing, or to some other pulp washing operation.

2.1.2 OXYGEN DEMAND

If oxidizable matter is discharged into a natural body of water, microorganisms naturally present therein will oxidize it in order to supply themselves with the energy they need for survival and reproduction. In so doing they require oxygen, the only source of which is oxygen dissolved in the water. Oxygen is not very soluble in water. Thus if the microorganisms are growing rapidly they can strip the water of its dissolved oxygen (D.O.) content to the detriment of other aerobic, aquatic species, such as fish.

Oxygen demand is measured by a test involving determination of the levels of D.O. in bottles containing wastewater and a microbial culture in a nutrient solution compared to levels observed in control bottles containing only the nutrient solution. This test result is called BOD. This test is time consuming and imprecise. A more precise test is the test for chemical oxygen demand (COD). This test can be done in a shorter time, however the chemical oxidation it utilizes can oxidize some compounds that microorganisms either cannot or do not oxidize in the time period available, 5 days in North America, 7 days in Europe.

The biologically oxidizable matter present in TMP/CTMP wastewaters is derived from the wood that is used as raw material in the pulping and bleaching processes. CTMP pulp yields, based on the wood charged to the process, are in the 80 to 90% range, thus 10 to 20% of the wood will appear in the wastewater, although a small fraction of this may be discharged to the air as volatile matter. Recycling of water used in the mill during TMP/CTMP processing decreases the effluent volume, however it increases the organic effluent concentration. Typical BOD values in North America and Europe range from 1000 to 4500 mg/l and corresponding COD values range from 2500 to 13000 mg/l (Cornacchio and Hall, 1988). Softwoods in general generate more BOD and COD than hardwoods.

Other oxygen demanding chemicals found in CTMP wastewater include methanol, resin acids, fatty acids, triglycerides, steryl esters, and assorted sulfur compounds (Welander, 1989). 10 - 30% of the total BOD discharge of QRP's TMP/CTMP effluent is associated to the resin acid content, which is due to the fact that most of the mills raw material consists of pine, a softwood species, as well as the fact that a lot of the resins are associated with fines present in the effluent. In addition, Malinen et al. (1985) reported that the addition of alkaline hydrogen peroxide as a bleaching chemical increased the BOD and COD loads substantially.

Acetic acid was found to contribute up to 1/6th of the total BOD load in the QRP effluent (see table 4.1). Chemical pretreatment and alkaline conditions increase the BOD loading by breaking down lignin and by releasing acetic acid (Virkola and Honkanen, 1985). Anderson et al. (1986) reported that at the Oestrand mill in Sweden the carbohydrates and acetic acid accounted for about half of the soluble COD. However, acetic acid is readily metabolized by both anaerobic and aerobic bacteria and does not pose any problems in effluent treatment efficiency.

In TMP most of the pollutants, including BOD and COD, are released from the wood in the primary refiner stage (Wong et al., 1979 and Wong et al., 1980). Little pollutant release occurs in the chip washing process. However since the wash water is recycled from elsewhere in the process the chip washer effluent contains a significant oxygen demand (Wong et al., 1979).

2.1.3 LIGNIN

Lignins provide mechanical strength to wood by binding cellulose fibres together. The chemistry of lignin is not very well defined since lignin composition is quite variable. Lignin accounts for 15 - 30% of the dry weight of plant material. The chemical pretreatment of the wood chips in CTMP manufactures enhances the solubility of low and high molecular weight lignins under alkaline conditions (Almemark et al., 1986). Urbantas and MacEwen (1985) found that CTMP effluents contain a smaller fraction of low molecular weight, biodegradable components than TMP effluents. Hydrogen peroxide bleaching may cause the production of more low molecular weight lignins and volatile organic acids (Almemark et al., 1986).

The larger fraction of high molecular weight, non-biodegradable material in CTMP effluents is the cause of the lower BOD values observed per gram of dissolved material for CTMP than for TMP. The COD test will oxidize these high molecular weight organics, which results in a higher COD measurement than BOD measurement. The BOD/COD ratios measured for several Canadian TMP and CTMP wastewaters were between 0.3 to 0.45 (Hall and Cornacchio, 1988). Thus, it is reasonable to expect that biological treatment alone will not be capable of removing more than 30 - 45% of the organic material (COD) in CTMP effluents.

Beak Consultants Ltd. (1986) reported that analytical data from the samples used in the bench tests gave an average ratio of 0.30:1 and 0.36:1 BOD_5/COD for TMP and CTMP respectively for QRP CTMP, effluent. However, it was recognized that the data was not derived from fresh composite samples and information from the QRP mill representing a few analysis suggested a higher ratio of 0.42:1 for both processes. They also found that alternating the production of TMP and CTMP has been a problem as the organic load in the untreated wastewater more than doubles during CTMP production.

2.1.4 COLOUR

Discharge of highly coloured wastewater to pristine receiving waters is aesthetically undesirable and may interfere with light transmission in the water and hence with the photosynthetic activities of aquatic plants. TMP/CTMP wastewater is brownish-yellowish in colour. Raw TMP wastewater has a reported colour of around 550 colour units (Wong, 1977) but during aerobic biological treatment its colour rises to around 1000 units.

2.1.5 TOXICITY

Toxic matter, as far as present day Canadian environmental legislation is concerned, is matter capable of killing fish. Killing fish via oxygen deprivation is excluded from the definition of toxicity. Toxicity is usually measured via a bioassay in which a test species is exposed to various concentrations of wastewater which has been diluted with clean water. The concentration (% dilution) which kills 50% of the test fish in a 96 hour exposure period is known as the 96 hour LC_{50}. The lower the LC_{50} the more toxic the wastewater. Environment Canada uses an $LC_{20} = 65$ test, meaning if 80% of the test fish survive 96 hours of exposure to 65% wastewater, that wastewater is deemed to be nontoxic. Exposure of fish to concentrations less than the LC_{50} can result in a variety of undesirable, sublethal effects (McLeay and Associates Ltd., 1987). Table 2.1 provides data on the LC_{50} values of TMP and CTMP. wastewaters.

A wide variety of chemical compounds that can be found in TMP/CTMP wastewaters are known to be toxic to fish. The most toxic chemical to be found in TMP/CTMP wastewaters are believed to be the resin acids. They are toxic to both fish and anaerobic bacteria. Resin acid concentrations ranged from 2 to 21 mg/l in four TMP effluents, and from 25 to 65 mg/l in two CTMP mill effluents surveyed in Canada (Novatec Consultants Inc. et al., 1987). The Canadian data was obtained from softwoods which contain much higher concentrations of resin acids than hardwood species. However, other investigators found resin acid concentrations as high as 559 mg/l in some Canadian

Table 2.1 LC_{50} values for TMP and CTMP wastewaters.

Wastewater information	LC_{50}	Reference
TMP	0.7 - 2.4	Servizi and Gordon (1986)
CTMP	0.4 - 1.8	Servizi and Gordon (1986)
TMP	1.3 - 35.3	Cornacchio and Hall (1988)
CTMP	0.8 - 1.8	Cornacchio and Hall (1988)
TMP	17 - 79	Wong et al. (1978)

softwood mill effluents (Cornacchio and Hall, 1988). It is generally believed that resin acids can be degraded aerobically if sufficient retention time and oxygen (~ 3 ppm BOD/ppm resin acid) are provided. Resin acids are only slightly biodegraded under anaerobic conditions (Cornacchio and Hall, 1988; MacLean et al., 1990; and Servizi and Gordon,1986). Less toxic are the fatty acids. Lignans, flavonoids, tropolones, juvabiones, and thujic acid may also be toxic to fish (Wong et al., 1978). There are probably many other such chemicals for which toxicity data is not available (McLeay and Associates Ltd., 1987).

Total phenol concentration in receiving waters should not exceed 1 microgram/l to prevent tainting of fish flesh (CCREM 1987). Dwernychuk (1990) reported total phenol values of 43 microgram/l in treated QRP effluent in his report on the environmental effects monitoring program examining physical/chemical/biological elements of systems related to pulp mill effluents of the upper Fraser River. Bosia et al. (1986) looked at CTMP pulping, papermaking and consequently, at effluent treatment in an activated sludge plant. They measured a phenol concentration of 890 mg/l in the raw wastewater using the Folin method. This method measures various phenolic compounds as well as polyphenols. They concluded that 30% of the phenol content is not removed by the biological treatment employed by them and that this fraction which was made up for the most part of

polyphenols of considerable chemical stability , such as lignin, would also prove extremely difficult to be eliminated by other biological treatment processes.

The disadvantages related to sulfite, which is one of the key-chemicals in CTMP production, have been studied and described by many researchers (Habets, 1986; Habets and de Vegt, 1990; Beak Consultants Ltd, 1986; Cornacchio and Hall, 1986; Anderson et al., 1986). The main part of the sulfur present in the CTMP effluent is as sulfate, because in the bleaching process, most of the residual sulfate gets oxidized to sulfate with the help of residual hydrogen peroxide, and a minor part is present as lignosulfate. Under anaerobic conditions sulfate and sulfite usually get biologically reduced to hydrogen sulfide, which when volatile will be stripped out with the biogas. If sulfide levels higher than 200 mg/l remain in the treatment process inhibition of the anaerobic bacteria may result. Sulfide can also lead to odour and toxicity problems. The presence of sulfite does not pose significant problems for an aerobic treatment system. Bosia et al. (1986) found that the inorganic sulfite fraction of the spent liquor was almost completely oxidized by an activated sludge treatment. The fate of the organically bound sulfur (lignosulfonates) is still unclear. Most authors assume that it remains unaffected. Almemark et al. (1986) suggested that sulfonated lignins may also contribute to the CTMP wastewater toxicity.

Chelating agents such as DTPA during peroxide bleaching of CTMP pulp may be of some concern during anaerobic treatment. Welander et al. (1988) have indicated that excess DTPA may be toxic to anaerobic bacteria.

2.1.6 TEMPERATURE AND pH

Discharges of hot water to receiving streams are unlikely to cause problems in cold waters outside the immediate discharge zone. Discharges to warm waters however, if they result in a significant rise in temperature of the receiving stream may overstress the fish therein (Welch, 1980). Wastewater temperature is an important factor in various kinds of wastewater treatment technology. Typical

discharge temperatures for CTMP mills are of the order of 50 to 80°C (Welander, 1989). Malinen et al. (1985) concluded in their study on characterization and treatment of chemithermomechanical pulping effluent that increased temperature and increased sulfite charge in the chemical pretreatment both resulted in a higher BOD and COD load, where temperature was the more sensitive parameter.

Discharges of wastewater to receiving waters or to biological treatment systems should be close to neutrality, *ie* pH = 7. CTMP wastewater pH's have been reported in Canada and in Europe to be in the range of 6.0 to 7.5 (Servizi and Gordon, 1986; Wilson et al., 1985; Lo et al.,1991; Bosia et al., 1986; Scarlata, 1981).

2.1.7 NUTRIENTS

Nitrogen (N) and phosphorus (P) are major nutrients required for bacterial growth during biological treatment. If biological systems are to function properly, nutrients must be available in adequate amounts. Based on an average cell composition of cell tissue of $C_5H_7NO_2$ about 12.4 percent by weight of nitrogen will be required and the phosphorus requirement is usually assumed to be about one-fifth of this value. This translates into a BOD:N:P ratio of 100:5:1 for aerobic fermentation. For anaerobic metabolism experimental data for carbohydrate waste indicate that 1.0 to 1.5 mg of N are required for every 100 mg of COD removed to provide for biomass synthesis. A survey of several Canadian TMP and CTMP mills (Hall and Cornacchio, 1988) indicated that effluent biodegradable COD/N ratios varied between 100:0.67 and 100:4. Corresponding biodegradable COD/P ratios were from 100:0.093 to 100:0.5.

In 1986 when the effluent treatment plant at QRP consisted of a primary clarifier and an aerated lagoon the treated effluents failed to meet federal regulations and provincial quality criteria for detoxification. Servizi and Gordon (1986) argued, after a pilot plant treatability study, that biological treatment was sensitive to supplemental nitrogen addition rates as well as to retention time. They concluded that increasing the treatment time of CTMP effluents from five to seven days or increasing

the supplemental BOD:N ratio from 100:1 to 100:2.22 of TMP or CTMP effluents resulted in lethal amounts of ammonia and/or nitrite. In the former case, endogenous metabolism by a high concentration of mixed liquor suspended solids (MLSS) was the apparent cause of elevated amounts of ammonia and nitrite. In the latter case, lethal amounts of nitrite were apparently derived from excess ammonia fed to the pilot plant. The authors further suspect that nitrite and ammonia may have been responsible for some occasional unexplained acute lethalities in biologically treated mill effluents with which they are acquainted. This problem with treated effluents has also been observed by Schnell et al. (1990), nutrient solubilization resulting from the decay of biological solids was apparently responsible. The addition of a ratio of BOD:P of 100:1 did not pose any problems on the treatment quality.

The aerated stabilization basin at QRP however, was unable to provide the effluent quality required by B.C. Level A guidelines. In 1986 Beak consultants Ltd. (1986) initiated a bench scale study using an anaerobic treatment system for the QRP effluents. A low nutrient level of BOD:N:P of 100:0.9:0.5 and 100:1.6:1 for CTMP respectively for TMP were added to the reactors. Yet, problems with the nutrient concentrations were noted. The ammonia nitrogen added to the raw TMP and CTMP effluents fed to the reactor was theoretically just sufficient based on the COD removal obtained. In contrast, only minor removals of NH_4^+ nitrogen or filtered total P were observed and significant residual concentrations of both N and P were present in the treated effluent.

When McLean et al. (1990) investigated a full-scale anaerobic/aerobic effluent treatment at QRP. Nutrients based on a COD:N:P ratio of 100:0.83:0.17 were added into the first stage of the treatment plant with no additional nutrients added to the treatment process. They concluded that the effluent had met government criteria.

A number of researchers have investigated CTMP effluent from the QRP mill. A comparison of CTMP wastewater characteristics from the QRP company between Beak Consultants Ltd. (1986), Cornacchio and Hall (1986), Habets and de Vegt (1990), Kennedy et al. (1990) and Servizi and

Gordon (1986) is listed in table 4.1.

2.2 ROTATING BIOLOGICAL CONTACTORS

The development of the RBC process began in Germany in the 1920's using wooden discs. By 1959, J. Conrad Stengelin was manufacturing two and three meter diameter polystyrene discs in West Germany, and by the late sixties a number of small West German communities were using RBC's for their wastewater treatment. The capital cost of these original units was quite high. However, the maintenance and energy costs proved to be low. The above is still a selling point used by RBC manufacturers. The Stengelin Company licensed the RBC process in the United States in the mid 1960's. In 1972, the American company Autotrol developed a more compact disc for the RBC process which increased the available surface area of the disc by 70 to 150%; and RBC's soon became cost competitive with other treatment processes. A cost-effective analysis was done by Lundberg and Pierce (1980) to compare air-driven and mechanically driven RBC processes with air and pure oxygen activated sludge processes. For the range of design flows studied (3-50 10^6gal/day) RBC's were found to require 40-60% of the power needed for pure oxygen activated sludge facilities and from 23-60% of the power needed for air activated sludge processes. The authors concluded that RBC processes were a viable alternative to activated sludge in the 3-50 10^6gal/day design range.

Perry's Chemical Engineering Handbook (1984) reports that rotating biological contactors have been very popular in treating industrial wastes because of their relatively small size, their low energy requirements, and consequently, their low cost. It further states that a number of problems have occurred which should be recognized prior to using RBC's. Strong industrial wastes tend to create excessive microbial growth which is not easily sheared off and which create high oxygen demand rates, and possibly the production of hydrogen sulfide and other obnoxious odours. Heavy microbial growth has damaged some of discs and has caused some shaft failures. It is recommended that RBC units work best under uniform organic loads, requiring surge tanks for many industrial wastes. A recent

survey of rotating biological contactors indicated that over 80 percent of the RBC's designed before 1980 have experienced operation problems (Harrison, 1988). Many of the past problems have been overcome with new designs where: (a) improved construction techniques (e.g. minimizing shaft or media failures) are used and (b) organic and hydraulic loadings have had a proper accounting.

2.2.1 MAJOR SYSTEM CHARACTERISTICS INFLUENCING RBC PERFORMANCE

One of the factors which initially enhanced RBC popularity with design engineers was the apparent simplicity of the RBC system and what were perceived to be easily definable design factors. Early investigators thought to establish the design of RBC systems on substrate removal rates per unit surface area at fixed optimal rotation speeds and detention times. Subsequent investigations, however, have revealed that RBC performance is considerably more complex and is based on numerous factors, some of which are analogous to other biological treatment systems, while others are unique to the RBC systems themselves. For better design and operation of the RBC process, it is important to understand the interaction of these parameters. The major factors influencing performance are discussed in the following subsections.

2.2.1.1 DISC ROTATIONAL SPEED

Disc rotational speed is expressed either as tip speed or peripheral velocity; it is related to the disc diameter and rotational velocity by the equation:

$$V = \frac{D}{2} \omega$$

where   V = tip speed (m/s)

D = disc diameter (m)

ω = rotational speed (1/s)

Most experimental investigators concerned with the effect of tip speed on RBC performance have reported that efficiency increased with increased speed, up to a limiting or maximum removal rate (Manual of Practice OM-10, WPCF, 1988; Bender, 1985). The exact or dominant mechanism by which rotational speed improves performance is not readily known, but can be assumed to be dependent on the specific rate-limiting condition, such as mixed liquor dissolved oxygen (D.O.) concentration and shearing of the biofilm. Practically, rotational velocity is a trade-off between increased process performance efficiency and power requirements.

A tip speed ranging between 0.21 m/s to 0.33 m/s is widely used in bench scale, pilot and full scale RBC design (Andreadakis, 1987; Brenner et al., 1984; Wilson and Murphy, 1980; Steels, 1974; Congram, 1976; Antonie et al., 1974; Chen et al. 1974; Lee and Mueller, 1975).

2.2.1.2 DISSOLVED OXYGEN

Previous literature has identified dissolved oxygen as a major performance parameter (Brenner et al., 1984; Bunch, 1984; Friedman, 1980; Hitdlebaugh and Miller, 1980; Huang, 1980; Lagnese, 1980; Steiner, 1980; Stover and Kincannon, 1982; Chesner and Molof, 1977; Torpey, 1971; Welch, 1968). Increases in oxygen concentration in the reactor liquid (Bender, 1985; Hartung, 1982; Hitdlebaugh and Miller, 1980; Langese, 1980; Chesner and Molof, 1977; Welch, 1968) up to recommended D.O. level of 1.5 ~ 2.0 mg/l produced beneficial results. Further increases didn't (Bender, 1985; Chesner and Molof, 1977; Welch, 1968). Augmenting the O_2 of the gas surrounding the discs tended to raise liquid D.O. levels and improve performance up to a limiting D.O. level (Bender, 1985; Huang, 1980; Torpey et al., 1971).

Dissolved oxygen deficiency can result if the wastewater has a high influent organic loading. This condition brings about an increase in the organic concentration in the reactor, which increases the

oxygen demand required for substrate utilization resulting in low D.O.

D.O. depletion within the biofilm and bulk liquid can result in the growth of nuisance organisms which competitively colonize the RBC media surface, leading to reduced removal rates, due to their lower metabolic rate (Manual of Practice, OM-10, WPCF, 1988; Bender, 1985; Brenner et al., 1984; Alleman et al., 1980). Further more, when sulfide is present, either in the influent wastewater or by its production deep within the biofilm or in the bulk liquid by anaerobic sulfate reducing bacteria Desulfovibrio, sulfide oxidizing organisms such as Beggiotoa can and frequently do grow on the biofilm surface. Sulfide serves as an energy source for Beggiotoa metabolism (Alleman et al., 1982). Beggiotoa compete with heterotrophic organism for oxygen and space on the RBC media surface. Their predominance can result in an increase in the concentration of biomass on an RBC unit while at the same time causing a substantial reduction in organic removal per unit area. This slow growing population has a smooth, milky white appearance when it is predominant on RBC surfaces (Bender, 1985; Brenner et al., 1984).

While low bulk liquid D.O.'s are indicative of an overloaded system, increasing D.O. levels in the bulk liquid will not necessarily overcome process performance difficulties that may develop. Two of the plants studied by Chesner and Iannone (1985) had nuisance organisms (Beggiotoa) present in the first stages despite bulk liquid D.O. levels of 1.5 to 2.0 mg/l. A similar observation was also made at an RBC facility in Edgewater, New Jersey (Gutierrez et al., 1980).

Hartung (1982) discussed the effects of supplemental aeration by comparing continuous application of air to intermittent application with regards to bio-disc loading and the protection of the bio-disc equipment of a municipal RBC plant at North Huntingdon, Pennsylvania. Positive displacement blowers were used to diffuse air beneath the bio-discs units capable of producing 185 cfm at 2 psi. A diffuser header was fabricated out of 2 in diameter PVC pipe with two rows of 30 diffusing holes 1/2 in. diameter, spaced 8 1/4 in. apart. The diffuser header was then anchored to a 3 in. steel channel and mounted directly under the center line of the bio-disc with the diffusing direction slightly angled

against rotation of the bio-disc. He concluded that intermittent dispersion of large volumes of air (370 cfm at 2 psi diffused to each individual disc for 30 min.) was more beneficial than a continuous mode. The advantages were that the blasting stripped off matured biomass to allow a new culture of the young and more active feeders to grow. He concluded further that this prevented anaerobic growth from occurring, maintained the total weight of the equipment within safe limits to prevent mechanical failures and prolonged the life of the equipment, at an inexpensive operational cost.

Air driven RBC systems may be an alternative solution to limiting D.O. problems for wastewaters with high organic concentrations. The drive assembly has 10 or 15 cm deep plastic cups attached to holders welded around the perimeter of the media and an air header placed beneath the media. Forced release of air (approx. 4 psi) into the cups creates a buoyant force that causes the shaft to turn (Manual of Practice OM-10, WPCF, 1988). Brenner et al. (1984) report that a major advantage of the air drive RBC system is claimed to be related to the increased turbulence which strips off excess biofilm as air bubbles rise through the media.

2.2.1.3 ORGANIC LOADING RATE

In the early days, and even today, many engineer's involved with RBC design have been concerned with either hydraulic flow rate or the concentration of the substrate applied to the system. Today organic loading rate (kg BOD/day/surface area) is considered the most important design parameter for an RBC system (Springer, 1986; Brenner et al, 1984; Stover and Kincannon, 1982; Bunch, 1980; Steiner, 1980; Weng and Molof, 1980). Organic loading rate design values ranging from 0.004 to 0.04 kg BOD/m^2/day are recommended by manufacturers and researchers. Typical, design, organic loading rates are: 0.0293 kg/m^2/day (based on max. total BOD) or 0.004883 to 0.00732 kg/m^2/day (based on max. soluble BOD) for refinery and municipal wastewaters (Stover and Kincannon (1982); 0.004 to 0.04 kg/m^2/day for municipal wastewater (Wilson and Murphy (1980); 0.0313 kg/m^2/day (total BOD) or 0.0127 to 0.0186 kg/m^2/day (soluble BOD) for industrial and municipal wastewater (Autotrol

Design Manual, 1978); 0.007194 kg/m^2/day for kraft wastewater (Lee and Mueller, 1975).

Stover and Kincannon (1982) studied the effects of organic loading rates from 1974 to 1979. They noted that organic loading rate is the product of concentration and hydraulic flowrate per unit of disc area. Thus various combinations of organic concentration and hydraulic loading can give the same loading rate. They concluded that the amount of organics removed by the system was the same at the same organic loading rate regardless of whether the loadings are accomplished by a low flow rate at a high organic concentration or vice versa.

Weng and Molof (1980) tested a six-stage laboratory RBC reactor using a synthetic substrate made from glucose, proteins and fatty acids. They concluded that an increase in influent concentration at a constant flow rate resulted in a decrease of both, percent chemical oxygen demand (COD) and D.O. content of the mixed liquor, while the rate of COD removal (mg/hour) increased. Increasing flow rate at a constant influent concentration had the same effects, but resulted also in a decrease of COD removal (mg/l) and, consequently an increase in effluent COD (mg/l).

It is not recommended to organically overload or underload the system. The problem caused by overloading usually results in limiting the oxygen transfer capability of the system and its consequences are described in section 2.2.1.2. Organic underloading is manifested by sparse growth on later stages and possible poor secondary clarifier operation because of excessive detention time.

2.2.1.4 BIOFILM STUDIES AND MICROBIOLOGY

Biologically, each RBC consists of a complex, interrelated population of predominantly heterotrophic, attached microorganisms. In general, the majority of this attached microbial population will be comprised of aerobic, facultative and anaerobic bacteria (Kinner et al., 1985; Alleman et al., 1980; McKinney and Ross, 1977). Metcalf & Eddy (1979) report that the biological community includes also fungi, algae and protozoa. Fungi contribute to waste stabilization; algae do not take directly part in wastewater degradation but add oxygen to the system, and protozoa do not stabilize the wastewater

but control the bacterial population.

In addition, as indicated by Kornegay (1975), a significant population of suspended microorganisms may also be present, if the system is operated at a long hydraulic retention time or high organic loading rate.

With respect to substrate removal, the concept of an "active" microbial depth has been adopted by several investigators, testing synthetic wastewater or sewage, and has been estimated to be between 70 and 200 micrometers in thickness (Nilsson and Dostalek, 1984; Characklis and Trulear, 1980; Famularo et al, 1978; Kornegay, 1975; Hoehn and Ray, 1973; Kornegay and Andrews, 1970; Sanders, 1966). This hypothesis divides the total microbial film thickness into two layers. The outermost layer is termed the active layer, while the "inactive layer", if present, is closer to the support media. Sanders (1966) evaluated active depth in terms of "critical" depth at which diffusion of oxygen within the slime layer became limiting. Tomlinson and Snaddon (1966) have also suggested that the active layer consists of an aerobic microorganisms zone. However, the presence of an anaerobic zone does not appear to offer sufficient proof to conclude that the active thickness and aerobic thickness are necessarily one and the same. Kornegay (1975), Atkinson and Davies (1974) and Grieves (1972) contend that the active depth should not only be defined with respect to oxygen diffusion but also applies to the diffusion of a metabolic substrate, and that in dilute media such as sewage the concentration of the substrate may be the rate limiting factor even when low oxygen concentration exist. In all investigations, maximum removal rates where defined within these ranges of depths; two investigations (Hoehn and Ray, 1973 and Sanders, 1966) reported decreased removal per unit depth of growth when the optimum depth was exceeded. This decreasing rate was attributed to anaerobic end products diffusing outward and interfering with aerobic activity. Conceptually, substrate removal from the bulk liquid phase requires diffusion of metabolic reactants into the attached biofilm, metabolism by the organism and diffusion of the metabolic by-product back through the biofilm and into either the bulk liquid or the atmosphere. For relatively thick biofilms significant concentration

gradients, resulting from mass transport resistances, can exist between the bulk liquid and the active microbial layer (Famularo 1978). A shaggy biomass surface makes the definition of the active depth somewhat imprecise. To date, no universally acceptable technique exists for measurement of active depth in any fixed film system.

Studies done by Namkung and Rittmann (1988), Characklis and Trulear (1980) and La Motta and Hickey (1980) have shown that biofilm processes not only utilize organic compounds for growth, but also produce a variety of organic materials. The bacteria attach to the media by excreting polysaccharides of different kinds.

Many investigators have related steady state, organic removal to biofilm thickness and age. Hoehn and Ray (1973) observed that nutrient utilization rates continued to increase until the biofilm reached approximately the level of limiting thickness. They further concluded that a quasi-steady-state nutrient utilization rate would be established at a maximum film thickness of 300 to 400 micrometers. These conclusions support those of Kornegay and Andrews (1970) and Tomlinson and Snaddon (1966).

Weng and Molof (1980) investigated organic removal in terms of biological film age and thickness. They noted that at film ages between 25 to 50 hours, corresponding to thicknesses between 135 to 265 micrometers the removal rates stabilized at some constant value. They further emphasized that these values were based on composite data, and therefore only useful in the determination of average results.

Torpey et al. (1971) found that, after cleaning, only 18 hours were required to restore biological growth on the disk surfaces of the first stage of an RBC thereby reestablishing normal treamtent efficiency. However, they did not report the procedures used for this evaluation.

Clogging or bridging of the open spaces between the discs can shield portions of the biofilm from exposure to oxygen and substrate. This would result in a reduction in effective RBC surface area and reduced performance. Huang (1980) and Antonie (1974) suggest that high hydraulic loading is beneficial in keeping a thin healthy biomass on the discs. Clogging is a particular concern in the

internal non-exposed portion of the RBC media which does not come in direct contact with the shearing forces of the liquid. The internal media present in newer types of RBC corrugated media configurations (Hormel, 1979 and Autotrol, 1978) are exposed to shearing forces generated by wastewater flowing in and out of the media.

2.2.1.5 WASTEWATER TEMPERATURE

The literature indicates that most full scale RBC systems operate between 3 to 25°C, while most lab scale RBC's usually are run at room temperature (approx. 20°C).

Design manuals suggest that wastewater temperatures should generally fall within a range of 7 to 38°C to insure proper process performance (Autotrol Corporation, 1978; Hormel Design Manual, 1979; Manual of Practice, OM-10, WPCF, 1988).

Some investigators have conducted studies on RBC's at elevated temperatures. Congram (1976) reported on a biodisk treating oil refinery waste. The biodisk unit treated 1,200 gpm at a wastewater temperature reaching 28°C during the summer. He did not report on any factors affecting performance effects related to summer temperatures. Studies reported by Antonie (1976) indicated that organic removal efficiency was unaffected by wastewater temperatures above 13°C. Both, Congram and Antonie, concluded that process performance deteriorated below 12 to 13°C.

In some highly loaded RBC systems, lower wastewater temperatures do not always result in decreased carbonaceous removal rates and, in fact, may enhance removal. When this phenomenon occurs, it may be attributed to increasing D.O. saturation values with decreasing temperature, which promote increased oxygen transfer, and possible reduction in the number of sulfide oxidizing organisms. For example, Scheible and Novak (1980) obtained a 15% increase in BOD removal when reducing the temperature from 26 to 11°C, using 12 ft. diameter RBC units. Others (Brenner et al., 1984) have reported increased removals in wintertime conditions for heavily loaded systems, such as at Alexandria, Virginia.

2.2.1.6 SUSPENDED GROWTH

Suspended solids in the trough of an RBC will occur naturally as a result of biological sloughing. The concentrations of such suspended solids are dependent on the organic loading rate and the RBC stage. Bender (1985) found that suspended solids measurements in RBC tanks are subject to wide variations because of the periodic nature of sloughing and difficulties in obtaining representative samples.

Suspended solids in the reactor provide additional biomass available for substrate utilization. This premise is the basis of the Surfact Process which combines an activated sludge and an RBC system (Guardino et al., 1977).

An excess of suspended growth, however, can reduce reactor dissolved oxygen concentration and can contribute to anaerobic conditions in the biofilm. Reported values (Antonie, 1975; Famularo et al., 1978) of the mass of fixed biomass solids relative to the normal suspended solids mass indicate that the quantity of active suspended solids under normal conditions is negligible relative to the fixed biomass. A more recent study (Kincannon and Groves, 1980) showed that suspended solids can affect kinetic performance, especially at low flowrates. This can result because the active biological suspended solids are wasted out of the system at a lower rate, therefore, playing a greater role in substrate removal.

2.2.1.7 STAGING

Staging refers to the physical separation of tanks in series, or sections of RBC media, within the same tank, by the use of baffles. One effect of a staged configuration is that each successive stage experiences an organic loading level lower than the previous. In each, a different environment may be established with different predominant strains of microorganisms developing in response to that environment. In chemical reaction kinetic theory, the use and effectiveness of staging is related to the order of reaction kinetics in the RBC tank or reactor and the nature of mixing in the reactor (e.g.

completely mixed or plug flow). If the RBC stages of a system are completely mixed, then a series of stages is more efficient than a single stage of equivalent capacity for first or higher order reaction rates.

Studies conducted by Antonie (1975) with 5.74 ft. diameter discs demonstrated that a four-stage RBC unit produced higher percentage BOD and suspended solids removals than obtained with a two-stage unit having the same overall surface area when treating the same municipal wastewater over a hydraulic loading range of 1 to 5 gpd/sq. ft. For the same hydraulic loading four-stage and six-stage operations, however, produced virtually identical performance. Bunch (1980) explains that under heavy organic loadings, the liquor from the first stage can be distinctly anaerobic and thus, any change in parameters can stress the system. He proposes that increasing the number of stages will increase the total treatment potential of the system, reducing the stress, because the excess organic material left untreated by the first stage can then be treated by successive stages.

Gillespie et al. (1974) recommends that a three-stage unit is sufficient for pulp and paper effluents, as usually nitrification takes place in the fourth stage.

Brenner et al. (1984) recommends ensuring that the organic loading to any individual stage is not excessive when selecting the number of stages for an RBC system design, implying that the first few stages may have to be larger than the others.

2.2.1.8 DISC DIAMETER AND SCALE-UP

A common RBC design practice in the past has been to scale up small pilot plant results to full-scale applications by setting the media tip or peripheral speed at the same value for both size units. Studies have shown that smaller systems exhibit greater removal capacities per unit surface area. This capacity has been attributed to the greater rotational velocity of smaller diameter systems. Reh et al. (1977) estimated that the oxygen transfer capacity of their 18 in. diameter unit was about 1.6 times greater than that of a 10.5 ft. diameter unit they evaluated. Stover and Kincannon (1982) and Severin et al.

(1980) propose scale-up design models based on oxygen transfer.

Other investigations concerned with process scale-up reported that the results of the scale-up evaluation indicated that the BOD_5 removal efficiency decreased as the RBC disc diameter increased under similar operating conditions (Wilson and Murphy, 1980; Wu et al., 1982).

Today, no proven scale-up technique from smaller diameter discs to larger diameter discs has been found universally acceptable. However, Brenner et al. (1984) suggest that if small-diameter units must be operated to collect design data, it is important that each stage be loaded below the oxygen transfer capability of a full-scale unit to minimize scale-up considerations. In general, RBC design manuals recommend keeping the diameter of the discs small for a given surface area, by increasing the number of discs.

2.2.2 OTHER DESIGN PARAMETERS

From available start-up characteristics it is apparent that a measurable biofilm will result one day to two weeks after start-up begins depending on the substrate utilized. Fry et al. (1982) report that growth of a biofilm began 24 hours after start-up for a municipal wastewater. Bracewell et al. (1980) observed that establishment of an observable biomass required two weeks in an RBC treatability study for phenol-formaldehyde resin wastewater. Torpey et al. (1971) found that only 18 hours after cleaning were required to restore a biological growth on the disc surfaces of the first stage of an RBC, with the reestablishment of normal efficiency of treatment. They did not report the procedure used for this evaluation.

Based on the available literature, steady state operation appears to be reached after two to three weeks of operation (Fry et al., 1982; Ahlberg and Kwong, 1974; Lue-Hing et al., 1974; Trinh (1981); Srinivasaraghavan et al., 1980). This information was based on steady-state COD removal data obtained from the RBC treatment of sewage.

Statements concerning the excellent ability of RBC units to successfully handle shock organic and

hydraulic loadings are frequently encountered. Wu et al. (1980) for example, noted that a major advantage of an RBC is its ability to resist organic and hydraulic shock loads. These statements are generally based on one or two characteristics of RBC plants. One important characteristic is the ability to retain the attached biomass when exposed to large hydraulic shocks.

An analysis of phenol-formaldehyde resin wastewater treatment by an RBC process found effluent COD values to be a function of the influent COD concentration. More importantly the pilot plant RBC unit functioned effectively "under varying climatic and loading conditions and exhibited excellent stability in withstanding periodic shock loadings" (Bracewell et al., 1980). Trinh (1981) reported that the biological slime of an RBC system weathered shock loads without sloughing and produced consistent effluent quality. However, diurnal flow variations caused a slight deterioration of effluent quality. These comments are based on a study which compared an extended aeration activated sludge process with a full-scale RBC system. A pilot plant study done by Fry et al. (1982), treating municipal sewage, tested an RBC with controlled shock loadings. They concluded that hydraulic shock loads depressed D.O. concentrations due to decreased hydraulic detention times and/or increased biological activity. However, the response to hydraulic shock loadings was not very reproducible. For the organic shock loads a D.O. depression did not occur and they hypothesized that this could be most likely attributed to a change in the organic constituents of the wastewater.

To reduce excessively heavy microbial growth on the initial discs of an RBC, influent load distribution or step-feeding can decrease the flow reaching the initial stages of the RBC and distribute the mass organic loadings more evenly to downstream shafts or stages. When compared to straight flow-through systems, step-feeding increased the total detention time of wastewater fed into the initial stages but did not affect the total detention time of wastewater fed into the later stages. Step-feeding may also be used to distribute the inflow more evenly into a multistage reactor providing for more complete mixing. However, the evaluation of the potential effectiveness of step-feeding requires fundamental knowledge of step-wise kinetics and available models have not specifically addressed

the effect of step-feeding (Bender, 1985).

2.2.3 INDUSTRIAL WASTEWATER TREATMENT USING AN RBC

Friedman (1980) investigated and described some of the failure modes and suggested preventative evaluation procedures for the consideration of designers working with industrial wastewaters. He found that RBC's have not proven to be quite the panacea promised, especially for industrial wastewaters. Even though they have been applied to or pilot tested with a large variety of industrial wastewaters with good success, failures with some industrial wastewaters have occurred and will probably continue to occur in the future. He found that the RBC process has many applications for the treatment of wastewaters. Escalating power costs make the process even more promising for the long term, cost effective treatment of industrial wastewaters. However, RBC's have distinct fundamental limitations that can lead to process failures for some wastewaters.

Because of unique wastewater characteristics, gross traditional parameters such as BOD_5 and suspended solids alone are inadequate for assessing RBC treatment for many industrial wastewaters. Friedman gives an example of bench scale RBC studies with tannery beamhouse wastewaters which illustrates a potential problem when a wastewater is not carefully characterized. After several months of continuous operation, an inorganic precipitate probably consisting of calcium sulfate-calcium carbonate complex was found throughout the biomass attached to the discs. Even though this one quarter to three-eigths inch thick layer did not appear to interfere with soluble COD removal for these experiments, it would likely put extra stress on the discs and possibly lead to bridging of the biomass between the discs, as shearing of biomass would be harder, because of the greater adhesive forces of the precipitate. Therefore, industrial wastewaters should be carefully characterized for constituents that may form precipitates in the RBC units as a result of oxidation and/or pH changes.

High loading conditions have created problems in the past by decreasing the D.O. content of the RBC and/or by developing excess biomass growth on the discs causing mechanical stresses, additional

power requirements and possible bridging conditions. Improper pilot plant operating conditions and poor data interpretation have also led to problems encountered in the use of RBC systems for industrial wastewaters.

Friedman concludes that only complete chemical characterization studies and careful pilot plant evaluation programs can prevent subsequent process failures and allow owners to obtain the full benefits potentially available for the RBC process.

Bracewell et al. (1980) used an RBC to treat a high strength phenol-formaldehyde resin wastewater. The wastewater was diluted 4-fold with domestic, primary treated sewage resulting in an average influent COD of 1550 mg/l before it was fed to the RBC. The experiment was conducted in the winter in a pilot plant, consisting of an RBC unit followed by a settling pond from which a recycling stream was drawn, both leased as a unit from Autotrol. The temperature of the wastewater ranged from 13 to 14°C. A 60% average COD removal was obtained throughout the operation. From this they concluded that the pilot system as a whole and the rotating biological contactor in particular performed well but less efficiently then expected when compared to literature values for activated sludge and trickling filters. Since the pilot program was carried out during winter conditions they hypothesized that the resulting low temperatures in the small pilot system undoubtedly reduced bacterial activity and thus prevented optimum removal rates from being attained.

2.3 TREATMENT OF CTMP EFFLUENT

Published literature indicates that TMP and CTMP effluents can be treated aerobically to reduce toxicity to acceptable levels. Combined anaerobic and aerobic treatment can reduce toxicity from highly concentrated TMP/CTMP effluent even more. Chemical treatment has found little application. Neither anaerobic nor chemical treatment alone has been shown in previous studies to reduce toxicity to acceptable levels.

Cornaccio and Hall (1988) observed that, because of the high BOD concentrations CTMP effluents

would be ideally suited to anaerobic treatment in which sludge production and energy consumption are minimized. The much higher aerobic sludge yields are potential drawbacks to aerobic treatment. They further concluded that the long term impacts of very high resin and fatty acid levels are not known. Evidence currently available suggests that these toxic compounds can be degraded aerobically. The presence of sulfite, hydrogen peroxide and chelating agents has little impact on aerobic treatment. Some of these toxic compounds can also be removed in an anaerobic process, however, if these compounds are present at high concentrations, inhibition of or toxicity to anaerobic bacteria could result.

2.3.1 TREATMENT OF PULPING EFFLUENT USING AN RBC

In the 1970's some investigators evaluated the rotating biological contactor as a potential method for secondary biological treatment of pulp and paper mill effluents. Influent BOD_5 concentrations in these studies ranged from 170 to 1200 mg/l. Some of the investigators fed the pulping wastewater at elevated temperatures to the RBC, but nobody performed investigations with temperature controlled tanks. The wastewater temperature fluctuated seasonally when tested with pilot plants at mills, lab scale models were usually run at room temperature.

The performance of an RBC pilot plant unit to treat groundwood pulp effluent was evaluated by Bennett et al. (1973). The RBC pilot plant was rented from the Autotrol Corporation. Their overall objective was to provide an effluent comparable to other biological treatment systems. Specific test objectives included evaluation of the RBC process during mill upset, investigation of sludge settling characteristics, establishment of the degree of toxicity removal, and generation of data with regards to colour and phosphate content of the RBC treated effluent. The BOD_5 influent concentration ranged from 246 to 295 mg/l and the TSS concentration ranged from 134 to 208 mg/l. Nutrients were added at a conventional BOD:N:P ratio of 100:5:1. It was concluded that the RBC pilot plant unit provided reduction levels of BOD_5 ranging from 67 to 89% and TSS ranging from 49 to 81%. The

biomass generated by this RBC treatment exhibited good settling characteristics and the unit recovered quickly during simulated mill upsets. The toxic properties were sufficiently reduced to comply with the Canadian federal effluent limitations. However, no reductions in effluent colour were observed. Influent phosphate was 60 to 70% removed and no major operational difficulties were encountered with the pilot plant. Bennett et al. further reported that the overall dissolved oxygen concentration in the tank increased from 0.78 to 3.13 mg/l from stage 1 to stage 4. The mixed liquor suspended solids (MLSS) or concentration of biomass in the tank was reported to range from 370 to 770 mg/l, and the attached biomass MLSS concentration ranged 24,000 to 5,100 mg/l from the first stage to the last stage. The authors recommended installation of a full-scale RBC process based on their findings.

Osterman (1974) evaluated the treatability of bleached kraft pulp mill effluent in Castelgar, B.C. using Autotrol's Bio-Surf pilot plant process. The influent wastewater was aerated in a holding tank to lower the temperature from 38 to 32 °C and was then fed to the RBC. At an influent BOD of 200 mg/l Osterman reported an efficiency of over 90% with a retention time less than 2 hours. He also obtained data on sludge characteristics, toxicity, reduction and recovery time from mill upsets and concluded that the Bio-Surf system was an economically viable alternative to more conventional systems. The variability in the rate of solids formation and the low percent solids of the clarifier sludge were considered as disadvantages of the system.

Chen et al. (1974) compared an oxygen activated sludge, an RBC, a trickling filter and an aerated stabilization basin for the biological treatability of bleached kraft and refiner groundwood pulp effluents. The influent BOD ranged from 123 to 230 mg/l and the influent temperature ranged from 30 to 35 °C. Nutrients for microbial growth were fed continuously to maintain a BOD:N:P ratio of 100:6:1. For the purpose of their investigations four pilot plants were installed at the Wauna mill, Oregon. The HRT's in the oxygen activated sludge and the RBC were set at 2 hours and at 1.5 hours, and longer for the two other systems. It was concluded that both the RBC and the oxygen activated

sludge system provided 90% BOD removal at moderate loading conditions. The oxygen activated sludge achieved consistently near 90% BOD removal for both retention times. The RBC required an HRT > 2 hours, while at an HRT < 1.5 hours the percent BOD removal dropped noticeably. In order to obtain the same degree of treatment, Chen et al. found that more than 10 days of HRT would be necessary for an aerated stabilization basin, and the degree of BOD removal in the trickling filter was less than expected. They further found that no reduction of TSS or colour was achieved by the biological treatment systems under study and the suspended solids did not settle without further treatment.

A pilot plant study using two RBC's was conducted at an unbleached kraft mill by McAliley (1974). The small RBC had 18 in. diameter discs and the large RBC pilot plant had of 12 ft. diameter discs. The purpose of the study was to compare the RBC process with the activated sludge system operated at the mill. Waste from a lignin plant along with unbleached kraft effluent were tested. It was concluded that the small pilot plant was capable of achieving 85% BOD removal from an influent containing 210 mg/l BOD at an HRT of one hour. However, the large pilot plant did not perform as well as the small pilot plant with respect to BOD removal per unit area. The author did not know whether this low performance was related to the irregular operation of the large pilot plant or to a scale-up problem. The correlation between BOD removal rate and BOD concentration was not significantly affected by hydraulic loading, rotational speed, or type of waste (kraft or kraft plus lignin) over the range of values they studied. The retention times of these RBC pilot plants were about 25% shorter than the retention times required for the activated sludge process. It was further calculated that the horsepower requirements for the RBC plants were about 40% of the horsepower requirements for the activated sludge process. Sludge filterability was about the same for both processes. Finally, it was concluded that the RBC pilot plants required very little operator skill or attention.

Gillespie et al. (1974) did a pilot scale evaluation of RBC treatment of pulp and paper mill wastes.

Different effluents from boardmill, kraft and sulfite mills were tested by installing pilot plant equipment from the two U.S. RBC manufacturers at various mill sites. They found for influent BOD concentrations up to 500 mg/l the RBC system was able to achieve high levels of BOD removal, producing effluent BOD levels in compliance with emerging U.S. Federal regulations. To achieve this, however, the systems would have to be designed with considerably lower hydraulic loading rates than those quoted by the manufacturers for domestic wastewater. For effluents of high strength (>500 mg/l), they suggested special design considerations, possibly including an enlarged first stage. They further reported that these systems gave excellent resistance to drastic changes in influent conditions. The sludge generation was much lower than that considered normal for activated sludge systems and it possessed good settling properties. Even at relatively modest BOD removal rates, the systems showed good ability to remove effluent toxicity. However, effluent samples were taken after the second clarifier, which was an integral part of the pilot plant, and not directly after the RBC. Finally, they concluded that no operational difficulties were encountered with any of the pilot plant equipment used in the study and that operation was quite simple in all cases.

Lee and Mueller (1975) tested an RBC lab model treating bleached kraft mill effluent. The lab scale model consisted of three stages and testing was conducted at room temperature. The influent BOD concentration ranged from 165 to 185 mg/l, the wastewater was treated at HRT's of 4, 8 and 16 hours. The dissolved oxygen of the unit increased from 3.3 mg/l in the first stage to 7.5 mg/l in the third stage. Microbial growth developed within the first three days of batch treatment. Lee and Mueller concluded that the RBC was capable of removing toxicity from bleach kraft mill effluents, as well as yielding high BOD removal efficiency (>90%) provided that nutrient levels, oxygen supply, pH control and mixing were proper.

Lee and Costantino (1977) did a labscale, RBC study at the Powell River mill treating groundwood washer effluents and TMP effluents. The influent BOD concentration ranged from 440 to 972 mg/l. The laboratory scale RBC model consisted of a 7 liter total trough which was divided into 3 stages,

each stage consisted of 33 discs 8 inch in diameter. Nutrients were added according to a BOD_5:N:P ratio of 100:5:1. Biomass development on the surface of the discs was achieved after a period of approximately 2 weeks. Tests were conducted at retention times of 2 and 4 hours and the influent temperature was set at 20°C. The groundwood washer effluent was used to test the RBC for temperature shocks by feeding hot effluent at 50 and 60°C to the reactor, as well as pH shocks to pH 9 and 10. Results of the temperature shocks showed a noticeable increase in biomass growth at the discs in the first stage when the biomass had cooled down to 32 to 38°C. At these temperatures a slime activity increase was observed. Results of pH shocks showed that the system had recovered after 16 hours, when the BOD removal efficiency was stabilized again. Their investigations with TMP effluents indicated the RBC unit was highly efficient at removing BOD. At an HRT of 4 hours 94% BOD removal and 100% detoxification of the effluent were achieved. However, data from colour tests on the TMP wastewater indicated an overall colour increase of 81%. Lee and Costantino hypothesized the colour increase might be due to the high organic content of the TMP effluent making it more prone to oxidation. Overall, the authors recommended the RBC system for the pulp and paper industry as a touch-up unit on selected streams for mills facing problems in meeting government guidelines pertaining to these pollutants.

A pilot plant study of biological treatment of magnesium base sulphite mill effluent was made by Baker et al. (1978). Investigations were conducted by comparing an aerated stabilization basin to an RBC. The two systems were independent but shared a common feed of the sulphite mill effluent. The influent BOD ranged from 1000 to 2000 mg/l. The 140,000 U.S. gallon, aerated lagoon was operated at 7 and 20 days retention time and achieved a satisfactory BOD removal ranging from 48 to 71% during winter months and from 80 to 91% during the summer months. The RBC was a 6 feet diameter pilot unit supplied by Autotrol, it was operated at different loading rates and two different rotational speeds. The BOD removal ranged from 62 to 80% at 3 RPM and from 71 to 85% at 4.5 RPM. Because of the anticipated high influent BOD concentration the flowrates were kept

considerably lower than recommended. Flowrates of 1, 2 and 3 GPM were tested. This created problems in trying to maintain a constant flowrate to the pilot unit, in addition some problems were encountered in keeping a constant flow from the sulphite mill because of electrical power failures in the region. This created problems in that the overall performance of the RBC unit was erratic. Because of its long residence time the lagoon was not as much affected by these feed problems as was the RBC with its much shorter hydraulic residence time. The reported data in this study did not include the period for which there were obvious known system problems. It was found that some BOD reduction was achieved under all operating conditions and an increase in rotational speed improved the BOD reduction. However, the authors were not able to tell if this performance represented an acclimatized biomass. As the pilot plant came complete with an integral clarifier the reported data was for the clarifier effluent and not only for the RBC, therefore it was suspected that the data for BOD removal was actually lower than reported. Baker et al. further reported that dewatering of the sludge by vacuum filtration was very difficult.

They concluded that the RBC performance was very sensitive to fluctuations in feed properties and suggested that this may be a property of all high rate systems operating on a variable strength waste such as a sulphite mill effluent.

2.3.2 TREATMENT OF CTMP EFFLUENT

Turk (1988) has reviewed aerobic and anaerobic treatment technologies presently used for treating CTMP wastewater in Canada, these included aerated lagoons with and without post settling, activated sludge systems and high rate anaerobic treatment processes with post aerobic lagoons. He presented a table comparing the advantages and disadvantages of these treatment processes with respect to fourteen parameters, as well as a table of cost comparisons between the different processes. The aerated lagoon ranked best in that it had the best rating for most parameters under investigation, however, its disadvantages include the large land requirement and the total annual cost which is

lowest only at lower wastewater flow rates. The activated sludge system ranked worst in both, parameter comparison and cost comparison. The high rate anaerobic treatment with post aerated lagoon rated between the aerated lagoon and the activated sludge process for the parameter comparison, however, it rated best in the cost comparison for higher effluent flow rates. This was attributed to the higher methane production which offset both capital and operating costs.

McAllen (1988) reviewed aerobic waste treatment for a bleached CTMP operation. He looked at the most common treatment systems in the pulp and paper industry in Canada which included aerated stabilization basins (lagoons), mixed air activated sludge and pure oxygen activated sludge systems. He concluded that all three systems were capable of high organic removal rates. Lagoons require more land than the other two systems, have very long retention times and the BOD removal efficiency is strongly dependent on wastewater temperatures usually limited to below 35°C. The major disadvatage of the air and oxygen activated sludge systems is the high production of biological solids. The advantages are high BOD removal efficiencies of 90 to 95% at optimum retention times. McAllen found that oxygen activated sludge systems were able to detoxify high strength wastewaters at short retention times. He concluded that an aerated lagoon has a high capital cost but low operational and energy costs. Both air and oxygen activated sludge systems exceed the total cost of an aerated lagoon by 2.5 times.

Since the QRP mill started production of TMP in 1981 and after modifications to include CTMP production, the effluent treatment consisted of a primary clarifier followed by an aerated stabilization basin. Servizi and Gordon (1986) studied the aerobic lagoon treatment system after numerous complications were encountered with the lagoon as its effluent consistently failed to meet with federal regulations. They concluded that such treatment fo CTMP and TMP effluents was sensitive to retention time and supplemental nitrogen addition.

Beak Consultants Ltd. (1986) proposed in September 1986 a treatment process consisting of a pretreatment for fiber removal and detoxification followed by an anaerobic treatment for COD/BOD$_5$

removal and an aerated polishing treatment for odour and toxicity removal at this mill.

An anaerobic/aerobic pilot study was then conducted starting in 1987. Based on the positive results of this study a full-scale upflow anaerobic sludge blanket (UASB) was built to treat the effluent prior discharging it to the existing aerated lagoon. The wastewater is first passed through a heat-exchanger to cool it to 35°C before it is passed through the acidogenic and methanogenic phases of the UASB. The hydraulic retention time in the anaerobic system is 9 to 16 hours overall and in the aerobic polishing state a 2 day hydraulic retention time is needed to polish the anaerobic effluent. Odourous gases produced in the UASB were collected and vented through a caustic scrubber for treatment and subsequent discharge to the atmosphere. McLean et al. (1990) concluded that the system had met the government Level A criteria consistently after initial primary clarifier problems were solved. These problems had occured because large fibers and wood chips accumulating in the anaerobic system were causing reduced sludge activity.

Some investigators have looked at aerobic treatment of the CTMP effluents from mills in Canada and other countries. Scarlata (1981) in Italy treated a bleached semichemical pulp effluent using a trickling filter and an activated sludge system. The influent BOD_5 concentration was 1600 mg/l and the COD concentration averaged 5000 mg/l. With a hydraulic retention time of 3.7 days a 90% BOD reduction was achieved when both systems were employed in series, however, the COD reduction was only 57 percent which exceeded the limit of 500 mg/l imposed by Italian law. The COD/BOD_5 ratio for the influent was 3, while for the effluent it was as high as 43. Sulphite levels dropped from 30 mg/l to 4 mg/l during treatment but the effluent level again exceeded the Italian limit of 2 mg/l. In a further attempt to reduce COD levels Scarlata set up activated sludge pilot plants containing powdered activated carbon. No difference in treatment efficiency was observed over a longer time period.

Shere and Day (1982) tested the treatability of a TMP effluent in a deep shaft, activated sludge bench scale model. The study was undertaken at PAPRICAN in Point Claire, Quebec. The influent

BOD and COD were 1000 mg/l and 2650 mg/l respectively. The system was run at hydraulic retention times of 1.6 to 7 hours while the D.O. level was maintained at 3 mg/l. The performance of the system was evaluated in terms of food/microorganism (F/M) ratios. The authors observed that the system achieved "under intense agitation and high oxygen availability a complete removal of high initial toxicity". They reported that BOD and COD removals of 95% and 80% were achieved at F/M values up to 1.7 per day. However, at F/M ratios of 3 per day higher reductions in COD, but not BOD, removal were measured. They further found that a low sludge yield was produced. Colour did not change during treatment and they encountered problems with excess foaming because of a high level of agitation.

A comparison between chemical precipitation with alum and activated sludge treatment was performed in Sweden by Malinen et al. (1985). Wastewater influent concentrations and the retention times of the activated sludge system were not given. The efficiency of these two processes were evaluated by looking at COD, BOD and colour removal. With alum precipitation the BOD was reduced by 30%, COD by up to 50% and colour removal was as high as 70 to 80%. Biological effluent treatment reduced BOD by 60 to 80%, COD by 40 to 60% and colour by about 30 to 40%. They concluded that chemical precipitation with alum was an inefficient treatment for BOD and COD removal, but for colour removal fairly good.

Bosia et al. (1986) reported on the performance of an activated sludge lab scale model in Italy. A CTMP effluent with a COD of 8,800 mg/l and a BOD_5 of 3,200 mg/l was tested. At a sludge retention time of more than 5 days a 95% BOD removal and a 70% COD removal were obtained. The sulphite level was reduced from 1,400 mg/l to 6 mg/l. They concluded that a full-scale activated sludge system for this high retention time would be very costly and that further studies should be concentrated on a treatment process comprising sulphite precipitation and anaerobic treatment.

Combined anaerobic/aerobic treatment of high strength CTMP effluent has been proposed by many researchers. Wilson et al. (1985) tested the feasibility of an aerated stabilization basin, an activated

sludge system including a secondary clarifier and a polishing basin, an anaerobic basin followed by an aerobic polishing basin and an anaerobic filter followed by an aerobic polishing basin. The wastewater tested was a combined NSSC and CTMP effluent from the Bathurst mill in New Brunswick. The BOD concentration of the influent was 1290 mg/l and the corresponding COD concentration was 2740 mg/l. Because of future mill water flow recycling these concentrations were estimated to double. It was concluded that the aerated lagoon with an overall 7 to 9 days retention time was able to produce a non-lethal effluent, the activated sludge basin with a 2.5 days retention time however, was unable to produce a non-lethal effluent. Nevertheless both aerobic systems were able to remove 80% BOD under normal summer conditions. Both high rate and low rate anaerobic systems did not achieve the targeted 80% BOD removal during the pilot trials. However, following a three to five day aerated basin both combined anaerobic/aerobic systems produced an effluent exceeding 95% BOD removal. The data showed that toxicity removal appeared to be dependent on hydraulic residence time with a total of six to seven days required to produce non-lethal aerobic effluent. Anaerobic treatment alone had only a small effect in reducing toxicity. As a result of this study it was concluded that a combined anaerobic/aerobic treatment system was feasible and worth further investigation. Wilson et al. (1988) then investigated, in 1986, three different anaerobic pilot processes consisting of a fluidized bed, a UASB and a contact basin, all followed by an aerated polishing basin. They concluded that the UASB pilot reactor performed best, with the result that a UASB followed by an aerated polishing basin was finally selected for the full scale installation at the Bathurst mill.

In a CTMP mill in Domsjoe in Sweden an anaerobic treatment plant followed by an aeration basin was chosen. Hultman and Hillstroem (1986) concluded that this was the cheapest solution for the "unbleached effluents" and provided a very efficient method to remove BOD.

Rintala and Vuoriranta (1988) treated a TMP effluent with a combined anaerobic/aerobic lab-scale treatment system in Tampere, Finland. The anaerobic system alone removed 60 to 70% COD, while the combined anaerobic/aerobic system was capable of removing 80 to 85% COD. The aerobic post

treatment using an activated sludge system produced effluent with stable quality, but it also included a reddish colour change. The change of the colour occurred also when anaerobically treated effluent alone was aerated for 30 minutes.

PAPRICAN investigated techniques for the improvement of effluent management at the Spruce Fall Power and Paper Company Ltd. integrated newsmill in Kapuskasing, Ont. A cost effective system had to be chosen for the mill. A high rate process was favoured because of restricted land availability. An activated sludge process was rejected, because although the degree of treatment and the operational reliability are usually high, the costs associated with aeration and the increased production of excess biological sludge are substantial. A pilot anaerobic process followed by an activated sludge system was investigated. Influent BOD ranged from 1100 to 2100 mg/l and influent COD ranged from 1900 to 4100 mg/l. Schnell et al. (1990) concluded that the anaerobic treatment alone produced insufficient removals of BOD and toxicity. Combined anaerobic/aerobic treatment gave a consistently high reduction in BOD resin and fatty acids. However, this required a total minimum HRT of 27 to 30 hours with the whole mill effluent. The effluent detoxification was inconsistent, due to lethal levels of non-ionized ammonia from nitrogen nutrient supplementation of the raw wastewater. The anaerobic high rate system had a considerable degree of operational risk, due to serious losses of excess sludge at high applied loading rates. Finally, Schnell et al. measured an increase in colour of 50-68% for the anaerobic system and 68-130% after aerobic treatment.

CHAPTER 3

METHODOLOGY

This chapter details the experimental methods used in this study. Section 3.1 specifies the equipment details, section 3.2 describes the operating procedures and section 3.3. outlines the testing procedures.

3.1 EXPERIMENTAL DESIGN

Initial operating experience including some quantitative analysis was obtained using a bench-scale RBC reactor obtained from the Civil Engineering Department at U.B.C. That 20 litre unit consisted of thirty four, 19.5 cm diameter polyethylene discs and was separated by baffles into two stages.

A more elaborate RBC unit was designed to allow for temperature control and rotational speed control. A schematic drawing of this rotating biological contactor is shown in Figure 3.1. The main design parameter used was the organic loading rate. After reviewing the literature (see section 2.2.1.3) the system was designed for an organic loading rate of 0.008 kg BOD/m^2/day. However, at this time the BOD_5 parameters had yet to be estimated. Special design consideration was given to the disc configuration. Because of the potential occurrence of excess biomass growth and possible bridging as described in section 2.2.1.2 and 2.2.1.4 glass discs were considered with a 1 inch spacing between them. The choice of glass as a material for the bio-discs arose from concerns related to the deformation of materials under elevated temperatures, i.e. it was aimed in this study to keep a liquid temperature in the trough as high as 30 to 35°C and maybe increase it up to 70°C for future thermophilic studies. At these temperatures most materials used for RBC lab-scale discs, such as

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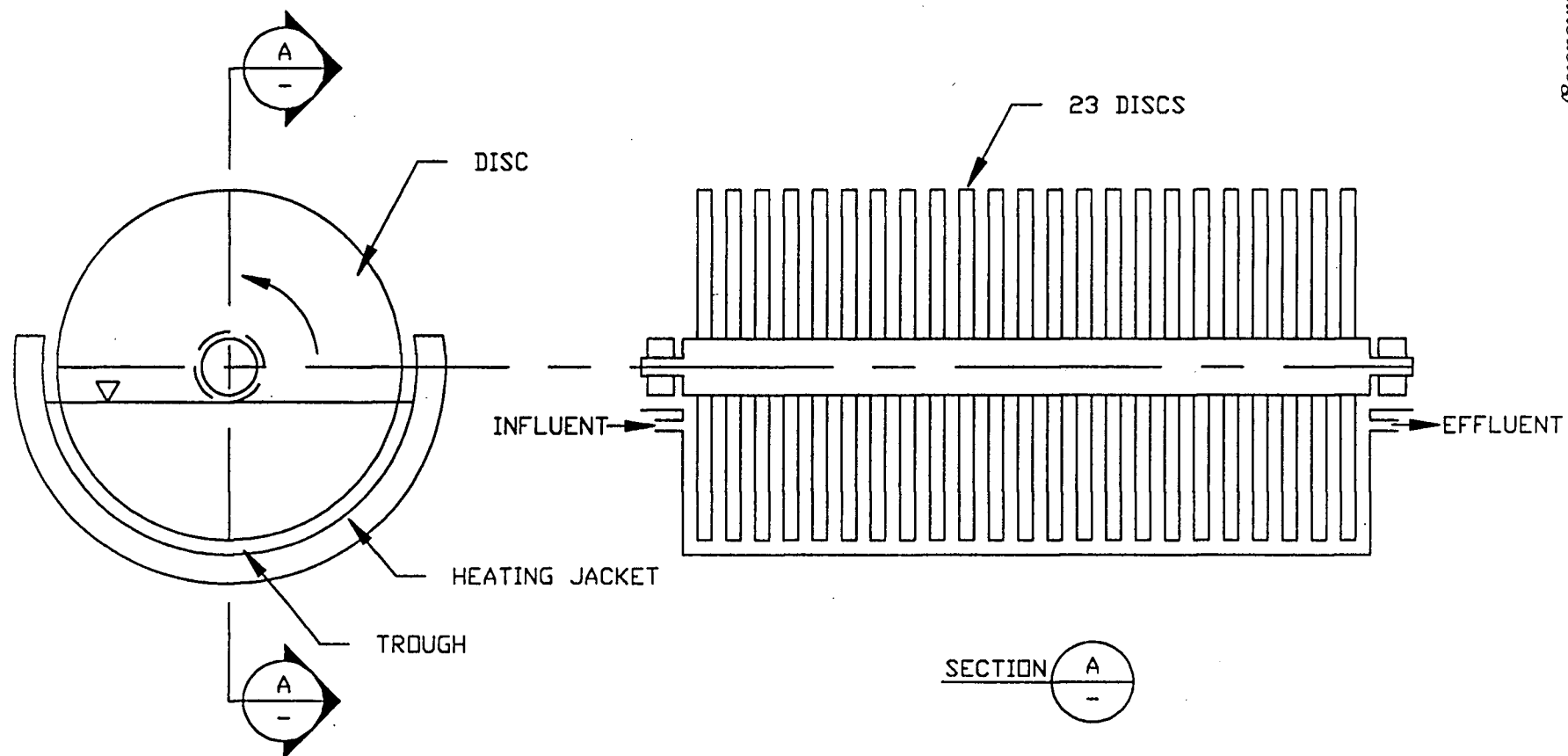
Fig. 3.1   Schematic drawing of the RBC lab-scale model

acrylic and polyethylene warp, which could result in easier bridging between some of the discs. The glass discs were sandblasted to give a rough surface enabling better biomass attachment. 1 inch spacing between the discs allowed for better observation of biomass growth and estimation of the biomass thickness during the runs. In order to allow for easy access into the trough for purposes of maintenance or taking grab samples a hydraulic jack attached with two levers to the shaft enabled easy lifting of the discs.

3.1.1 EXPERIMENTAL LAYOUT AND EQUIPMENT DETAILS

A schematic layout of the process is shown in Figure 3.2, where the elements of this experimental set-up are outlined.

Initially, a 14 litre acrylic reaction vessel rectangular in plan with a cylindrical bottom and a heating jacket spaced 1 inch (2.54 cm) apart was used. However, during run 1 leaks in the bio-reactor caused problems. These were caused by glueing problems and elevated temperatures in the waterbath. The majority of leaks were between the waterjacket and the bio-reactor. A stainless steel bio-reactor was built after run I. This 12 litre vessel measured 13 by 24 in. (32.5 by 60 cm). Twenty three, 10 inch (25 cm) diameter, glass discs were attached to a 3/4 inch (1.9 cm) diameter, stainless steel shaft. The total surface area of the discs was 1.89 m² and the total surface area including the wetted bio-reactor walls was 1.93 m². The shaft was 23 in. (57.5 cm) long. Individual discs were fitted to the shaft 1 inch (2.54 cm) apart, and the group of 23 discs was spaced 1.5 in. (3.8 cm) from each end of the shaft.

The shaft was connected, using a sliding stainless steel rod to allow for the lifting and lowering of the discs, to a 1/2 hp Dayton DC gear motor model 6Z417 used for rotation of the discs. The motor was connected to a Penta KB Power variable speed controller (CHE no. 3896). The discs were rotated at a constant tip speed of 0.31 m/s throughout the whole experiment.

A parallel to the disc shaft influent/effluent configuration was used, however, the option for a
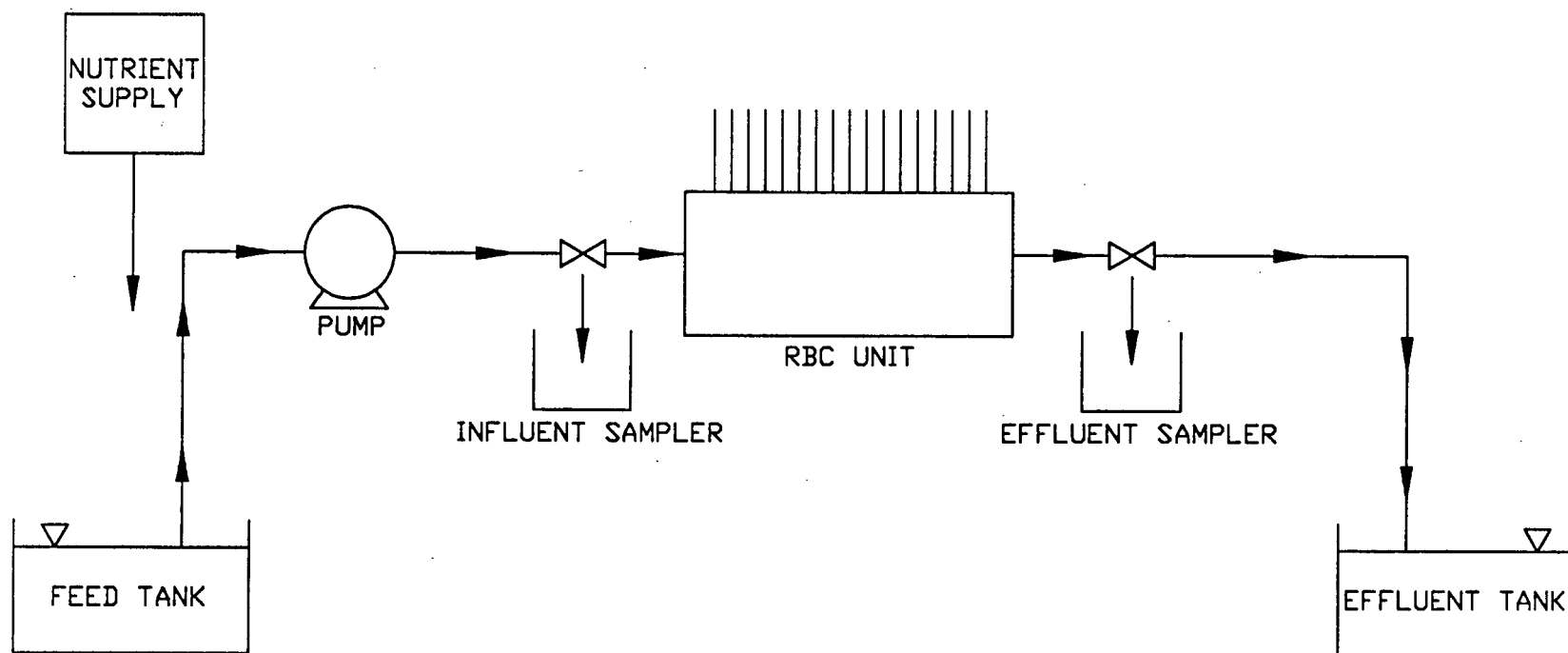
Fig. 3.2   Schematic lay-out and flowsheet of the laboratory experimental set-up
of the biological RBC treatment system

perpendicular inlet/outlet configuration was available. The feed was pumped into the reactor using a peristaltic, Masterflex, variable speed pump Model 7523-10 (CHE no. 3668E). A number 16 Masterflex pump head was used for this pump, requiring Masterflex tubing of 4 mm inner diameter. The effluent left the reactor through an effluent hole which was set 3.5 in. (9 cm) from the inner bottom of the vessel to ensure 40% submergence of the discs in the liquid.

For controlling the temperature in the RBC a Lauda constant temperature bath (CHE no. 1517) was used. 6 mm inner diameter Tygon tubing was utilized to connect the waterbath to the jacket of the RBC.

Thermometers where placed at each end of the reactor, i.e. of the inlet and outlet. The temperature of the liquid in the reactor was read manually every day.

3.2 OPERATING PROCEDURES

The entire experimental period lasted approximately 9 months. This period was sub-divided into a qualitative analysis period using the bench scale reactor, borrowed from the Environmental Engineering group of U.B.C.'s Civil Engineering Department, which lasted about 2 months, followed by runs I, II, III and IV, using the RBC equipment described above. Each run lasted between 21 and 23 days followed by 3 weeks of analytical evaluation for each run. Further, a 'sterile' run was attempted lasting 2 weeks, a hydraulic characterization experiment was conducted during 5 days and a 1 day start-up experiment running wastewater without the addition of biomass innoculum through the bio-reactor was performed.

3.2.1 WASTEWATER SOURCE

The wastewater used during this study was obtained from the QRP mill in Quesnel, B.C. Wastewater, in 1 m^3 containers, was shipped from the mill to the Pulp and Paper Centre at U.B.C. It was subsequently stored in 5 gallon plastic buckets in the laboratory cold room at 2°C.

3.2.2 SEEDING

Seeding of the borrowed RBC was undertaken by using seed sludge previously grown on sewage and CTMP wastewater. Five litres of a 50:50 mixture of raw sewage, obtained from a pilot scale activated sludge plant at the University of British Columbia and well adjusted CTMP sludge, obtained from an aerobic sequencing batch lab reactor treating CTMP effluent at the Pulp and Paper Centre at U.B.C., were added to the reactor. The MLSS concentration of the added sludge was approximately 15,000 mg/l. The reactor was then filled with a mixture of CTMP wastewater and deionized water, and operated in batch mode at a disc speed of 3 RPM. Additional air was supplied to the sludge with an aquarium air stone. Each day, for the next five days, the disc rotation and air supply were stopped and the 'mixed liquor' in the reaction vessel was allowed to settle. Approximately 2 litres of the supernatant was decanted and that removed volume was replaced with fresh CTMP wastewater. Supplemental N and P in the form of urea ($CO(NH_2)_2$) and phosphoric acid (H_3PO_4) at a conventional ratio of 100 BOD_5:5N:1P were added to the wastewater to ensure nutrient levels were adequate. After five days the batch mode was replaced by continuous feeding of CTMP effluent to the reactor at a flowrate resulting in a 5 day HRT and aeration was discontinued.

Seeding in the larger glass disc RBC was undertaken simply by adding 5 litres of acclimatized mixed liquor from the borrowed RBC diluted with 9 liters of deionized water to the acrylic trough unit and 7 litres of deionized water to the smaller stainless steel trough of a 50:50 mixture of CTMP wastewater diluted with deionized water. Immediately after, fresh wastewater was continuously fed to the reactor at the flowrate under investigation for the particular run.

3.2.3 OPERATION OF THE RBC

For each run only one parameter was changed to investigate its effect. For runs I, II and III the flowrate was changed resulting in a retention time of 2 days for run I, 1 day for run II, and 1.5 days

for run III. The temperature in the trough was maintained at 30°C for these three runs. Run IV was conducted by changing the temperature in the trough to 20°C at a retention time of 1.5 days. The 'sterile' run was performed at 1.5 days retention time and a temperature of 30°C, while the tracer test was undertaken at a 1.5 day retention time and a temperature of 20°C in the trough.

Runs I, II , III and IV were done using the following procedure: Every day the time, the influent volume, the effluent volume, the temperature, the D.O. and pH were measured and recorded. On top of these measurements the oxidation reduction potential was measured daily during run III and the relative humidity was measured daily during run IV.

Dissolved oxygen, pH and oxidation reduction potential were measured along the flow path at three different places, the beginning, the midpoint and the end within the trough. In addition, pH and ORP where measured on influent and effluent samples.

The feed to and the effluent from the RBC were stored in calibrated plastic tanks (each with a capacity of 20 litres). The feed tank was refilled every one to two days with QRP, CTMP wastewater, previously stored at 2°C in the laboratory cold room. Nutrients were added directly into the feed tank by pipetting. To ensure that N and P would not be limiting the conventional concentration ratio $BOD_5:N:P = 100:5:1$ was used throughout the experiment. The feed plastic tank had to be cleaned every day to minimize any bacterial activity in the feed tank itself prior to RBC treatment.

After each run the inlet, outlet and sampling tubing were cleaned or if necessary replaced. Biomass which tended to bridge between the discs was removed, as well as excess sludge accumulating in the tank.

For the attempted 'sterile' runs the same procedure as for runs I to III were used. However, dissolved oxygen, oxidation reduction potential and relative humidity were not measured. 50 mg/l of mercuric chloride ($HgCl_2$), which according to Gledhill (1975) would sterilize the solution, were mixed in a large bucket with 60 litres of CTMP wastewater. Each run was carried out lasting two theoretical hydraulic retention times.

Prior to the start-up run experiment, using CTMP wastewater without the addition of microorganism innoculum, the discs and the reactor were cleaned. The trough was then filled with the raw CTMP effluent at the same setting as for run III. Measurements were taken and recorded, these included BOD_5 and MLVSS, dissolved oxygen, pH and temperature readings, taken every half hour.

The tracer test was conducted in order to obtain information on the residence time distribution and flow regime in the RBC reactor. This was accomplished by employing a step change of sodium chloride tracer concentration to the reactor and measuring the tracer concentration in the effluent. The experiment was performed following run IV and none of the parameters were changed. A large 20 IMP gallon container was used to mix enough raw CTMP wastewater to last for the whole experiment. The background conductivity of wastewater was measured and an amount of sodium chloride about 6 times the background conductivity was added to the feed bucket, measured and recorded. At time zero conductivity measurements of the effluent at the sampling port were taken and recorded every half hour. Later, during the experiment, measurements were recorded every hour, every two hours, and finally towards the end every 4 to 6 hours. The conductivity in the feed bucket was remeasured every day during the five days of the run.

3.2.4 SAMPLING PROCEDURES

Sampling was carried out at the influent and effluent sampling ports, except for the MLSS which were sampled in the reactor vessel. These ports were located 6 to 8 cm away from the bio-reactor (see Figure 3.2). For the first two weeks effluent samples for BOD_5 and COD analysis were taken daily, and feed samples were taken for every new bucket used from the cold storage. It was assumed that after two weeks steady state was reached (Fry et al., 1982; Tringh, 1981; Srinivasarghavan et al., 1980; Ahlberg and Kwong, 1974; Lue-Hing et al., 1974). During this time until the end of the experiment samples for BOD_5 and COD analysis were withdrawn every two days. In addition to the regular BOD_5

and COD samples TKN, TP, and solids tests of the inlet, outlet and in the trough (for MLSS) were carried out once a week during the last 2 weeks of each run.

For runs II and III additional samples of the influent and effluent were withdrawn for analysis of acetic acid and sulfur compounds. Acetic acid samples were taken every 3 days and sulfur samples were taken twice during each run at the same time the solids samples were withdrawn.

Two BOD_5, COD, acetic acid and sulfur samples were taken during the 'sterile' run, at the beginning and end of the second HRT.

The procedure for taking MLSS samples involved lifting the discs out of the vessel using a hydraulic jack. The liquor was then mixed by stirring and a grab sample was withdrawn.

3.3. TESTING PROCEDURES

All filtrations of the samples during this study were done using Whatman No. 4 filter, except during solids analysis in which Whatman 934-AH glass fibre filters were used. Samples for TKN, total phosphorus and acetic acid were preserved with concentrated sulfuric acid (pH < 2.0) in accordance with the Standard Methods (A.P.H.A., 16th ed., 1985). If samples were not filtered prior to testing, the sample content was allowed to settle and the supernatant was withdrawn for analysis.

3.3.1 BIOLOGICAL OXYGEN DEMAND (BOD_5)

The determination of 5-day BOD was done immediately after sampling in accordance with the Standard Methods (A.P.H.A., 16th ed., 1985).

3.3.2 CHEMICAL OXYGEN DEMAND (COD)

The samples were preserved by freezing and analyzed in accordance with the Standard Methods (A.P.H.A., 16th ed., 1985) using the open reflux method. However, for run 1 the Hach DR/2000 spectrophotometer was used and the reagents were prepared as outlined in the Standard Methods

(A.P.H.A., 16th ed., 1985) for the closed reflux, colorimetric method.

3.3.3 DISSOLVED OXYGEN (D.O.)

Dissolved oxygen concentrations in the bio-reactor and for BOD_5 analysis were measured manually by using a Model 54 ARC dissolved oxygen meter (Yellow Spring Instrument Co.). The membranes and electrolytes in the probes were replaced once a week on average. Prior to taking measurements the probe used in the bio-reactor was calibrated with air, while the BOD probe was calibrated with distilled water. The exact procedures are outlined in the manufacturer's manual and the Standard Methods (A.P.H.A., 16th ed., 1985).

3.3.4 pH

The pH was measured with a Cole Palmer Microcomputer pH-meter Model 05669-20 with glass and reference electrode combined in a single probe. The meter was standardized against pH 10 and pH 7 buffer solution as outlined in the Standard Methods (A.P.H.A., 16th ed., 1985).

3.3.5 OXIDATION REDUCTION POTENTIAL (ORP)

ORP measurements were made using a Broadley James Corporation's Ag/AgCl probe. The probe was connected to a Orion Research digital ion analyzer Model 601A. The probe was calibrated in accordance with the manufacturer's manual.

3.3.6 RELATIVE HUMIDITY (RH)

The relative humidity in the lab was measured because of the high evaporation of the wastewater in the bio-reactor experienced during the experiment. A humidity probe HP1 was used for this purpose, connected to a Fluke 77 multimeter. The RH probe was calibrated weekly as outlined in the manufacturer's instruction manual.

3.3.7 CONDUCTIVITY MEASUREMENTS

Conductivity measurements were performed using a Jenway 4020 Conductivity meter. The programmable conductivity meter was equipped for print interval modes. The printout parameter consisted of date/time, sample number, conductivity and temperature readings. The equipment was operated and calibrated according to the manufacturer's operating manual (4020/REV B).

3.3.8 TOTAL KJELDAHL NITROGEN (TKN)

Samples were digested in a Technicon block digester 40 and analyzed according to Technicon Block digester instruction manual (1974).

3.3.9 TOTAL PHOSPHORUS

The samples were first subjected to acid digestion using a Technicon block digester 40, prior to analysis by Technicon Auto-analyzer II, according to the Technicon Industrial Method No.327-73W (1974).

3.3.10 SOLIDS

All TS, VS, TSS, VSS were examined to see the contribution of solids in the wastewater (TS,VS) initially and after RBC treatment, as well as the contribution of biomass (VSS) before and after RBC treatment.

(a) TOTAL SOLIDS (TS)

A known sample was put into a crucible and oven dried for a minimum of 1 hour at 104°C, as outlined in the Standard Methods (A.P.H.A., 16th ed., 1985).

(b) VOLATILE SOLIDS (VS)

This was determined by igniting the solid obtained in 3.3.10 (a) at 550°C, as outlined in the Standard Methods (A.P.H.A., 15th ed., 1985).

(c) TOTAL SUSPENDED SOLIDS (TSS)

This was done by vacuum filtering a known volume of sample through a pre-washed and oven dried Whatmann 934-AH glass fibre filter and oven drying for a minimum of 1 hour at 104°C, as outlined in the Standard Methods (A.P.H.A., 16th ed., 1985).

(d) VOLATILE SUSPENDED SOLIDS (VSS)

This was determined by igniting the nonfilterable solids obtained in 3.3.10 (c) at 550°C, as outlined in the Standard Methods (A.P.H.A., 16th ed., 1985).

(e) MIXED LIQUOR VOLATILE SUSPENDED SOLIDS (MLVSS)

This was determined as described in 3.3.10 (c) and (d).

(f) BIOFILM DRYING

Biofilm was scraped off the disc at the end of run 1 and run 3. The total volume and weight were recorded. A known sample was then taken and was proceeded as described in 3.3.10 (c) and (d).

3.3.11 VOLATILE FATTY ACIDS (VFA)

The volatile fatty acids measurements were done using a computer-controlled Hewlett-Packard 5880A gas chromatograph, equipped with a flame ionization detector (FID) and using helium as the carrier gas. The glass column (0.91 m long with a 6 mm external diameter and a 2 mm internal diameter) was packed with 0.3% Carbowax/0.1% H_3PO_4 on Supelco Carpopak C (supplied by Supelco Inc.). The

column was conditioned according to the procedure outlined in the Supelco Bulletin 751E (1982).

Experimental conditions for the chromatograph were as follows:

Injection port temperature = 150°C

Detector port temperature = 200°C

Isothermal oven temperature = 120°C

Flow rate of carrier gas (helium) = 20 ml/min.

Volatile fatty acids analysis included acetic, propionic and butyric acids with quantification done by the external standard methods , using reagent grade standards. However, concentrations propionic and butyric acids were < 0.01% compared to acetic acid concentrations and often not detected by the analyzer.

3.3.12 SULFUR

(a) SULFATE (SO$_4$)

Sulfate analysis were done by using the Hach DR/2000 spectrophotometer as well as the Hach reagents specific for the sulfate test. The analysis was performed in accordance with the Hach Procedure Manual (1988).

(b) SULFITE (SO$_3$)

Sulfite tests were conducted using a back-titration of the method given in the Standard Methods (A.P.H.A., 16th ed., 1985). This allowed for a sharper end-point.

(c) SULFIDE (S^{2-})

Sulfide analysis were done by using the Hach DR/2000 spectrophotometer as well as the Hach reagents specific for the sulfide test. The analysis was performed in accordance with the Hach Procedure Manual (1988).

3.3.13 QUALITY CONTROL

Quality control was performed on all the chemical analysis done.

Standard solutions with known concentrations were tested in accordance with the instrument procedure manuals and the Standard Methods (A.P.H.A., 16th ed., 1985). In the case of BOD_5 and COD analysis two different U.S. EPA samples (no. 3405 WP 1088, Batch 823 and Batch 860) with a know BOD_5 and COD concentration were tested.

3.3.14 MICROBIOLOGY

A solid medium of glucose agar in a petri dish was supplied from the Microbiology department at U.B.C. for determination of mixed bacterial cultures. A sterile loop was used to streak the plate with the wastewater sample under investigation. Three replicate plates were used for each sample. The plates were then incubated for 48 hours at 35°C.

3.3.15 STATISTICS AND GRAPHICAL PRESENTATION

The data was processed using the software Lotus, release 2.2. The graphical solutions and linear regressions were done using Grapher (version 2) from the Golden Software, Inc., Golden, Colorado. The three dimensional graphs were done using Surfer (version 4.15) from the Golden Software, Inc., Golden Colorado. The constants for the BOD curve were determined using the least square curve fitting program from the NAG Fortran Library (function EO4FDF) and the curve fitting for the flow characterization was done using the numerical analysis program Polymath from Cache Corporation, Austin, Texas.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the bench scale experiments conducted in this study are detailed and discussed in this chapter. Experimental results of the four individual runs are presented in section 4.1. Data analysis and discussion of these four runs are presented in section 4.2. Finally, section 4.3 outlines an attempted 'sterile' run and subsequent tests to reveal some problems related to this experiment, as well as a tracer test done to determine the residence time distribution of the RBC reactor.

4.1 RESULTS

The daily logs from runs I, II, III, and IV and the corresponding raw data are listed in Appendices I, II, III, and IV respectively.

4.2 DISCUSSION

Data from the experiments are shown as time plots in what follows. Most of these graphs plot various information for all four runs on one page. They are plotted in the order in which the runs were performed, *ie* from left to right run I (HRT=2 days) and run II (HRT=1 day), followed below by run III (HRT=1.5 days, Temp.=32°C) and run IV (HRT=1.5 days, Temp.=20°C). Any bargraphs and tables which follow show values of parameters averaged after 10 days of running the system for each run when steady state response was assumed. With run IV data was measured only after 10 days of operation.

4.2.1 CHARACTERIZATION OF POLLUTANTS

4.2.1.1 CHARACTERISTICS OF QRP CTMP WASTEWATER

DATA ANALYSIS: Table 4.1 presents a summary of QRP, CTMP wastewater characteristics as selected from the literature which are then compared to the measured values of the raw wastewater (Appendices I-IV, raw data) used in this study. Four different batches of the QRP CTMP wastewater have been used, one per run, throughout this work. The values for the characteristics have been averaged over all four runs. The BOD_5/COD ratio was 0.42 and compared well with the other studies. This indicates that any biological system alone will not be capable of removing all of the organic matter from this CTMP effluent. The pH was lower than reported in the studies from Servizi and Gordon (1986) and Beak Consultants Ltd. (1986).

Measured data of the raw wastewater differed for each batch. Table 4.2 shows wastewater characteristics data for the four individual batches used during this study.

DISCUSSION: The values of this study (Table 4.1) correlate well with literature values, considering that the mill supplying the wastewater has gone through process changes during the past years. The normal operating pH range for the CTMP stock is 6.3 - 6.8 (Thakore et al., 1987), the present observations are somewhat lower.

Measured values for individual batches (Table 4.2) indicate that BOD values were highest during run II and IV and pH values were lowest during run I and VI. COD data from run I do not compare very well to the three other runs. A colourimetric method (see section 3.3.2) was used for COD measurements during run I. Problems with this method were encountered because of interferences caused by particles and precipitates. Another problem with this method was the underestimation of measurements at high COD concentrations which are said to be typical for the colourimetric method. COD values from run I do not compare very well to literature values and to COD analysis done by other researchers on the same raw QRP, CTMP effluent.

Table 4.1 Comparison of CTMP Wastewater Characteristics
from the Quesnel River Pulp Co.

SOURCE		Beak Consultants Ltd., 1986	Habets and de Vegt, 1990	Kennedy et al., 1990	Cornacchio and Hall, 1988	Servizi and Gordon, 1986	This study
COD (mg/l)	Range			5000 – 9000	3400 – 8500		6750 – 8600
	Average	8180	7200				7960
COD(soluble) (mg/l)	Range			3000 – 6000			5800 – 7450
	Average						6660
BOD_5	Range				1549 – 4500		2500 – 4550
	Average	2920	3100			3302	3310
BOD_5/COD	Range				0.30 – 0.45		
	Average	0.36	0.43				0.42
Acetic Acid (mg/l)	Range	400 – 800		500 – 1000			383 – 492
	Average						436
Sulfate (mg/l)	Range				254 – 300		430 – 470
	Average	300					445
Sulfite (mg/l)	Range				100 – 300		56.0 – 69.5
	Average	0					61.5
TKN (mg/l)	Range						16.2 – 16.4
	Average	minimal				28	16.3
Phosphorus total(mg/l)	Range						2.7 – 6.1
	Average	5.0				2.2	4.0
TSS (mg/l)	Range			1000 – 1600			900 – 3600
	Average	2200	400		220	221	1480
VSS (mg/l)	Range			700 – 1400			300 – 1000
	Average						700
pH	Range						5.37 – 6.55
	Average	7 – 8				7.15	6.11

Table 4.2 Comparison of CTMP Wastewater Characteristics of Individual Batches Used for Runs I, II, III, and IV.

SOURCE		Run I	Run II	Run III	Run IV
COD (mg/l)	Range	3840 − 4920	7300 − 8500	6750 − 8600	7250 − 8500
	Average	4600	7970	7960	7960
BOD(soluble) (mg/l)	Range		2350 − 4450	2350 − 2900	
	Average		3400	2520	
BOD$_5$	Range	2600 − 3450	5400 − 2600	2500 − 3900	2900 − 4300
	Average	3010	3690	3025	3530
BOD$_5$/COD	Range				
	Average	0.65	0.46	0.38	0.44
Acetic Acid (mg/l)	Range		383 − 463	421 − 492	
	Average		422	449	
Sulfate (mg/l)	Range		430 − 440	440 − 470	
	Average		435	455	
Sulfite (mg/l)	Range		61.5 − 69.5	56 − 59	
	Average		65.5	57.5	
TKN (mg/l)	Range				
	Average	16.3	16.4	16.2	
Phosphorus total(mg/l)	Range				
	Average	2.69	3.0	6.12	
TSS (mg/l)	Range		4850 − 5000	900 − 1100	900 − 1000
	Average	3600	4925	1000	950
VSS (mg/l)	Range		800 − 900	900 − 1000	
	Average	250	850	950	900
pH	Range			6.15 − 6.55	5.37 − 5.70
	Average	5.8	6.42	6.37	5.56

4.2.1.2 BOD CURVE

OBJECTIVE: To find out if the concentration of nitrogen in the wastewater is present at a level were nitrifying bacteria compete with the carbonaceous organism for available oxygen.

PROCEDURE: BOD tests were done as described in section 3.3.1. Enough BOD bottles were prepared and incubated to read the D.O. daily for 30 days. The test was done from June 20, 1990 to July 10, 1990 and repeated on July 3, 1990 until August 2, 1990.

RESULTS: See Figure 4.1

DISCUSSION: The biochemical oxygen demand is equal to the amount of dissolved oxygen which is consumed by a substrate incubated for a specific length of time at 20°C. The BOD determined after a 5-day incubation period is the most common. Five days is not long enough for interference by slow growing bacteria which is exerted only after 6 to 10 days. The presence of nitrogenous oxygen demand can be determined from such a BOD curve as it appears on the graph like a second stage curve superimposed on the original curve. No nitrogenous interference was found in the QRP wastewater. Figure 4.1 shows that the BOD curve exhibits first order behaviour.

$$y(t) = K(1 - e^{-t/\tau})$$

where $y = BOD_5$

$t =$ time

$K =$ steady-state gain $= 5600$ mg/l

$\tau =$ time constant of process $= 5.6$ days

Figure 4.1 indicates that the BOD_5 is between 60 and 65 percent of the ultimate BOD and oxidation is more or less complete in 18 to 20 days. Metcalf and Eddy (1979) state that within a 20-day period, the oxidation of sewage is about 95 to 99 percent complete, and in the 5-day period used for the
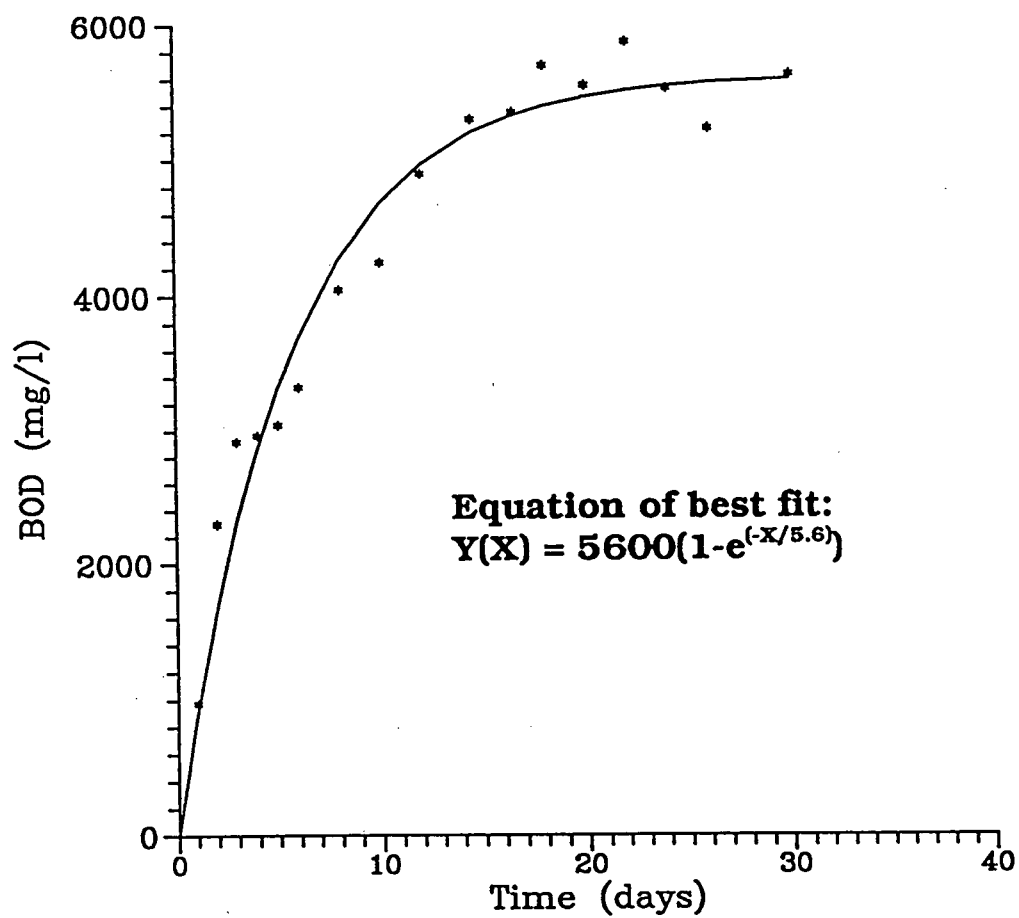
Figure 4.1   BOD curve.

BOD$_5$ test, oxidation is from 60 to 70 percent complete. Therefore, the rate of oxidation of the CTMP wastewater is comparable with that of sewage.

4.2.3 EVAPORATION

DATA ANALYSIS: Since most of the experiments were conducted at approximately 30°C in a device which exposes a thin film of liquid to the air over an extensive surface, a lot of evaporation occurred. The amount of this evaporation had to be quantified. Figure 4.2 shows the effects of such evaporation during the four runs. Runs I,II, and III were all conducted at temperatures ranging from 30 to 34°C, but at different HRT's. The evaporation data from run I (HRT=2 days) were erratic. This was caused by leakage of water from the waterjacket into the bio-reactor. During the time when there were no leaks, evaporation would go as high as 90%, however it averaged 74%. During run II (HRT=1 day) evaporation slowly increased from 62% to 90% at the end of run II and averaged 78%. Run III (HRT=1.5 days) showed a constant evaporation throughout the run of 87% average. Following these three runs, run IV (HRT=1.5 days) was conducted by lowering ΔT (temperature difference between wastewater in the trough and room air temperature). It resulted in a much lower average evaporation of 29%.

The results of Figure 4.3 for run IV show the effects of relative humidity on evaporation while ΔT was almost zero. As expected, when the relative humidity in the room went up less water was evaporated from the RBC.

DISCUSSION: Evaporation of water in the RBC is a function of available surface area, volume to surface area ratio, mixing, temperature difference (ΔT), and relative humidity. A lot of water evaporates from the surfaces of the discs which carry a thin film of liquid on the surface of the layer of biomass attached to the discs. For this small, lab-bench RBC the trough volume to disc surface area ratios were 0.00074 m for the 14 litre vessel used for run I and 0.00063 m for the 12 litre vessel used during run II to IV. In these lab scale RBC's the discs are usually flat, whereas in full scale units
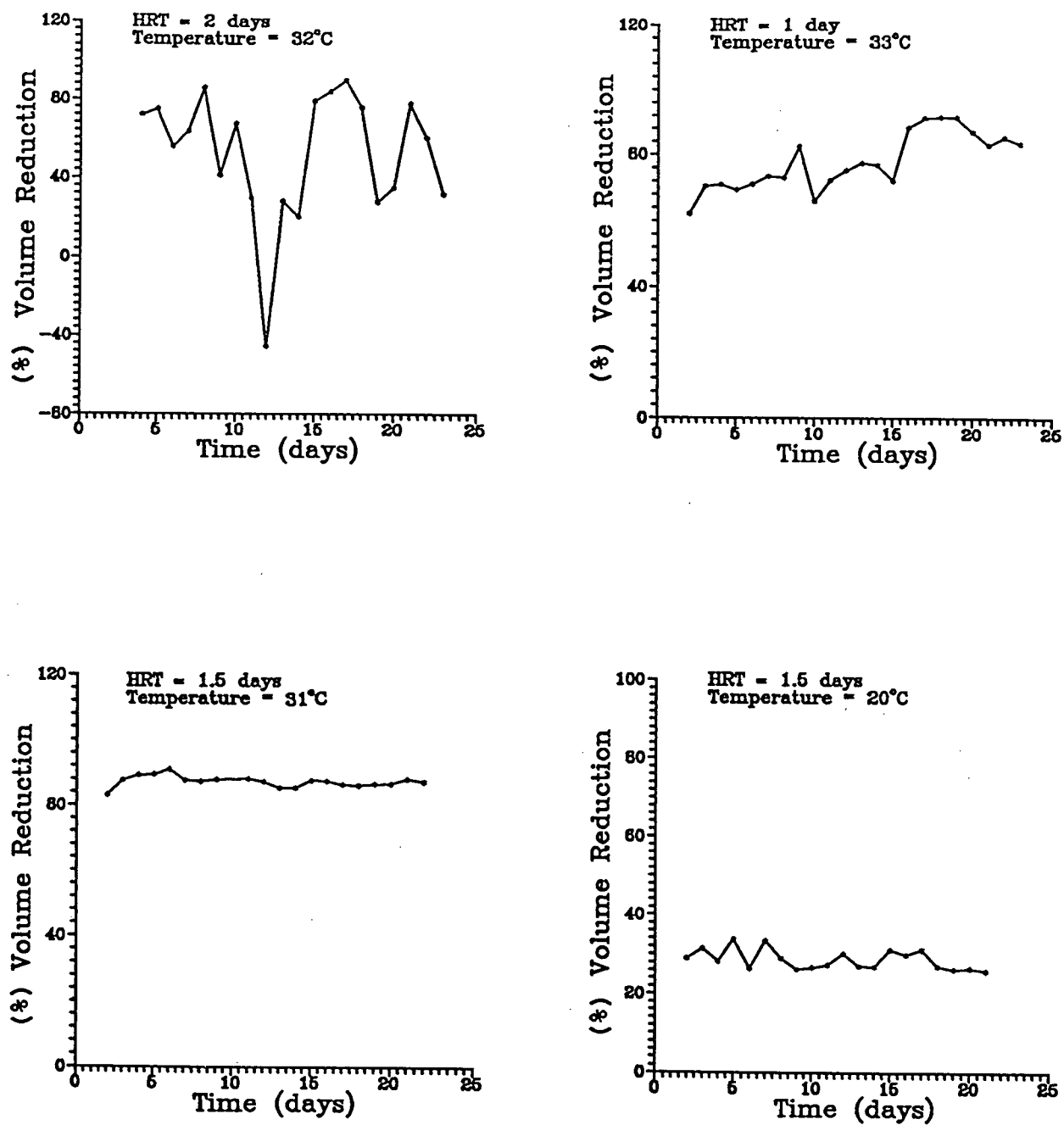
Figure 4.2   Percent volume reduction due to evaporation in runs I
            to IV.
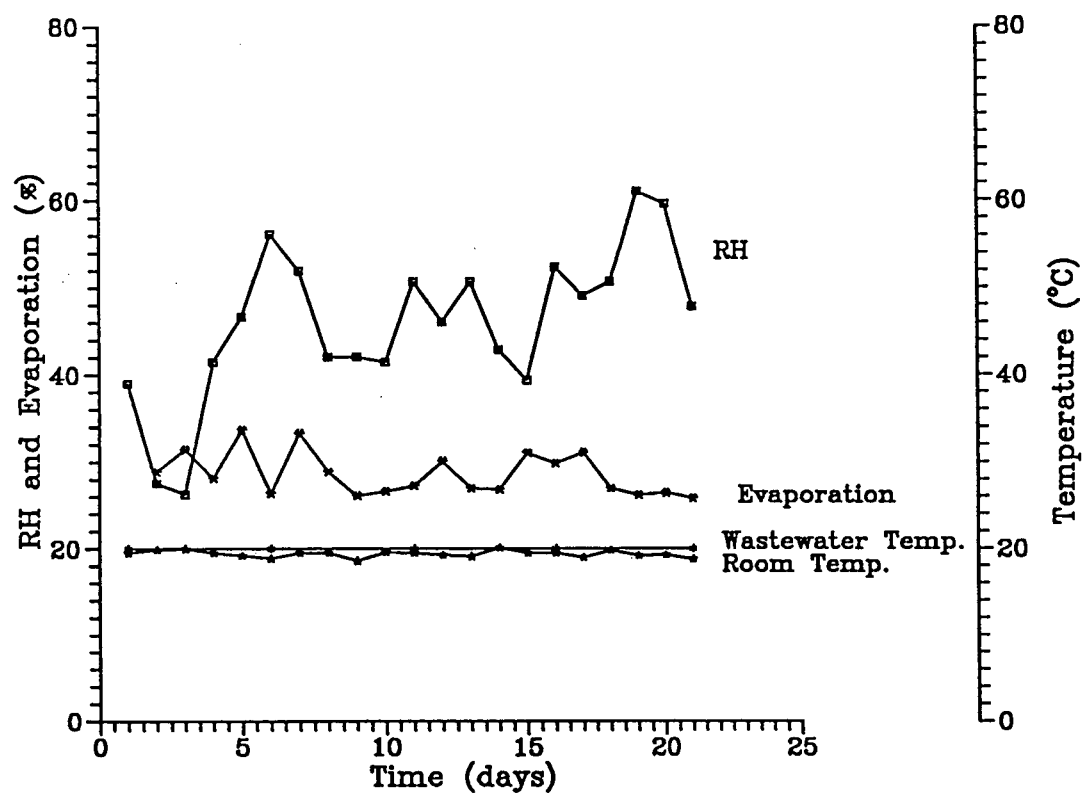
Figure 4.3   Effects of relative humidity on evaporation at low ΔT during run IV.

extended surfaces are used, which increase the area by 70 to 150%, giving a lower volume to surface ratio (Autotrol, 1978). Disc rotation tends to cause turbulence in the trough wastewater, which facilitates mass transfer of water from the trough liquid surface to the air. Run I was performed during July/August 1990. The temperature in the room at that time ranged between 24 and 28°C resulting in a ΔT ranging from 4 to 8°C; the relative humidity ranged from 30 to 45%. Run II (HRT=1 day) was started up during mid-November 1990 with the new stainless steel vessel which had a 15% smaller volume to surface area ratio. The temperature difference was approximately 11 to 16°C, considering a constant room temperature of 16 to 20°C. Evaporation started to increase during this run which lasted until the beginning of December 1990. The relative humidity decreased gradually from 35% to 14%. By the middle of November the outside temperature started to drop and the relative humidity began to decrease. The temperature inside the room was at a constant level of 20°C during the day, however, temperatures dropped to 12 to 15°C during the night, when heating was lowered in the building. During run III (December 7, 1990 - December 28, 1990) a constant low relative humidity ranging from 14 to 18% and a ΔT ranging between 9 and 11°C resulted in a constant high evaporation of 87%. By decreasing the temperature in the bio-vessel during run IV (May 1, 1991 - May 21, 1991) the water loss was decreased by 58% of run III.

To summarize these results, the following general observations were made based on the evaporation data:

1. With the dependent parameters, surface area, volume to surface area ratio, and mixing kept constant, ΔT and %RH were major parameters affecting the water loss in the RBC during this study.

2. The fact that run I was performed during the summer, while run II and III were done at the end of fall into the winter, and finally run IV was done in the spring, indicated that seasonal changes can have a major impact on evaporation when running an RBC system inside a temperature controlled building.

3. Since many of the parameters measured in this study are concentrations, corrections had to be made because the evaporation of solvent water tends to increase the concentration of things like BOD and COD.

4.2.4 ORGANIC REMOVAL

Flowrate of wastewater to the RBC is one factor in determining the rate of organic addition and defines the retention time of the liquid in the RBC system. The effect of flow rate was studied at 7 litres/day (run I), 12 litres/day (run II) and 9 litres/day (run III). Run III and run IV were conducted at the same flowrate but at different wastewater temperatures of 31°C and 20°C respectively. Since hydraulic retention time (HRT) equals RBC volume divided by influent flowrate these flowrates are equivalent to HRT's of 2 days, 1 day and 1.5 days.

Graphs for percent organic removal, organic removal rate and percent of organic removal vs. loading rate (Figures 4.4 to 4.11 and Figure 4.14) were corrected for water loss.

4.2.4.1 BOD$_5$ REMOVAL

DATA ANALYSIS: Figure 4.4 shows plots of percent BOD removal over the time periods during which each of the four experiments were run. Figure 4.5 shows BOD removal rates (mg/hour) during the four runs. Since the active disc surface area was constant in all of these runs at 1.75 m^2 the rates shown can be put on a per unit disc area basis by dividing by 1.75.

For run I (HRT=2 day) BOD removals ranged from 62 to 98% and averaged 86%, while the BOD removal rates ranged from 429 to 1915 mg/hr and averaged 817 mg/hr. For run II (HRT=1 day) BOD removals ranged from 70 to 91% and averaged 77%, while BOD removal rates ranged from 902 to 1756 mg/hr and averaged 1432 mg/hr. For run III (HRT=1.5 days) BOD removals ranged from 77 to 86% and averaged 83%, while BOD removal rates ranged from 787 to 1373 mg/hr and averaged 1001 mg/hr. For run IV BOD removals ranged from 64 to 77% and averaged 70%, while BOD
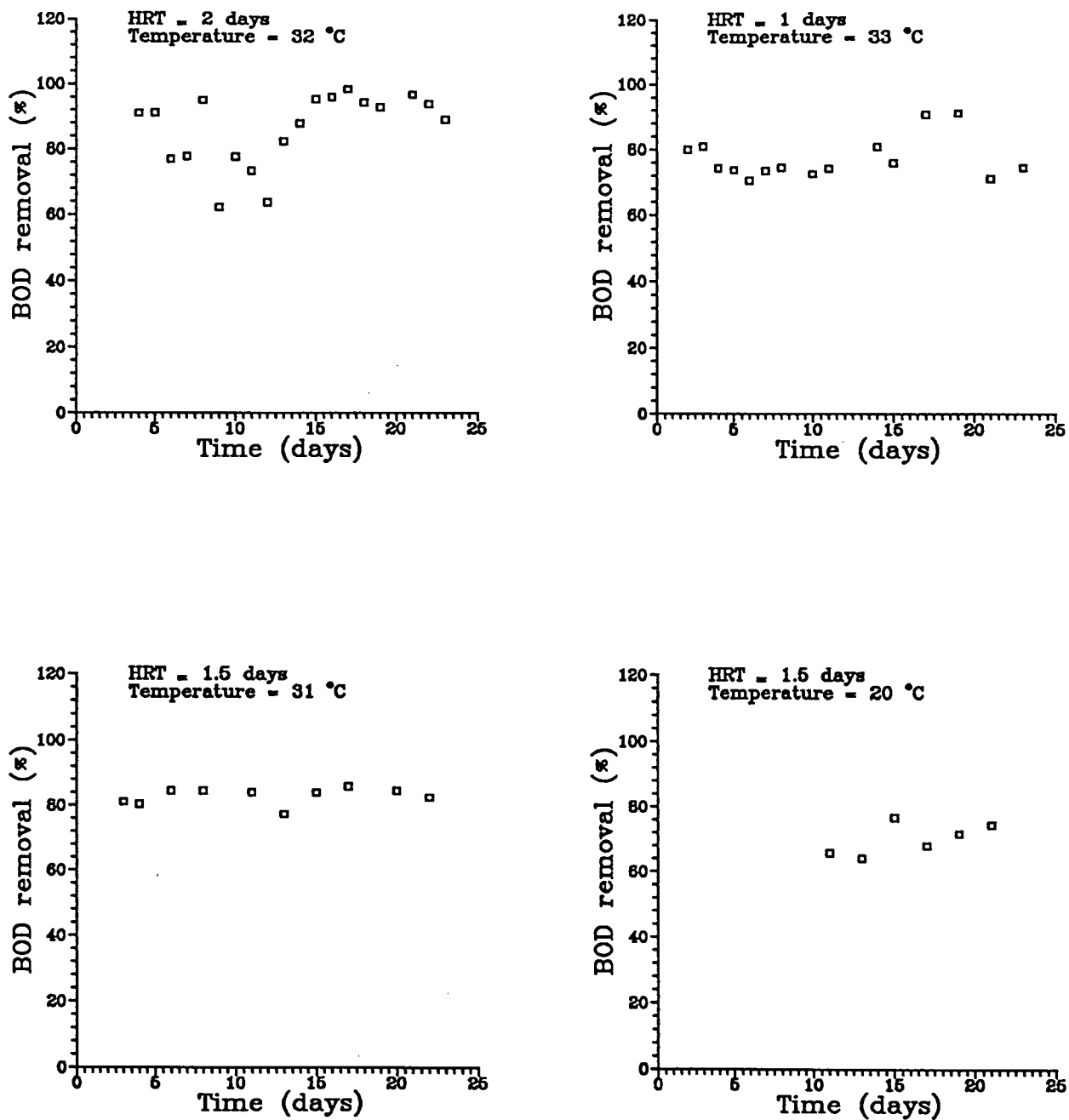
Figure 4.4   Percent BOD removed during runs I, II, III and IV.
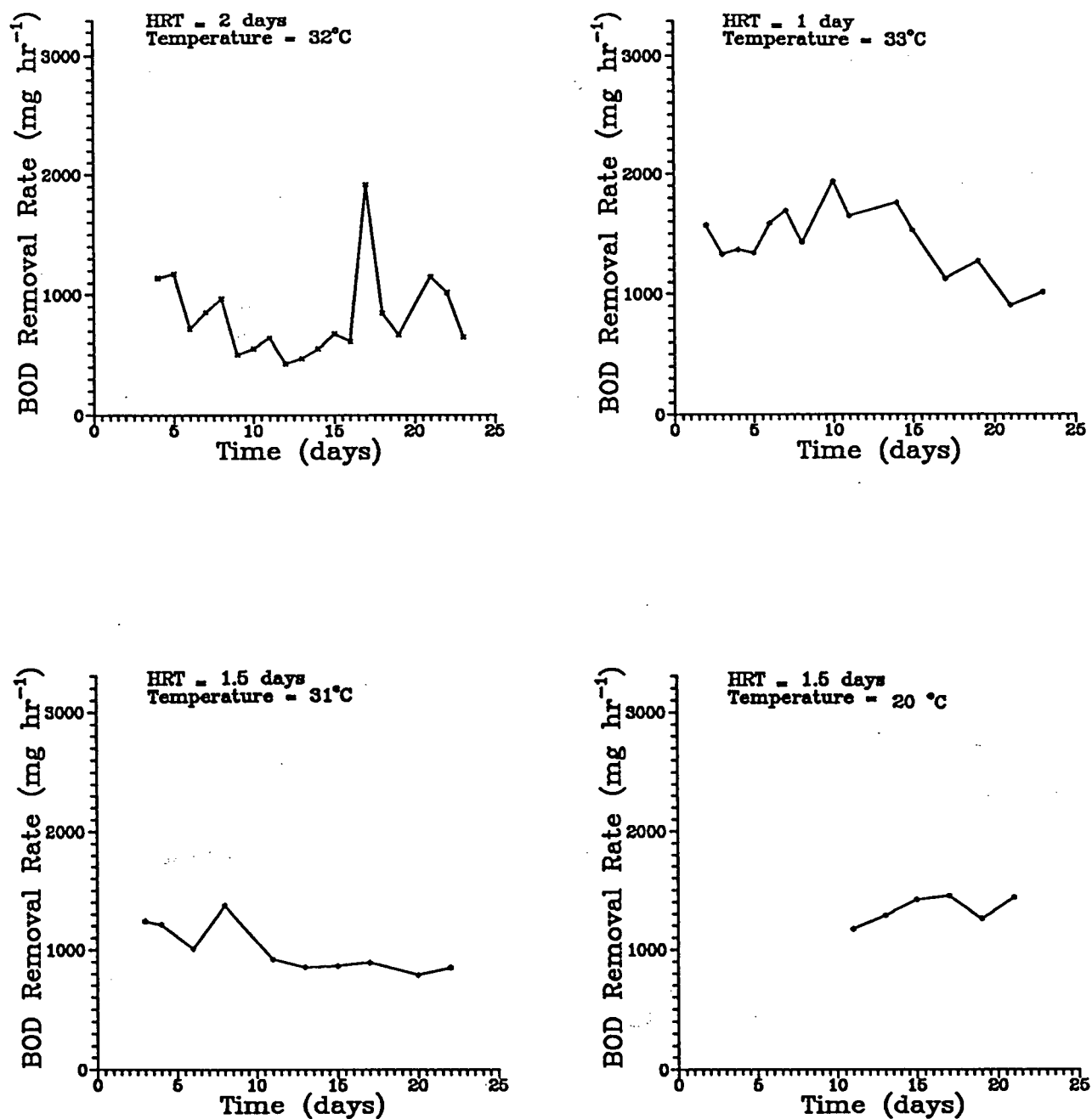
Figure 4.5 BOD removal rates during runs I, II, III and IV.

removal rates ranged from 806 to 1073 mg/hr and averages 901 mg/hr. Figure 4.6 shows average BOD$_5$ percent removal versus HRT and Figure 4.7 shows average BOD$_5$ removal rates versus HRT for runs I, II and III.

DISCUSSION: BOD analysis were started from day 2 and it appears from Figure 4.4 (runs I to III) that the system was at steady state during the experiment.

Figure 4.4 and Figure 4.6 indicate that the average percent BOD removed slightly decreased with an increase in flowrate (consequently a decrease in HRT) and decreased with a lower wastewater temperature at a constant flowrate (runs III and IV).

Figure 4.5 shows that for an increase in flowrate (decrease in HRT), BOD removal rate increased, while the percent BOD removed decreased. Rate of BOD (COD) removal can be affected by several factors BOD (COD) concentration, organic loading rate, disc speed, temperature, MLVSS concentration, D.O. concentration, nutrient concentration, etc.

For runs I, II, III and IV the disc speed was constant so this can be eliminated. Runs I, II and III were at constant temperature, more or less, so this can be eliminated as a factor for these three experiments.

The organic loading rate increased with increasing flowrate (see section 4.2.4.4) it was lowest in run I at 0.0128 kg BOD/m^2/day average and increased in run III to 0.0166 kg BOD/m^2/day average and was highest during run II at 0.0257 kg BOD/m^2/day average, so perhaps organic loading rate explains the difference in BOD removal rate which was lowest in run I and increased from run III to run II. Furthermore, Figure 4.12 shows the actual levels of BOD (COD) concentrations in the trough of the RBC. BOD levels were higher in runs II and III than in run I. However there is not much difference in BOD concentration between runs II and III, yet run III has a lower removal rate than run II.

Similar remarks apply to COD removal rate although this was not constant throughout runs II and III.
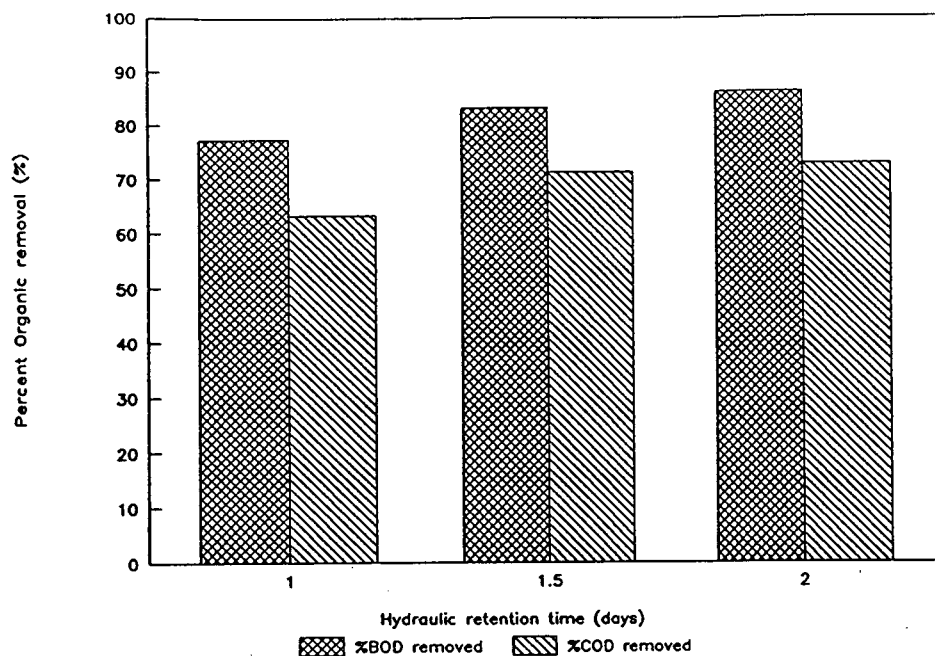
Figure 4.6 Effect of hydraulic retention time on %BOD and %COD removal.
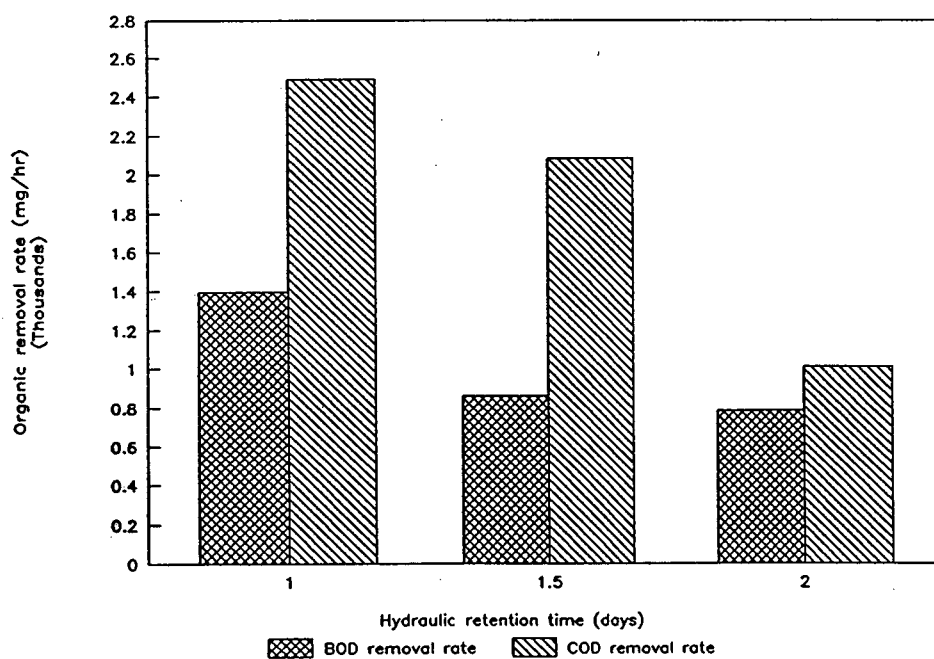
Figure 4.7 Effect of hydraulic retention time on BOD and COD removal rates.

Run I had a higher D.O. concentration (see section 4.2.6) than run II or III, yet had a lower BOD_5 removal rate thus D.O. does not appear to play any part in explaining the differences in BOD removal rate for these three runs.

The results presented below in section 4.2.9.3 indicate that MLVSS levels cannot shed any light on these BOD (COD) removal rate differences. MLVSS measures only those organisms in suspension in the RBC trough. The amount of active biomass on the discs should be more or less constant if one assumes that there is a thin layer of active organisms at the surface of the biofilm.

Nutrients were added at a constant BOD_5:nitrogen:phosphorus ratio. Data presented in section 4.2.11 suggest that nutrient concentrations were not rate limiting.

The effects of percent BOD removal ($\%BOD_{rem}$) and BOD removal rate (BOD_{rr}) can also be explained from a mathematical point of view. $\%BOD_{rem}$ is calculated by

$$\frac{BOD_{into}-BOD_{out}}{BOD_{into}}100=\%BOD_{rem} \qquad (1)$$

and BOD_{rr} is calculated

$$(BOD_{into}-BOD_{out})\ flowrate_{into}=BOD_{rr} \qquad (2)$$

equating (1) and (2) gives

$$\%BOD_{rem}flowrate_{into}\frac{BOD_{into}}{100}=BOD_{rr} \qquad (3)$$

Equation (3) indicates that both $\%BOD_{rem}$ and flowrate into the RBC are directly related to BOD_{rr}. The increase in flowrate during runs I, II and III were proportionally larger than the decrease in $\%BOD_{rem}$. Therefore BOD_{rr} increased with increasing flowrate, while $\%BOD_{rem}$ decreased slightly.

In addition, increasing the flowrate will increase the organic loading into the RBC *ie* the food supply to the bacteria will increase, which in turn may explain the increase in organic removal rate and support the above argument. The same trends were observed for COD.

Comparing runs III and IV (see Figure 4.4. and 4.5) shows that, for a decrease in temperature, percent BOD removed and the BOD removal rate both decreased. The decrease in BOD removal rate is due to the lower rate of reaction at lower temperature.

Increasing the hydraulic retention time (see Figure 4.6) will increase percent BOD and COD removals, these results indicate that removal might increase still further above HRT=2 days. However, without modifying the RBC to control evaporation loss, conducting tests at a greater HRT might result in a complete evaporation of the water at a temperatures of 32 ±2°C. Lo et al., (1991) used an activated sludge system to treat a CTMP wastewater with a BOD_5 influent concentration of 3000 mg/l and a corresponding COD concentration of 6200 mg/l. The best BOD and COD removal was achieved between 2 to 2.5 days HRT with 98% BOD reduction and 80% COD reduction at 20°C.

It has been noted, that because of evaporation the hydraulic residence time in the reactor increased as did the organic concentration. Stover and Kincannon state that the amount of organics removed by the system is the same at the same loading rate regardless of weather. The loadings are accomplished by a low flow rate at a high organic concentration or a high flow rate at a low organic concentration.

Other investigators have treated CTMP wastewaters of similar strength by different kinds of biological treatment systems and achieved the following BOD and COD removals: (1) Baker et al. (1978) compared an aerated lagoon to an RBC using wastewater from a magnesium base sulphite mill with an influent BOD ranging from 1000 to 2000 mg/l. The aerated lagoon achieved BOD removal rates of 48 to 71% during the winter months and 80 to 91% during the summer months, while the RBC's removal ranged from 62 to 85%, they did not report the actual hydraulic residence time used during their investigations. (2) Scarlata (1981) used a trickling filter and an activated sludge system

which removed 90% of the BOD from an influent BOD_5 concentration of 1600 mg/l and removed

57% of the COD from an influent COD concentration of 5000 mg/l with a total hydraulic retention

time of 3.7 days. (3) Wilson et al. (1985) compared an aerated lagoon, an activated sludge system and

a combined anaerobic/aerobic treatment system treating CTMP effluent with a BOD concentration

of 1290 mg/l and a COD concentration of 2740 mg/l. The aerated lagoon with a 7 to 9 days HRT

produced a non-lethal effluent, the activated sludge system with a 2.5 day HRT did not produce a

non-lethal effluent but both systems achieved 80% BOD reductions during the summer months. The

combined anaerobic/aerobic treatment system (high rate or low rate anaerobic system followed by an

aerated lagoon) produced an effluent exceeding 95% BOD removal after a 6 to 7 days total hydraulic

retention time. (4) Schnell et al. (1990) treated wastewater from an integrated newsprint mill with

an influent BOD ranging from 1100 to 2100 mg/l and an influent COD ranging from 1900 to 4100

mg/l. A combined anaerobic/aerobic treatment system gave a consistently high reduction in BOD,

requiring a total HRT of 27 to 30 hours.

4.2.4.2 COD REMOVAL

DATA ANALYSIS: Figure 4.6 and Figure 4.7 show the percent COD removed versus HRT and the

COD removal rate versus HRT for runs I, II and III. Figure 4.8 shows the graphed results of the

percent COD removed during runs I to IV, while Figure 4.9 shows the COD removal rate during runs

I to IV.

For run I (HRT=2 days) the average percent COD removed was 72%, while the average COD

removal rate was 1063 mg/hr. The percent COD removed during run II (HRT=1 day) ranged from

54 to 82% and averaged 63%, while the COD removal rate ranged from 2116 to 3091 mg/hr and
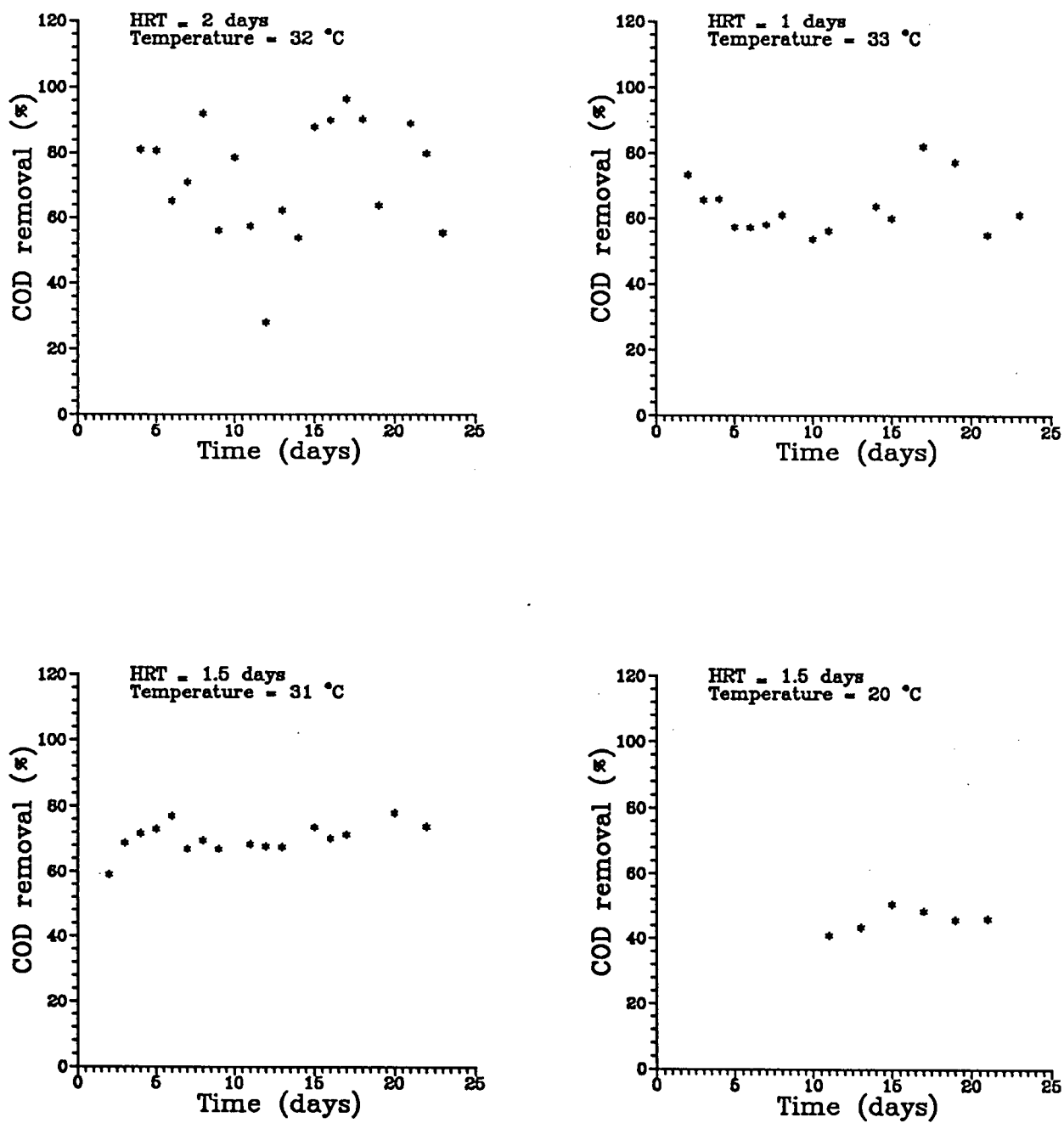
Figure 4.8   Percent COD removal during runs I, II, III and IV.
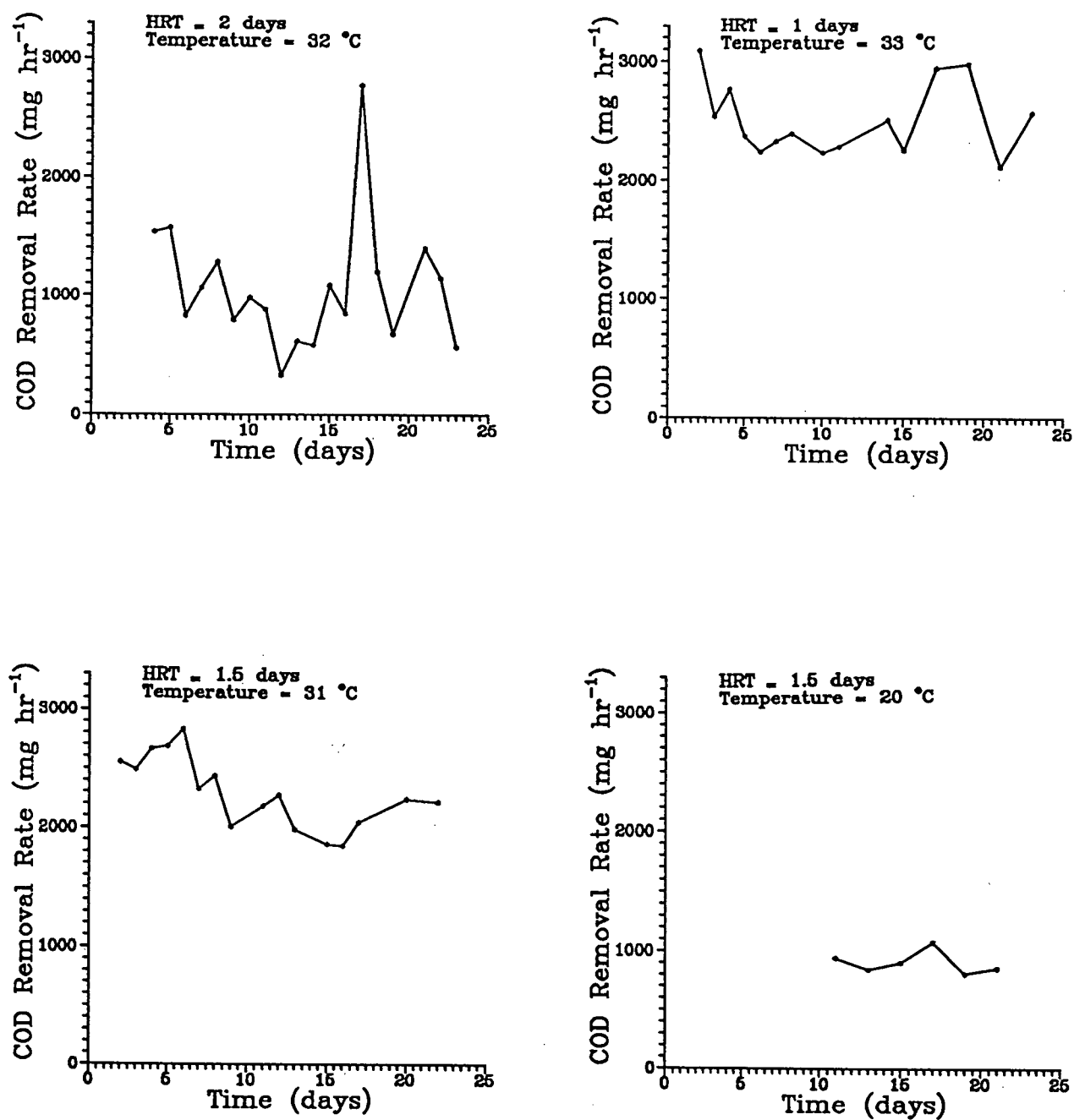
Figure 4.9 COD removal rate during runs I, II, III and IV.

averaged 2511 mg/hr. The percent COD removed during run III (HRT=1.5 days) ranged from 59 to 78% and averaged 71%, while the COD removal rate ranged from 1982 to 2829 mg/hr and averaged 2289 mg/hr. The percent COD removed during run IV ranged from 41 to 51% and averaged 46%, while the COD removal rate ranged from 1173 to 1450 mg/l and averaged 1337 mg/hr. DISCUSSION: The same trends as for the BOD analysis were observed for the COD results.

It is interesting to note that the difference between the COD removal rates of run III and run IV is much larger than the difference between the corresponding BOD removal rates (Figure 4.5 and 4.9). For a 13% decrease of percent BOD removed and a 10% decrease in BOD removal rate from run III to run IV the corresponding percent COD removed indicates a 24% decrease while the COD removal rate indicates a 42% decrease.

Comparing Figure 4.6 and 4.7 show that the ratio of COD removal rate to BOD removal rate is much larger than the corresponding ratio of percent COD removed to percent BOD removed. When comparing Figure 4.7 to 4.12 COD and BOD ratios indicate a similar trend, which may indicate that organic concentrations (BOD and COD) in the trough are dependent variables of organic removal rates.

4.2.4.3 BOD$_5$ VERSUS COD REMOVAL

DATA ANALYSIS: Comparisons of percent BOD and COD removed and of BOD and COD removal rate for all four runs are presented in Figure 4.10 and Figure 4.11. The average %COD/%BOD removed from start-up to the end of a run was 0.842 during run I, 0.817 during run II, 0.842 during run III, and 0.654 during run IV (see Figure 4.10).

Figure 4.11 shows the COD and BOD removal rates for the four runs. The average ratio of COD/BOD removal rate from start-up to the end of a run was 1.30 during run I, 1.75 during run II, 2.29 during run III, and 1.48 during run IV.

Samples for BOD$_5$ and COD analysis were usually withdrawn from settled wastewater. However,
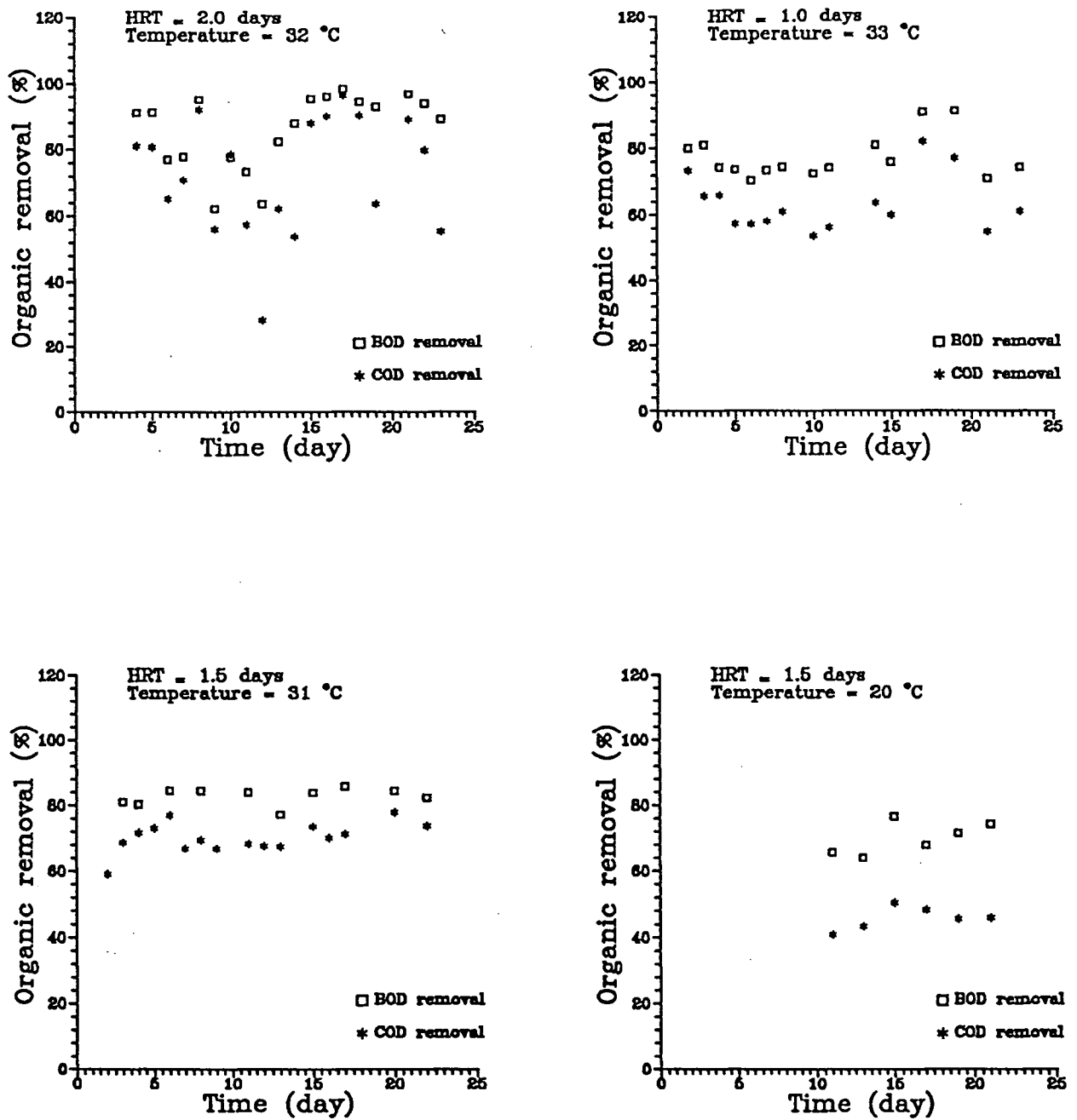
Figure 4.10   Comparison of percent BOD and percent COD removed
              during runs I, II, III and IV.
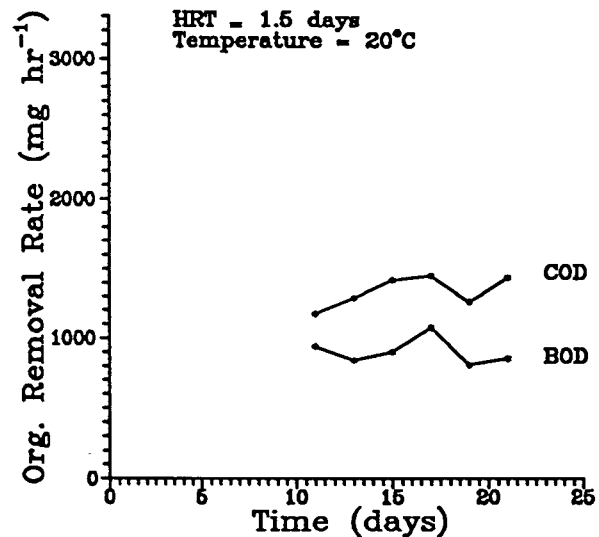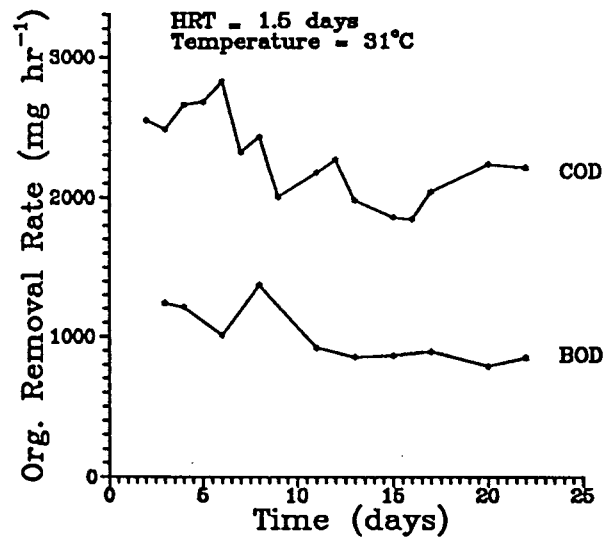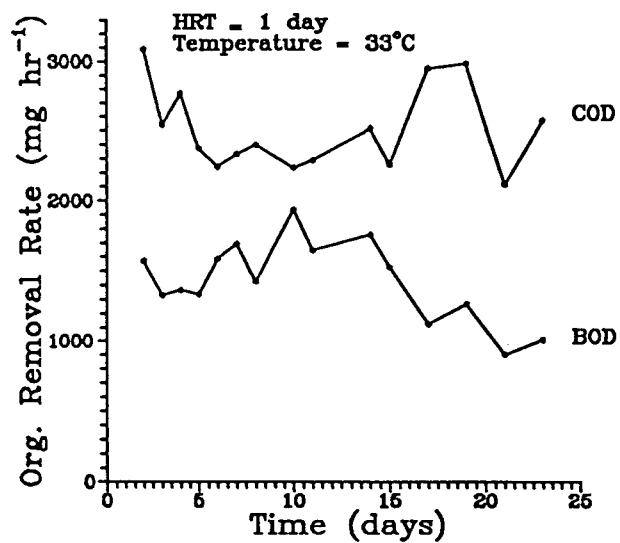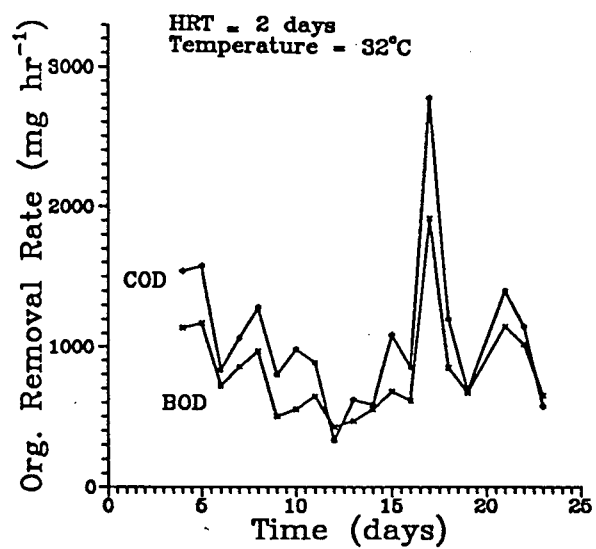
Figure 4.11   Comparison of BOD and COD removal rates during runs I, II, III and IV.

during runs II and III BOD and COD analyses (see Appendix I to IV, raw wastewater data) were also done on filtered influent and effluent samples. The percent BOD and COD removal using filtered samples showed little difference from the results of the settled BOD and COD analysis. The reason for this was that the solids content was high in both the raw wastewater and the RBC effluent (see Table 4.9, and Appendix I, II, III and IV - filtered BOD and COD data). This resulted in a proportional decrease of the filtered influent and effluent organic concentration (BOD and COD), eliminating the effect when taking the difference to calculate percent organic removal.

DISCUSSION: The results plotted in Figure 4.10 show that at a temperature of 30°C (run I,II and III) a higher percentage COD can be removed than at lower temperature of 20°C (run IV). The ratio of %COD/%BOD removed was lower at the lower temperature. No significant difference could be seen for runs I and III.

Figure 4.11 also suggests that the removal rate of COD compared to the removal rate of BOD is much higher at elevated temperatures (comparing run I,II and III to run IV). However, when comparing COD/BOD removal rates for runs I, II and III no explainable difference could be observed.

For the raw wastewater the average BOD_5/COD ratio was 0.42. The average effluent BOD_5/COD ratios were calculated, after correcting the effluent values for water loss, to be 0.33 for run I, 0.29 for run II, 0.22 for run III, and 0.24 for run IV. Meaning that more BOD_5 in relation to COD was removed during all four runs. The same trend is observed here as in Figure 4.4: Decreasing flowrate increases the BOD removal. However, again the reason for the high ratio during run I may be because of underestimation in the COD analysis.

4.2.4.4 ORGANIC LOADING

Because of evaporation in the bio-reactor during the four runs the organic concentration in the vessel tended to increase, while the hydraulic residence time tended to decrease. It was felt that the

following graphs could describe the effect of the actual concentration distribution in the tank over time caused by evaporation and biological degradation.

DATA ANALYSIS: The tracer test results (see section 4.3.4) indicate that it can be assumed that the RBC behaves very like a CSTR, from that it follows that the organic concentration leaving the reactor is equal to the organic concentration in the reactor. Figure 4.12 shows both BOD_5 and COD concentration in the reactor throughout each run. The numbers on the plots indicate the influent concentrations. These can be compared to the actual concentrations in the tank which are graphed as the lines on the plots. For run I the maximum BOD concentration in the tank was 2700 mg/l for a corresponding 3100 mg/l influent BOD, while the maximum COD concentration was 3720 mg/l for a corresponding 4660 mg/l influent COD; for run II the maximum BOD concentration in the tank was 4800 mg/l for a 2800 mg/l influent BOD, while the maximum COD concentration was 22800 mg/l for an 8350 mg/l influent COD; for run III the maximum BOD concentration in the tank was 6300 mg/l for a 3450 mg/l influent BOD, while the maximum COD concentration was 22450 mg/l for an 8350 mg/l influent COD; and for run IV the maximum BOD concentration in the tank was 2000 mg/l for a 4300 mg/l influent BOD, while the maximum COD concentration was 6200 mg/l for an 8000 mg/l influent COD. Figure 4.13 complements Figure 4.12 by showing the percent organic concentrations (*ie* organic concentration in the tank divided by the influent concentration times 100) in the tank relative to the influent concentrations plotted versus time. For 100% organic influent concentration the maximum percent concentration in the tank for run I was 68% BOD and 80% COD, for run II it was 172% BOD and 273% COD, for run III it was 183% BOD and 269% COD, and for run IV it is 49% BOD and 81% COD.

The plot in Figure 4.14 shows the distribution of percent BOD removed over the range of organic loading rates tested. The organic concentration of each CTMP batch shipped to us varied (see table 4.2).

DISCUSSION: The BOD and COD concentration in the tank (see Figure 4.12) did not exceed the
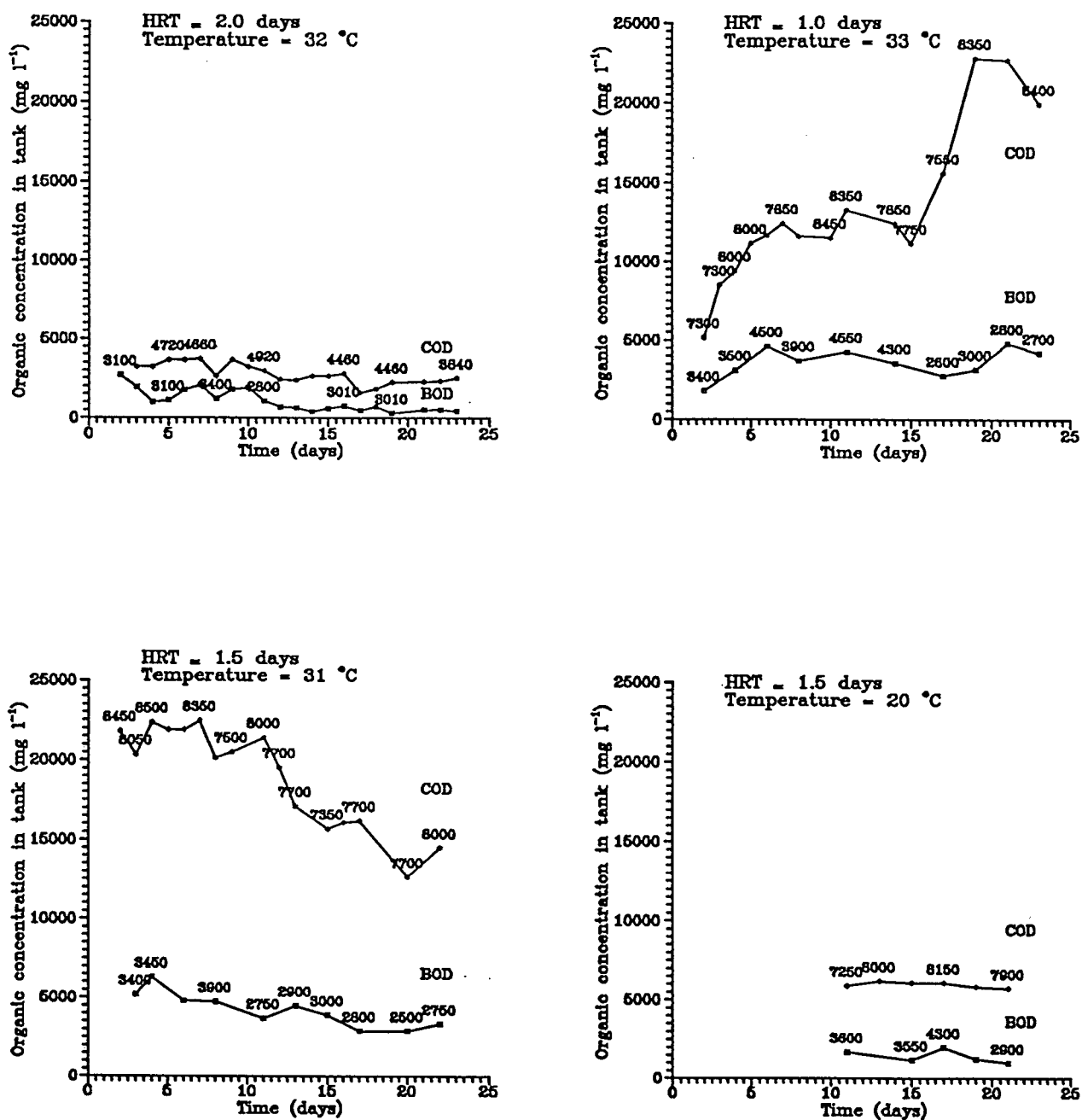
Figure 4.12   BOD and COD concentrations in the RBC tank as lines.
Influent BOD's and COD's as superimposed numbers.
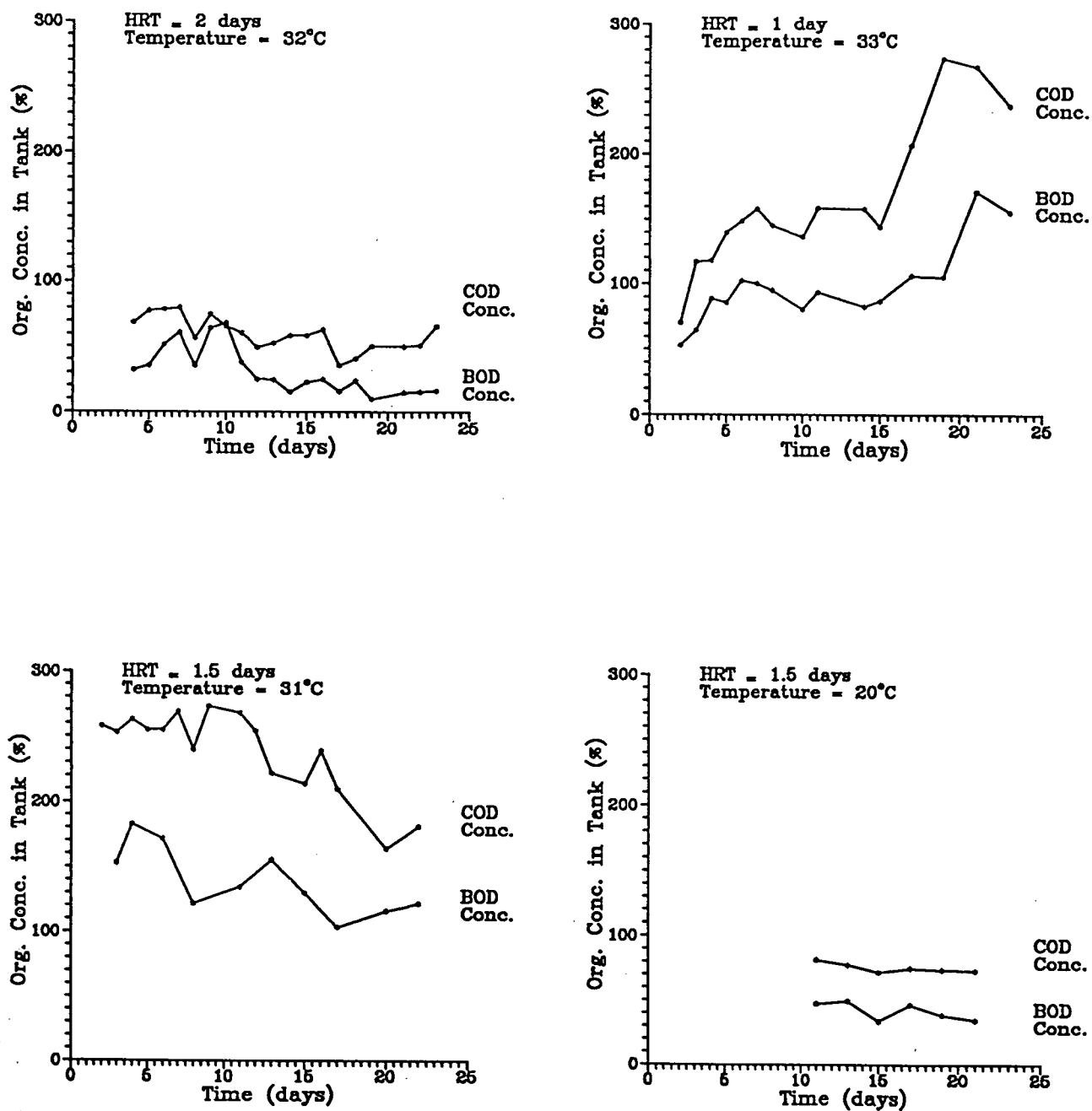
Figure 4.13   Percent BOD and COD concentrations in tank relative to BOD and COD influent concentrations.
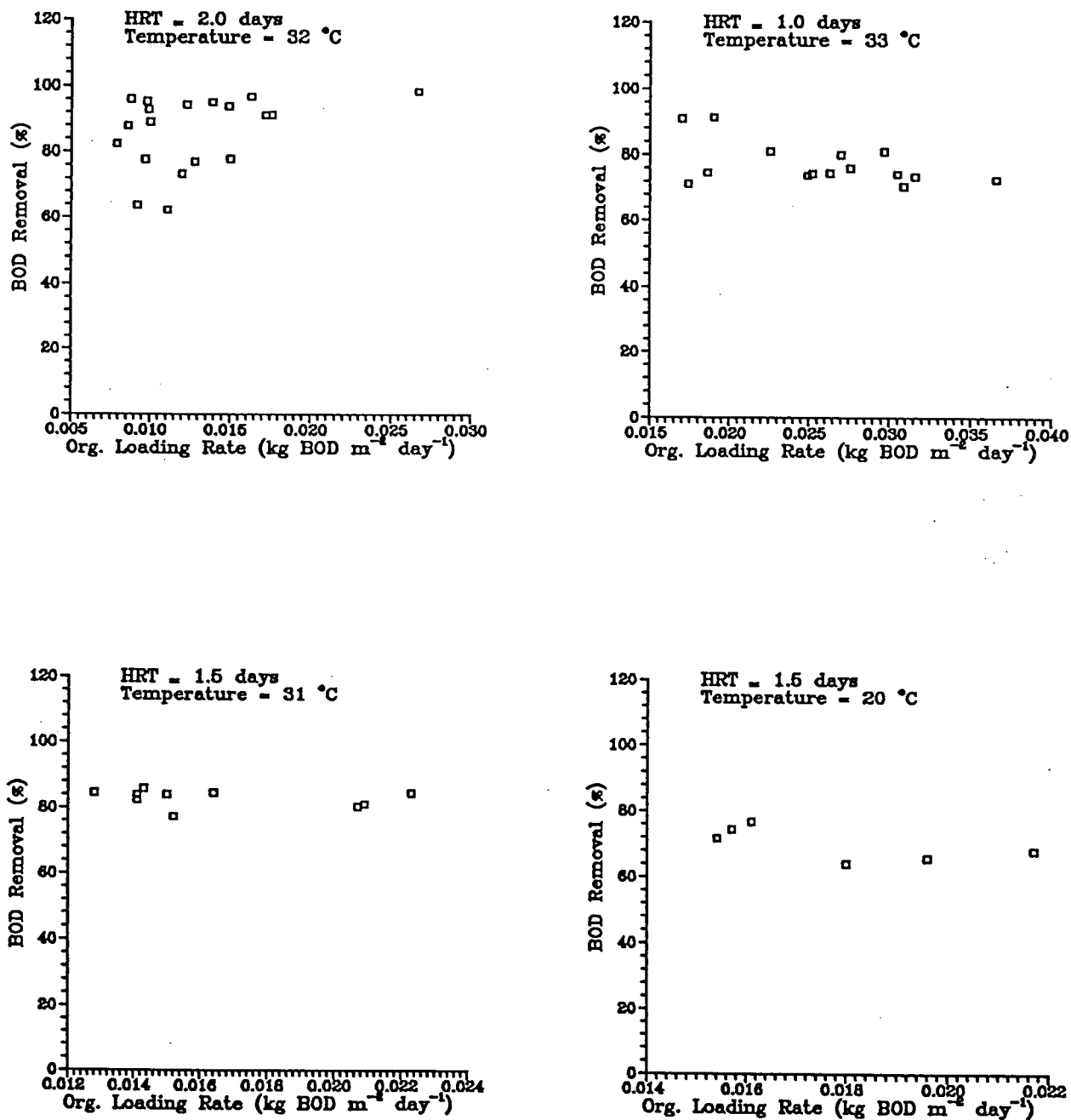
Figure 4.14   Percent BOD removal versus BOD loading.

influent concentration during run I. However, leakages into the reactor would dilute the wastewater and may have distorted the picture of the actual concentration distribution in the tank during this run. A new reactor was re-started for run II and was continuously run until the end of run III. Evaporation during these two runs was highest throughout the experiment with an average water loss of 78% during run II and 87% during run III. BOD concentration in the tank stayed almost constant throughout run II and III. It is interesting to note the gradual increase of COD concentration relative to BOD concentration during run II, while during run III the COD concentration indicates a decreasing trend. The COD concentration increased during run II, as it was not biodegraded, but only concentrated in the tank, while the BOD concentration, which was biodegraded, stayed at an almost constant concentration level throughout run II and III despite the evaporation. Thus, the decrease in COD concentration in the plot of run III suggests that more of the high molecular weight compounds, which contribute to COD, were able to be attacked by the bacteria after about 35 days of acclimating them in a continuously running RBC reactor.

Run IV never exceeded the influent concentration and shows a steady organic concentration in the tank throughout the run.

Figure 4.13 is another way of presenting the data graphed in Figure 4.12. During runs II and III the maximum percent COD concentration in the tank was almost double the corresponding maximum percent BOD concentration in the tank. Percent BOD concentration and COD concentration show a simultaneous increase during run II and a simultaneous decrease during run III.

Originally, the RBC was designed for an organic loading rate of 0.008 kg BOD/m²/day as described in section 3.1. The actual organic loading rate varied from 0.0079 to 0.0366 kg BOD/m²/day during the four runs.

Figure 4.14 indicates that percent BOD removal was not much affected, over the range of organic loading rates tested for each HRT, by organic loading rate. Most of the data points of the organic loading rate curve for run I were distributed around the lower end of the scale, however one data

point had a higher value indicating an increasing slope towards that one point at the higher end of the x-axis. This may be missleading and indicating that the reactor would be able to withstand a higher organic loading rate for the same degree of treatment. The organic loading rate increased with decreasing HRT. However, it almost doubled from run I (HRT=2 days) to run II (HRT=1 day). This was caused because the flowrate was increased and the BOD_{in} was higher during run II (see table 4.2) The organic loading rate was higher during run IV (HRT=1.5 days) than during run III (HRT=1.5 days) because the BOD concentration in run IV was higher than the one in run III (see table 4.2). The organic concentration was calculated using the influent BOD_5 concentration and the influent flowrate. However, considering the decrease in hydraulic residence time and the increase in concentration within the bio-vessel caused by the evaporation, the organic loading rate was also calculated using the effluent BOD_5 concentration and the effluent flowrate. These calculations showed little change from the original results which were used to plot Figure 4.14. Stover and Kincannon (1982) showed that the removal rate and efficiency were indeed dependent on the amount of total organics applied to the RBC rather than its concentration or flowrate.

4.2.5 EFFECTS OF TEMPERATURE

DATA ANALYSIS: The effect of treatment temperature was investigated because of the large evaporation experienced during runs I to III. Treatment efficiency was investigated with all conditions fixed as during run III and temperature was changed to 20°C. Table 4.3 shows a comparison of averaged percent BOD_5 and COD removal during these two runs.

Table 4.3   Comparison of organic removal rate at different
            wastewater (WW) temperatures

Parameters	WW Temp. = 31°C HRT = 1.5 days	WW Temp. = 20°C HRT = 1.5 days
BOD$_5$ removal (%)	83.0	70.1
COD removal (%)	71.4	45.8
%COD/%BOD$_5$ removal	0.861	0.654

DISCUSSION: Temperature of the wastewater determines the rate of reaction. Treatment efficiency

of aerobic biological systems will increase with increasing temperature up to a limiting temperature

(usually 40°C in the mesophyllic range). The data from table 4.3 indicate that the organic removal

increases with increasing temperature and that more COD relative to BOD can be removed at higher

temperature. This is not in agreement with the findings of Lo et al. (1991), who tested the effect of

treatment temperature for a CTMP wastewater (BOD=3000 mg/l and COD=6200 mg/l) using an

activated sludge system. Both BOD and COD removals were reduced when the temperature was

raised from 20 to 30°C.

4.2.6 EFFECT OF DISSOLVED OXYGEN CONCENTRATION

DATA ANALYSIS: Three-dimensional (3-D) plots were used to illustrate surface trends revealed

by the D.O. concentration as a function of time and reactor length (from inlet to outlet). To fit the

3-D curve a minimal curve method was used. Figure 4.15 shows the data for runs I, II, III and IV.

DISCUSSION: Run I revealed an average D.O. concentration of 0.5 mg/l throughout the reactor

rising to peak values between day 12 to 15 and rising again between 18 and 19 and finally between

day 22 and 23. Run II and run III (Figure 4.15) show an average D.O. concentration of 0.26 mg/l and

0.28 mg/l respectively, throughout the RBC reactor and during the entire length of these runs. Run

IV showed an initially high average D.O. concentration of 6.5 mg/l at start-up. The D.O. was
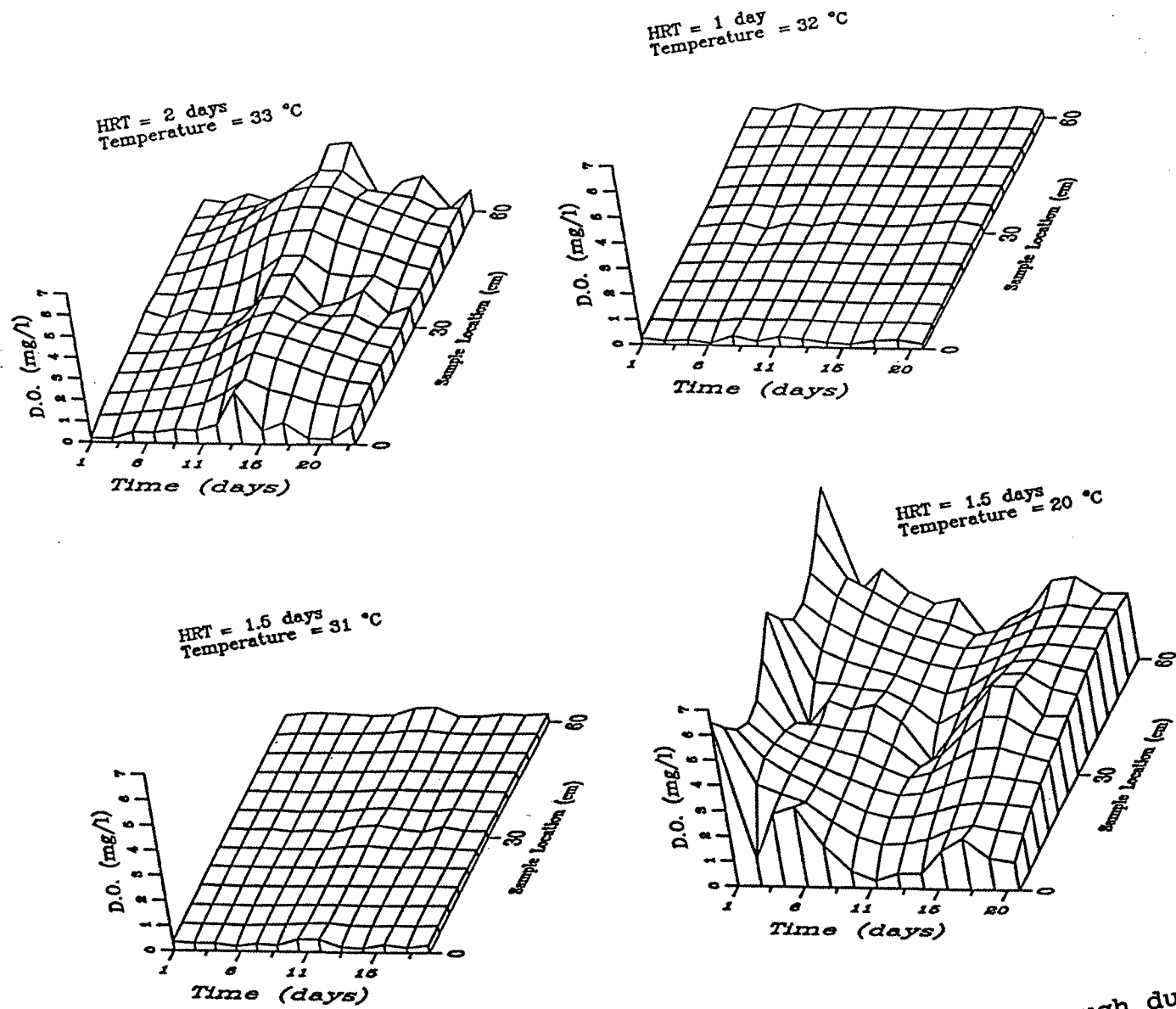
Figure 4.15 Dissolved oxygen concentrations in RBC trough during runs I, II, III and IV.

measured every 1/2 hour and after 4 hours the D.O. concentration had decreased to an average of 2 mg/l when it was observed that biomass started to adhere to the discs.

At low D.O. concentrations (below 0.5 mg/l) one would expect that BOD removal rate might be limited by the availability of D.O. Yet, comparison of the D.O. data (Figure 4.15) for run I with the BOD removal rate data of Figure 4.5 shows no evidence of such limitation. Since BOD removal rates were as high or higher in runs II and III and D.O. levels were lower it appears that D.O., as measured in the trough, is not an indicator of the availability of D.O. to the organisms in the biofilm.

Additional support for this argument is found by examining the MLVSS data. In run II (section 4.2.10.2) MLTSS in the trough increased throughout the run (see Figure 4.18) yet, BOD removal rate (see Figure 4.5) decreased. The conclusion could be made that either the microorganisms in suspension in the trough were inactive or were limited in their ability to remove BOD by lack of D.O during run II. This inactivity my have come about by a change of population (from aerobic to anaerobic) in the trough and a period of readjustment would be required. This argument is supported by Figure 4.12 which shows an increase in COD accumulation during run II and a decrease during run III, which was continued after run II. The higher levels of D.O. observed in run IV are due to the greater solubility of oxygen in water at lower temperatures and the lower BOD concentration (see Figure 4.12) in the trough due to a decrease in water loss.

In general, dissolved oxygen levels did not appear to have an effect on BOD and COD removal. Lo et al. (1991) tested the effect of D.O. on treatment efficiency. They used an activated sludge reactor at 3 days HRT, 20°C and a CTMP wastewater with similar organic composition to that used in this study. They found that D.O. had an insignificant effect on BOD_5 removal and COD removal increased slightly with a large increase in D.O. concentration. However, their tests were conducted at D.O. concentrations ranging from 2.5 to 8.2 mg/l.

Tests were also performed to observe the effects of variation in disc rotational speed (RPM) and the addition of air by means of a submerged diffuser on D.O. concentration. At the end of run III,

at which time the D.O. level was very low, neither an increase in the RPM of the discs nor the provision of additional air by means of aerators was sufficient to change the D.O. concentration in the RBC reactor. However, when the same tests were repeated after run IV, in which the D.O. concentration was not limiting, it was found that the increase in D.O. was more sensitive to an increase in RPM than to aeration. D.O. measurements were performed at the inlet end of the RBC vessel which measured a D.O. concentration of 0.7 mg/l at a tip speed of 0.31 m/s. Increasing the RPM 1.5 times increased the D.O. to 1.4 mg/l. Doubling the RPM increased the D.O. to 2.2 mg/l, and when tripled the D.O. concentration was measured at 3.15 mg/l. The tip speed was then again set at 0.31 m/s and an airstone was added to the reactor at the inlet end. Airflow was not measured, but the D.O. did not respond as well as during the RPM test. Increasing the airflow from small dispersed air bubbles to the point where air bubbles created intense turbulence resulted in a D.O. concentration which varied from 1.5 to 2 mg/l maximum.

4.2.7 EFFECT OF OXIDATION REDUCTION POTENTIAL

DATA ANALYSIS: Based on the low D.O. concentration in the reactor during run II, the oxidation reduction potential (O.R.P.) in the RBC was measured daily during run III. The O.R.P. in the trough was measured to be -325 ± 57 mV and the O.R.P. of the influent was measured at -230 ± 24 mV. These values were averaged over run III.

DISCUSSION: The oxidation reduction potential measures the oxidizing or reducing properties of a solution. The chief oxidant is oxygen, and its presence raises the potential. Reducing agents lower it. Aerobes oxidize organic materials and aerobic processes are dominant when oxygen levels and ORP's are high (positive). Anaerobic processes are prominent when the oxygen level is low and the ORP is also low (negative). An electron activity (pE-pH) diagram can be used to illustrate major oxidation-reduction zones in aqueous systems (Sawyer and McCarty, 1978, p.210). It shows that for an average pH of 8.93 (during run III) completely aerobic conditions are associated with an O.R.P.

of about 750 mV and completely anaerobic conditions are associated with an O.R.P. of about -400 mV. In between these extremes lies a transition zone. Based on the above values the results from this experiment seem to indicate that conditions in the trough during run III, and probably during run II, were anaerobic.

4.2.8 EFFECT OF pH

DATA ANALYSIS: pH was measured daily during all four runs at three points in the trough (see section 3.2.2). An average of the pH values was taken because no significant deviation in the data as a function of position was observed. Table 4.4 shows the averaged values for each run.

Table 4.4   pH in RBC and pH of raw wastewater during
            runs I, II, III and IV

Parameters	pH in RBC		pH of influent
	Range	Average	
HRT = 2 days Temp. = 32°C	8.26 - 8.89	8.68	5.9
HRT = 1 day Temp. = 33°C	7.54 - 9.11	8.68	6.42
HRT = 1.5 days Temp. = 31°C	8.35 - 9.07	8.93	6.37
HRT = 1.5 days Temp. = 20°C	8.46 - 8.81	8.59	5.56

DISCUSSION: It was observed during all four runs that the pH became basic after RBC treatment. The biochemical oxidation of organic matter by microorganisms can be described by the following equation:

$$\text{CTMP wastewater} + O_2 \rightarrow CO_2 + H_2O + \text{more sludge}$$
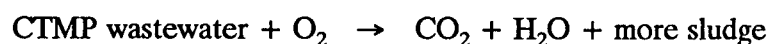
The acids in the CTMP wastewater are oxidized to CO_2 which is exchanged between the atmosphere

and the water. This will increase the pH and shift the equilibrium to the bicarbonate form. CO_2 volatility decreases with increasing pH. This process continuous until the carbonic acid stays in its buffer form, and at pH of ≈ 9 almost all alkalinity is in the bicarbonate (HCO_3^-) form. The volatility of carbon dioxide increases with increasing temperature. From the data there is no apparent trend noticeable when relating the influent and effluent pH with temperature or hydraulic residence time. Keeping in mind that each CTMP batch had a different composition of organic compounds (see table 4.2), different amounts of acids will be oxidized by microorganisms.

4.2.9 ANALYSIS OF VOLATILE COMPOUNDS

High evaporation rates especially during run II and III led to the suspicion that other volatile compounds besides water vapour might be escaping from the RBC. Our measurements, as do literature values, indicate that a significant amount of acetic acid and sulfur compounds are present in the CTMP wastewater. Because of the low D.O. concentration in the trough during run II and III, hydrogen sulfide may have been generated by anaerobic microorganisms, as well. Both these compounds are volatile under certain conditions, and could be removed simply by evaporation. To determine whether or not this was important, inlet and outlet samples of acetic acid and of sulfur compounds were analyzed during runs II and III and compared to the 'sterile' runs because the pH differed (see section 4.3.1). Equilibrium calculations of the concentrations of the volatile and nonvolatile forms of known compounds in the CTMP wastewater at the pH of operation have been done according to Benefield et al. (1982).

DATA ANALYSIS: Table 4.5 shows the equilibrium concentrations of the measured compounds during runs II and III compared to the 'sterile' run at HRT=2 days, 1.5 days and 1 day. Other volatile compounds in the CTMP wastewater, some of which were measured by other investigators and which are present in small quantities and others which are by-products from bacterial fermentation, were investigated for their volatility. They are listed in Table 4.6.

Table 4.5 Equilibrium concentrations of measured chemical compounds
in the CTMP wastewater

Compounds: Chemical equation: Equilib. const.[1]:	Acetic Acid $CH_3COOH \rightleftharpoons CH^3COO^- + H^+$ pKa = 4.7		Sulfide $H_2S \rightleftharpoons HS^- + H^+$ pKa = 6.992	
Components:	volatile CH₃COOH	non-volatile CH₃COO⁻	volatile H₂S	non-volatile HS⁻
Concentration for HRT=1 day (mg/l): - at pH 8.93[2] - at pH 7.43[3]	0.0265 1.58	449.21 443.63	0.041 1.48	3.51 2.10
Concentration for HRT=1.5 days (mg/l): - at pH 8.94[2] - at pH 7.24[3]	0.024 1.29	422.13 443.92	0.038 1.29	3.40 2.29
Concentration for HRT=2 days (mg/l): - at pH 8.8[2] - at pH 7.15[3]	not done 0.827	not done 444.38	not done 0.96	not done 2.62
Effect of pH:	Increasing the pH shifts the reaction equilibrium to the right which decreases the volatilization of CH₃OOH. Minimal volatilization occurs at pH > 9.		Increasing the pH moves the reaction equilibrium to the right which decreases the volatilization of H₂S. Minimal volatilization occurs at pH > 10.	
Effect of temperature:	pKa is temperature independent.		A larger increase in temperature moves the reaction equilibrium to the right which decreases the volatilization of H₂S.	

[1]Values for pKa and enthalpy are from Handbook of Chemistry and Physics, 64th edition, 1983-84. Temperature corrections are adjusted to 30° C.

[2]pH values for runs I, II and III (HRT = 2, 1, and 1.5 days) were averaged over the steady state period.

[3]pH values for the 'sterile' runs were averaged.

Table 4.6   Equilibrium considerations of chemical compounds
(not measured) in the CTMP wastewater.

Components:	Chemical equation:	Equilibrium constant (pKa)[1]:	Comments:
Phenol	$C_6H_5OH \rightleftharpoons C_6H_5O^- + H^+$ volatile: C_6H_5OH non-volatile: $C_6H_5O^-$	9.9^2	Increasing the pH moves the reaction equilibrium to the right which decreases the volatilization of C_6H_5OH. Minimal volatilization occurs at pH >13.
Alcohol	$R - OH$		The OH group does not ionize and chemistry of alcohol relays entirely on OH group (Sawyer and McCarty, 1978). Therefore alcohols are not affected by pH. Volatilization depends on molecular weight and vapour pressure of species. Alcohols have generally a high vapour pressure. They are volatile up to a molecular weight of ~ C_{10} at 1 atm.
Carbonic Acid	ª $CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$ volatile: CO_2 non-volatile: HCO_3^- ᵇ $HCO_3^- \rightleftharpoons CO_3^- + H^+$	6.43^3 10.26^3	ªIncreasing the pH moves the reaction equilibrium to the right which decreases the volatilization of CO_2. Minimal volatilization occurs at pH > 9. Almost all alkalinity is in the bi-carbonate form at a pH ranging from 7.5 - 9. A large increase in temperature moves the reaction equilibrium to the right which decreases the volatilization of CO_2. ᵇIncrease in pH moves the reaction equilibrium to the right, increasing the carbonate concentration in solution. A large increase in temperature moves the reaction equilibrium to the left increasing the bi-carbonate concentration.
Hydrocarbons	many forms: -saturated -unsaturated		Volatilization depends on molecular weight and vapour pressure of species. Saturated and unsaturated hydrocarbons are generally volatile up to a molecular weight of ~ C_5 resp. ~ C_4 at 1 atm.
Resin acids	many forms		Resin acids are generally non-volatile because of their high molecular weight and complex structure.

[1]Values for pKa and enthalpy are from Handbook of Chemistry and
Physics, 64th edition, 1983-84.
[2]pKa values for 25 °C.
[3]pKa values adjusted to 30 °C.

DISCUSSION: From Table 4.5 it appears that at the pH of the wastewater in the trough during the

bacterial runs acetic acid and hydrogen sulfide exist almost completely in their non-volatile forms.

However, the pH during the 'sterile' experiment was at a lower average value of 7.3. At that pH

approximately 40% of H_2S could be volatile.

Table 4.6 shows that the volatilization of hydrocarbons and alcohols can only be determined if the

form of the hydrocarbons or the type of alcohol is known. Phenols, which are usually present in

CTMP wastewaters at smaller concentrations, are volatile up to a pH of 13.

4.2.9.1 ACETIC ACID ANALYSIS

DATA ANALYSIS: Table 4.7 shows the results of the acetic acid analysis. All effluent concentrations

were corrected for water loss. Because of the high acetic acid concentration in the CTMP wastewater,

BOD_5 and COD analyses of known concentrations of acetic acid were performed to find out the

contribution of acetic acid to the total BOD_5 and COD concentration. It was found that the BOD

of acetic acid was equal to 0.9 times the acetic acid concentration and that the COD of acetic acid

was equal to 1.033 times the acetic acid concentration. Figure 4.16 then shows a bar graph comparing

influent and effluent concentrations of acetic acid at various HRT's.

Table 4.7   Comparison of acetic acid concentration to BOD and COD
concentrations and effect of acetic acid on hydraulic
retention time.

Parameters: (days)	Acetic Acid Concentration (mg/l)		BOD conc. of Acetic Acid (mg/l)		COD conc. of Acetic Acid (mg/l)	
	in	out	in	out	in	out
HRT = 1	422.16	13.64	379.95	12.28	436.24	14.09
HRT = 1.5	449.25	3.49	404.31	3.61	464.21	3.61

DISCUSSION: The BOD value for acetic acid is very close to the actual acetic acid concentration,
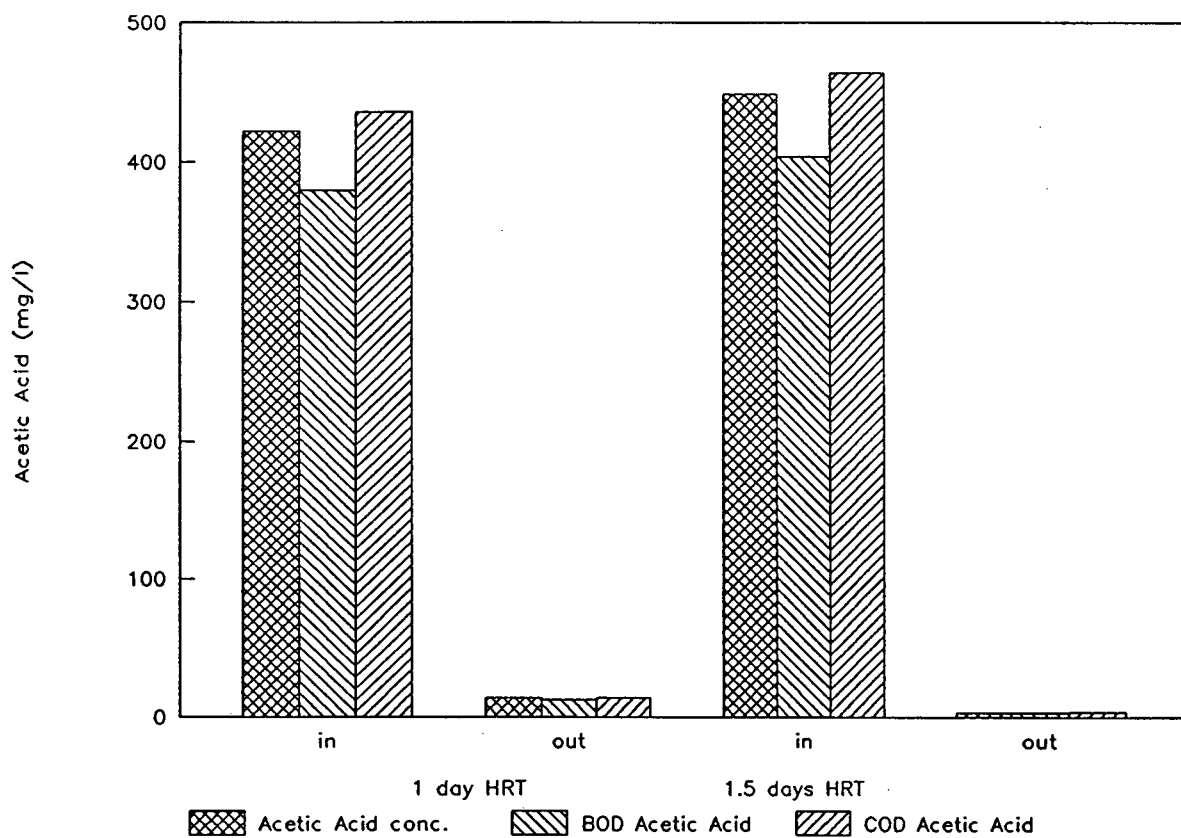
Figure 4.16 Effect of hydraulic retention time on acetic acid concentration, $BOD_{acetic\ acid}$ and $COD_{acetic\ acid}$.

indicating that 90% of acetic acid is biodegradable. This shows that acetic acid is readily available to the organisms and may be one of the compounds in the CTMP wastewater which is consumed by them first. The theoretical oxygen demand of acetic acid was calculated to be 1.067. This value differs by 3% from the measured COD value.

Figure 4.16 shows that almost all of the acetic acid was biodegraded and a larger amount was removed when the HRT was increased from 1 day to 1.5 days.

4.2.9.2 SULFUR COMPOUNDS

DATA ANALYSIS: Table 4.8 shows the results from the sulfur compounds analysis. Analysis was done for sulfate ($SO_4^=$), sulfite ($SO_3^=$) and sulfide ($S^=$). All effluent concentrations were corrected for water loss. Figure 4.17 shows the effects of HRT on sulfate, sulfite and sulfide.

Table 4.8 $SO_4^=$, $SO_3^=$ and $S^=$ concentrations during run II and run III.

Parameters: (days)	$SO_4^=$ (mg/l)		$SO_3^=$ (mg/l)		$S^=$ (mg/l)	
	in	out	in	out	in	out
HRT = 1	435.0	514.5	65.5	8.95	3.55	0.97
HRT = 1.5	455.0	498.0	57.5	5.70	3.44	0.26

DISCUSSION: Sulfate and sulfite compounds were analyzed because they exist in large concentrations in the CTMP wastewater; sulfide was analyzed to see if anaerobic bacteria were reducing $SO_4^=$ and $SO_3^=$ to $S^=$ to produce hydrogen sulfide. Sulfur may also exist, in organic form, in the wastewater as lignosulfate. However, lignosulfate is said to be present only as a minor part of the raw CTMP effluent (Almemark et al., 1986; Cornacchio and Hall, 1986).

The results in Table 4.8 show that most of the sulfite was oxidized to sulfate during RBC treatment. It appears that small amounts of H_2S escaped, but it is not evident from the data
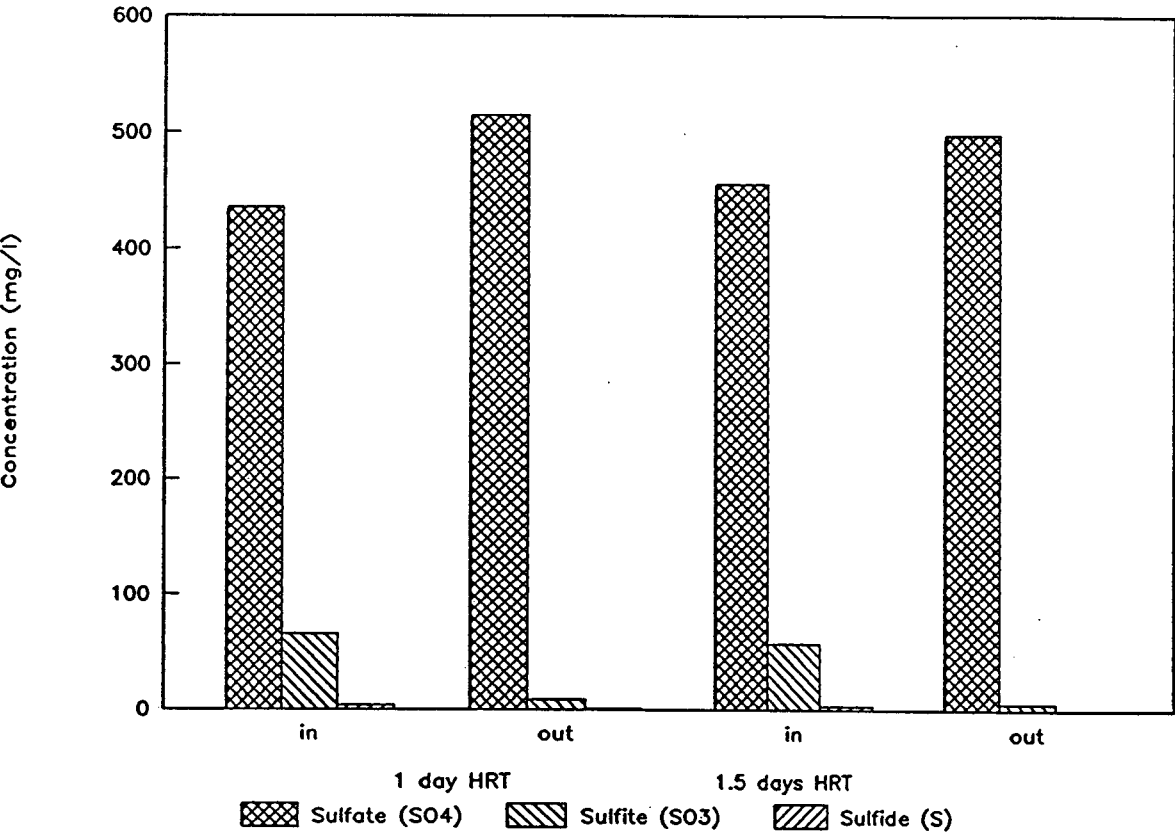
Figure 4.17 Effect of hydraulic retention time on sulfate, sulfite and sulfide.

if any sulfide was produced by anaerobic fermentation in the trough during RBC treatment. Sulfate and sulfite were present at different concentrations in the raw wastewater during run II and run III and no apparent relationship can be seen from the data. From Table 4.8 and Figure 4.17 it appears that more hydrogen sulfide evaporated at a longer HRT.

4.2.10 SOLIDS ANALYSIS

4.2.10.1 EFFECTS OF TS, VS, TSS AND VSS

DATA ANALYSIS: The results for TS, VS, TSS and VSS obtained during runs I, II, III and IV are presented in Table 4.9. Effluent concentrations are shown both, corrected and not corrected for water loss.

Table 4.9   Comparison of influent and effluent solids during runs I, II, III and IV.

Solids (mg/l)	HRT=2 days Temp.= 32°C	HRT=1 day Temp.= 33°C	HRT=1.5 days Temp.= 31°C	HRT=1.5 days Temp.= 20°C
TS in	6200	6925	7350	7250
out	6700	26675	22350	6800
corr.	4850	3350	3000	5000
VS in	4200	4925	5225	5250
out	1900	12875	9100	4000
corr.	1375	1625	1225	2950
TSS in	3600	900	1000	950
out	4950	8925	4350	2250
corr.	3575	1125	575	1650
VSS in	250	850	950	900
out	1400	6700	3775	2100
corr.	1000	850	500	1550

DISCUSSION: Total solids (TS) and volatile solids (VS) analysis were done to compare to total suspended solids (TSS) and to volatile suspended solids (VSS) data. Most of the matter in TS and VS tests is in the dissolved form and consists mainly of inorganic salts, small amounts of organic matter and dissolved gases (Sawyer and McCarty, 1978). Undissolved substances are measured as TSS and VSS.

Comparing the TS with the TSS test indicated that approximately 87% of the solids in the CTMP wastewater during runs II, III and IV consisted of dissolved matter. However, during run I approximately 42% of the raw CTMP effluent solids consisted of dissolved material. The TS test can also be compared to BOD_5 and COD analysis. It was originally devised as a means of evaluating the pollutant matter present in wastewaters. TS values compare well to the BOD_5 and COD measurements obtained in this study (see Figure 4.12, section 4.2.4.4 and Appendices I to IV, raw data). However, BOD_5 and COD tests are said to evaluate the strength of such materials more exactly (Sawyer and McCarty, 1978).

The volatile content, VS, of the total solids test is used to measure the amount of organic matter present in the wastewater. The large difference in value, when comparing the VS data to the VSS data confirms the amount of inert organic matter, such as the lignin present in the CTMP wastewater. The corrected VS values after RBC treatment indicated that during run I (HRT=1 day) and run II (HRT=1 day) 67% of the VS was removed while during run III (HRT=1.5 days, T=31°C) 70% of VS was removed and during run IV (HRT=1.5 days, T=20°C) 44% was removed. This confirms the observations made in section 4.2.5 that a larger amount of high molecular weight compounds such as lignin can be removed biologically at a higher wastewater temperature. The best VS removal was attained during run III at HRT=1.5 days, while the best BOD removal was achieved during run I at HRT=2 days.

TSS values show the amount of undissolved matter in the wastewater. These amount to about 13% in the raw wastewater during runs II, III and IV, however, they account for about 58% during run

I. Data for the corrected RBC effluent values show that the best removal of undissolved material was reached during run III with 43% removed, while the VSS concentration during run II and IV actually increased. Because almost all of the TSS is in form of VSS during runs II, III and IV the increase in TSS is attributed to bacterial washout. Run I was not compared because its TSS and VSS composition seemed to differ from the CTMP batches tested during runs II, III and IV.

VSS data in table 4.9 indicate that a large amount of organic solids is present in the raw CTMP effluent prior to treatment. About 95% of the TSS was in the form of VSS in the CTMP wastewater used for runs II, III and VI. However, only about 7% of TSS was in the form of VSS during run I. Corrected effluent data shows that the VSS concentration increased because of bacterial washout. The data reflect a decrease in VSS with a decrease in effluent flowrate, which was most noted in run IV followed by runs I, II and run III were the effluent flowrate was lowest.

4.2.10.2 BIOMASS GROWTH IN REACTOR OVER TIME

OBJECTIVE: To investigate the growth of biomass in the trough over time.

PROCEDURE: During run II (HRT=1 day) from November 28, 1990 over a weeks period until December 5, 1990 daily samples of the mixed liquor were withdrawn as described in section 3.2.3 and the mixed liquor total suspended solids (MLTSS) concentration was determined as described in section 3.3.10 (c).

RESULTS: See results of the raw data Appendix II (Run II) and Figure 4.18.

DISCUSSION: During run II it was observed that the sludge production in the trough increased visibly. Some of the bacterial increase was contributed to biomass sloughing off the discs, as well as to microbial growth occurring in the trough. The result of this experiment shows that the sludge concentration during the run doubled within a week from 6000 to 11,950 mg/l. These MLTSS values correspond to MLVSS concentrations ranging from ~ 5,275 mg/l (calculated value based on the data that the MLVSS is 87.9% of the MLTSS) to 10,500 mg/l. This confirmed that the biomass was
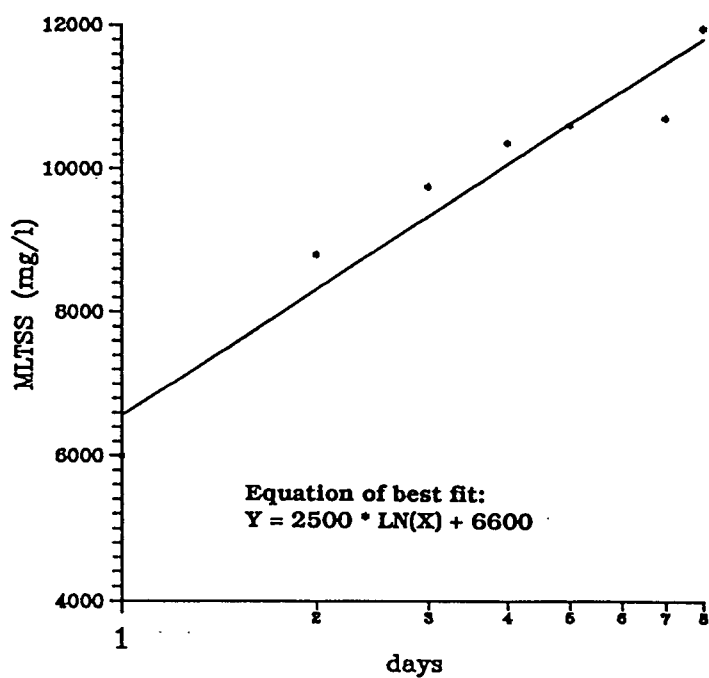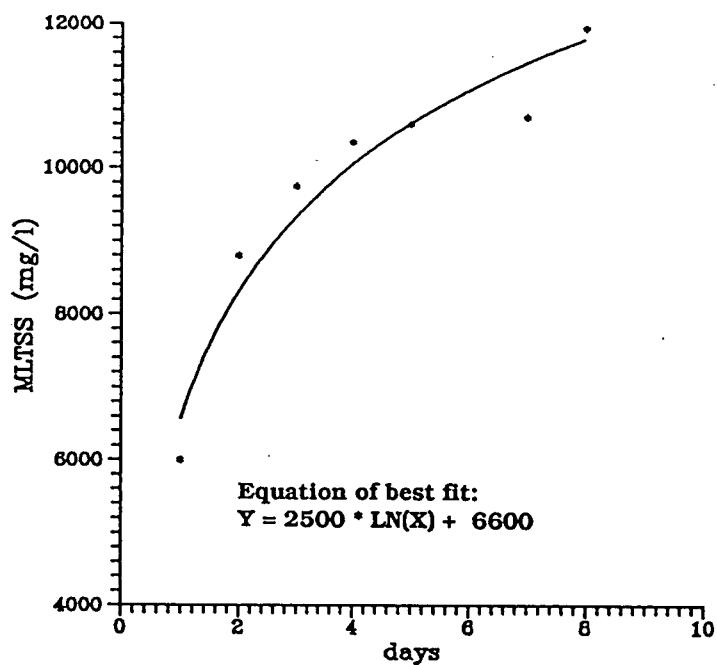
Figure 4.18   Biomass growth in RBC over time during run II.

actively being created, however, during the time the MLTSS analysis was done, biomass was sloughing off most the discs and because of the high evaporation (87% average) during this run hardly any washout of sludge occurred. Because of the large concentration of biomass present in the trough any D.O. transferred into the trough liquid was probably consumed instantaneously.

4.2.10.3 ANALYSIS OF MLVSS

DATA ANALYSIS: Figure 4.19 shows a bar graph of the average MLVSS concentrations in the RBC for runs I, II, III and IV. Samples were taken after running the RBC for 10 days. For run I (HRT=2 days, T=32°C) the MLVSS concentration was 2400 mg/l, for run II (HRT=1 day, T=33°C) the MLVSS was 9800 mg/l, for run III (HRT=1.5 days, T=31°C) the MLVSS was 10,650 mg/l, and for run IV (HRT=1.5 days, T=20°C) the MLVSS was 3800 mg/l.

DISCUSSION: Not much in the way of conclusion can be drawn from the MLVSS data. That run III has a higher MLVSS than run II is because run III followed directly on run II without removing sludge. Washout of sludge in these two runs was low due to high levels of evaporation. Thus sludge which sloughed off the discs tended to accumulate in the RBC trough. This suspended biomass did not seem to contribute to BOD removal as noted above in section 4.2.5 perhaps because of low levels of D.O. However, may have contributed to COD removal in run III (see Figure 4.12).

Sludge was scraped of the discs and measured after runs I and III. The collected sludge was drained and weighed. The weighed amount was then divided by the total disc area. 0.446 kg/m² of disc were found for run I and for run III 0.526 kg/m² of disc. Further, a sample of the drained sludge was withdrawn for TSS and VSS and measured according to section 3.3.10. The TSS was 55,800 mg/l and the VSS was 32,000 mg/l for run I, and the TSS was 58,600 mg/l and the VSS was 17,000 mg/l for run III.
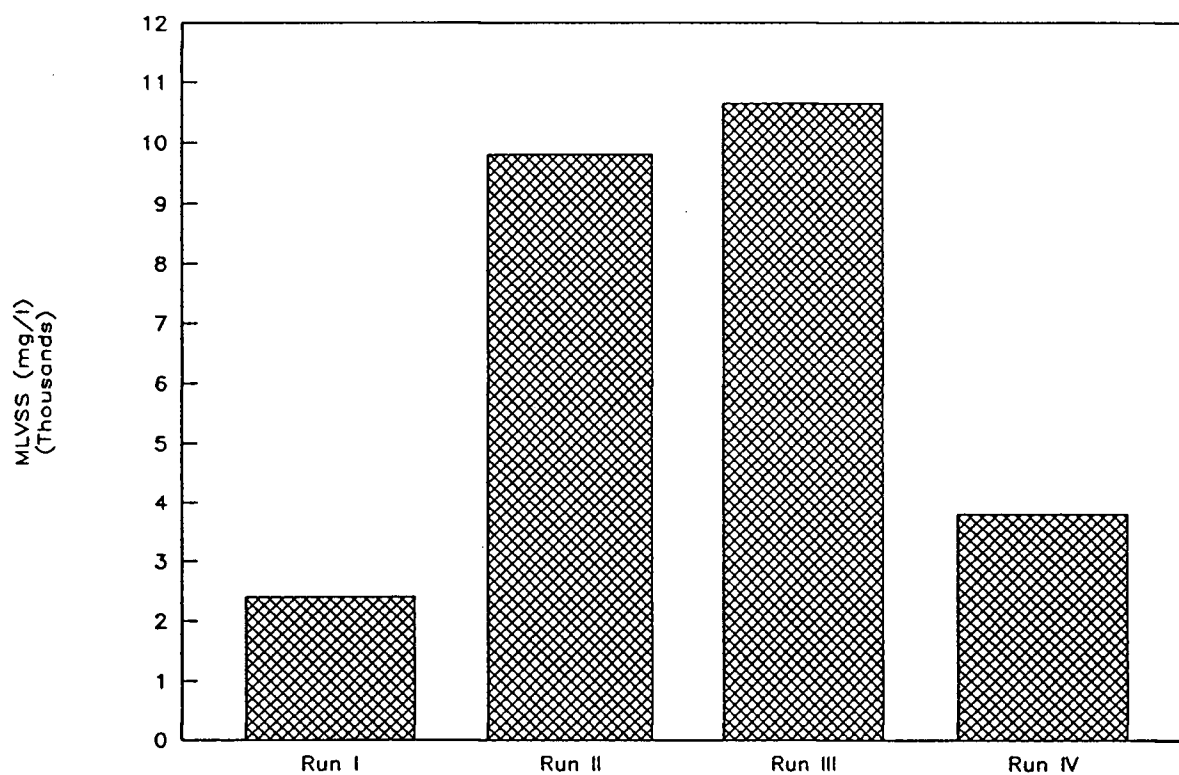
Figure 4.19 MLVSS concentration in the bio-reactor during runs I, II, III and IV.

4.2.11 NUTRIENT ADDITION

DATA ANALYSIS: Nutrients were measured as total Kjeldahl nitrogen (TKN), which determines the total organic nitrogen present, and as total phosphorus (TP). Table 4.10 shows data of the nutrient ratios for run I, II and III for influent and effluent CTMP wastewater.

Table 4.10 Ratio of nutrient addition of
             Carbon:Nitrogen:Phosphorus measured as BOD_5:TKN:TP

	BOD:TKN:TP ratio		
	HRT = 1 day	HRT = 1.5 days	HRT = 2 days
Raw CTMP wastewater	100:0.46:0.08	100:0.54:0.2	100:0.54:0.09
Influent with nutrient	100:5:1	100:5:1	100:5:1
RBC effluent	100:8.15:0.52	100:4.68:0.29	100:16.2:1.53
RBC effluent corrected	100:8.25:0.53	100:4.47:0.28	100:16.3:1.54

A mass balance was also done on the nitrogen and phosphorus addition to the RBC treatment system during steady state.

Nutrient   -   nutrient   =   nutrient consumed   +   ammonia
flowrate in   flowrate out   by bacteria   loss to the
                                                                  environment

Table 4.11 shows the results of the mass balance.

Table 4.11   Results of mass balance for nitrogen and phosphorus
flowrate for RBC treatment during runs I, II and III.

Nutrients	HRT (days)	Nutrient flowrate in (g/day)	Nutrient flowrate out (g/day)	Nutrients consumed by bacteria + ammonia loss
TKN	1	2.000	0.716	1.285
	1.5	1.296	0.178	1.118
	2	1.145	0.260	0.885
TP	1	0.401	0.046	0.355
	1.5	0.260	0.011	0.249
	2	0.228	0.025	0.203

DISCUSSION: The data from Table 4.10 indicated that the BOD_5:TKN:TP ratio measured in the raw wastewater was too low to encourage optimal microbial growth. Nitrogen and phosphorus were added to the wastewater at a conservative ratio of 100:5:1 to assure that nitrogen and phosphorus would not become limiting factors during this study. However, the RBC effluent data showed an increase of TKN during runs I and II (HRT = 2 days resp. 1 day). These results agree with previous research (Servizi and Gordon, 1986; Beak Consultants Ltd, 1986; and Schnell et al., 1990). During run III (HRT = 1.5 days) however, the nitrogen concentration did not change much.

The results of the mass balance from Table 4.11 indicate that nutrient consumption of the bacteria and possible ammonia loss increased when the BOD (COD) removal rate increased (see Figure 4.5 and 4.9).

Concentrations of effluent TKN ranged from 391 to 86 mg/l in the concentrated effluent and from 66 to 20 mg/l when correcting the effluent TKN concentration for evaporative water loss. These nitrogen concentrations are very high considering that the lethal level for ammonia is 0.2 mg/l (Servizi and Gordon, 1986).

4.3. OTHER ANALYSIS

4.3.1 'STERILE' RUN

OBJECTIVE: To investigate if volatile compounds could be removed simply by evaporation baseline runs though to be devoid of microbial activity were conducted at various HRT's as described in section 3.2.2.

PROCEDURE: 50 mg/l of mercuric chloride (HgCl$_2$) was added to the raw wastewater as described by Gledhill (1975) to try to sterilize the CTMP wastewater.

RESULTS: The raw data is presented in Appendix V, A.V.1. Equilibrium concentration results are shown in Table 4.5 and results of percent organic removals (BOD$_5$ and COD) are shown in Figure 4.20.

DISCUSSION: Each of the runs was carried out for two theoretical hydraulic retention times. After analyzing the BOD and COD data, it was a surprise to find out that both BOD and COD reductions were higher with HgCl$_2$ addition, than when it was not present, especially during run II (HRT=1 day) and run III (HRT=2 days). At first it was assumed that the cause was an analytical error and both, BOD and COD analyses were repeated twice with other sample effluents which had been collected during these runs, but the results were consistent. Since the organics had been somehow degraded the only other conclusion was that HgCl$_2$ addition failed to kill the active microorganisms.

To investigate further, the wastewater was plated on an agar nutrient media to find out if the runs were indeed sterile (see section 4.3.2). These tests revealed that the addition of mercuric chloride did not kill all the organisms present in the wastewater.

The BOD$_5$/COD removal ratio during these runs was almost 1:1 compared to the lower values (around 0.83) noted in section 4.2.4.3.

4.3.2 MICROBIOLOGY

OBJECTIVE: To investigate if the sterile runs (section 4.3.1) were indeed sterile.
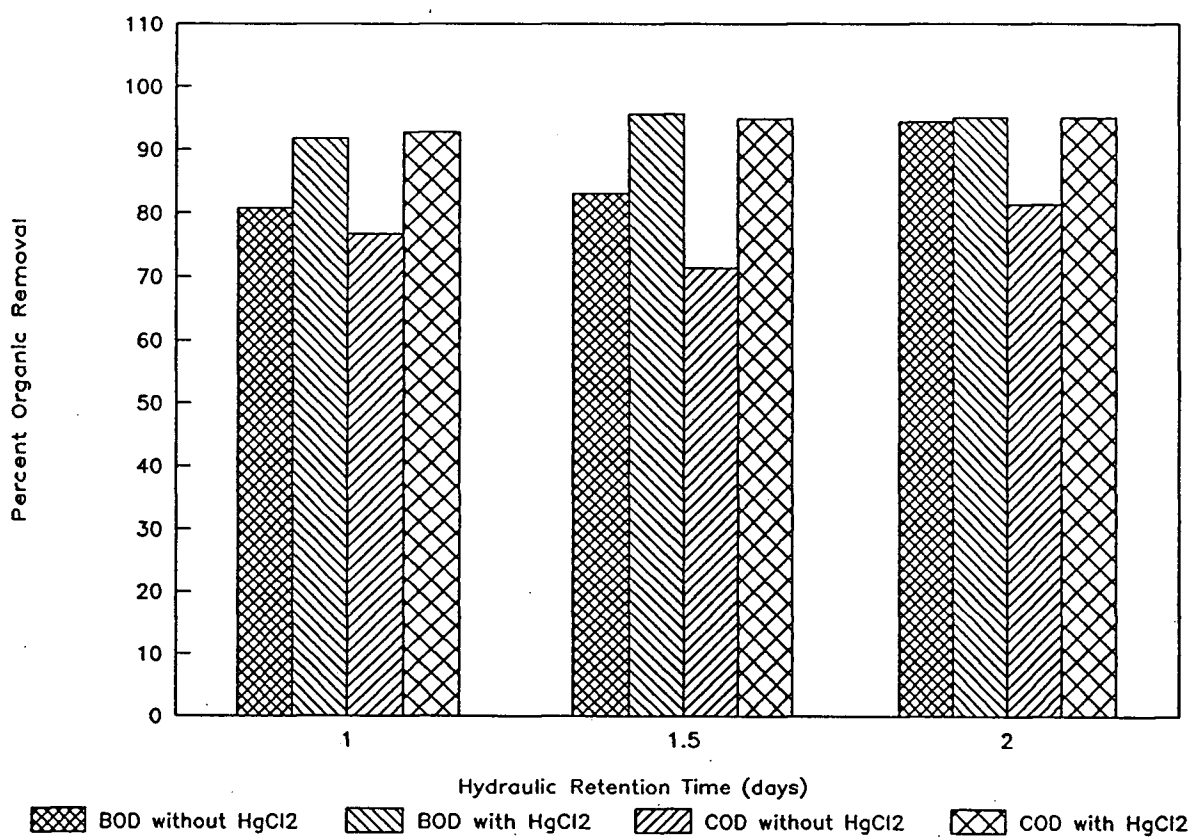
Figure 4.20   Comparison of %organic removals between bacterial and
'sterile' runs for runs I, II and III.

PROCEDURE: A grab sample of CTMP wastewater was plated as described in section 3.3.14 under the following conditions: (1) raw wastewater, (2) settled residue from wastewater, (3) raw wastewater with mercuric chloride addition, (4) raw wastewater inoculated with aerobic microorganism, (5) raw wastewater inoculated with aerobic microorganism and with mercuric chloride addition.

RESULTS: Photographs of the plates were taken after 48 hours of incubation (see Appendix V, Figure A.V.1).

DISCUSSION: Comparison of picture (4) and (5) in Figure A.V.1 indicates that the addition of $HgCl_2$ kills most bacteria, however organisms believed to be fungi were not affected by it. These photos suggest that bacteria and the fungi could be competing with each other and when bacteria are not inhibited, as by $HgCl_2$, they dominate over the fungi.

It is well known that fungi such as the white-rot fungus have been used in the past to degrade lignin (Joyce et al., 1983; Matsumoto et al., 1985), which may explain the high COD removal during these runs. It was also noted that the pH of the wastewater did not go up as much during the runs (see table 4.5) to which $HgCl_2$ was added as it did during the runs without $HgCl_2$.

Picture (1) did not show any bacterial growth in raw CTMP wastewater and consequently, when adding $HgCl_2$ to the same sample no growth was found on the plate in picture (3). However, when plating settled wastewater (2) some bacterial growth, pink in colour, was found on the plates. These bacteria may be facultative anaerobes.

4.3.3 START-UP RUN WITHOUT BIOMASS INOCULUM

OBJECTIVE: To investigate and confirm that BOD is not removed simply by evaporation as was indicated by the 'sterile run'.

PROCEDURE: Raw CTMP wastewater was added to the reactor without bacterial inoculum and the reactor was run under the same conditions as during run III for three hours. During this time measurements of D.O., pH, temperature in the RBC, BOD_{in}, BOD_{out} and MLVSS were done every

1/2 hour. After the test a sample was plated for possible microbial growth during the run.

RESULTS: Results are presented in Appendix V, A.V.2 and Figure A.V.1 (6). The pH increased from 5.91 to 6.4 and the BOD reduction increased from 3.17 to 10.08% during the three hours of the run. The D.O. concentration decreased from 7.7 to 6.2 mg/l while the temperature changed from 28 to 31°C, all other parameters stayed constant.

DISCUSSION: During the three hours of the run acetic acid may have been evaporated as its volatility is increased at an average pH of 6.25 or maybe microorganism started to grow on the discs. This decrease of acetic acid in the wastewater increased the pH as well as the BOD reduction.

Plating of the wastewater in the trough did not show any microbial growth (Figure A.V.1 (6)). The increase of temperature was probably responsible for the decrease in D.O., which did not reach steady state as fast as the other parameters (see also section 4.2.5).

4.3.4 HYDRAULIC CHARACTERIZATION OF THE REACTOR

OBJECTIVE: To obtain information on the hydraulic residence time distribution (RTD) and flow regime in the RBC.

PROCEDURE: A step change of sodium chloride tracer of concentration Co was added to the fluid stream entering the reactor and the time dependent tracer concentration in the exit stream (C) from the vessel was measured. The experimental procedures are described in chapter 3, section 3.2.2 and 3.3.7.

RESULTS: The raw data and the results are listed in Appendix VI. The effluent sodium chloride concentration obtained and measured as C/C_o is plotted as a function of time to show residence time distribution. Figure A.VI.1 (Appendix VI) shows a plot of the F-curve (step-change input).

DISCUSSION: The effluent conductivity (C) was corrected for a 25% water loss. The observed residence time distribution data for the RBC reactor was statistically analyzed to estimate the mean residence time, the variance and the dispersion number (Levenspiel, 1984). The analysis gave

estimates of the mean residence time of 35.1 hours which is close to the theoretical residence time of 36 hours. The variance or distribution about the mean (σ^2) was 1150.4 hours^2 and the corresponding σ_θ^2 was 0.932. To characterize the nonideal flow within the RBC vessel the dispersion model and the model for a network of ideal mixers (CSTR) in series were used. The dispersion model indicates plug flow condition, if the dispersion number is zero, and CSTR conditions if the dispersion number goes to ∞. The condition for using the dispersion model implies that there exists no stagnant pockets and no gross bypassing or short-circuiting of fluid in the vessel (Levenspiel, 1972). For a first approximation, assuming there was no backmixing the dispersion model for large extents of dispersion was used. Fitting this model gave a dispersion number of 0.2385 which is considered a large amount of dispersion and is close to the mixed flow regime (Levenspiel, Ch.9, Fig.17). Because the dispersion number and the variance both are large the tracer data of the RBC was also fitted to the CSTR in-series model which is given by the equation:

$$No. \, tanks = \frac{1}{\sigma_\theta^2}$$

This model indicates plugflow conditions for a large number of tanks and CSTR conditions for one tank. Its value was calculated as 1.073 tanks in-series which shows indeed that the reactor behaves like a CSTR.

For the RBC reactor design, these analysis indicate that: (1) good mixing is provided in the vessel leaving essentially no dead space; (2) short circuiting is eliminated due to the presence of the rotating media plates; (3) almost complete mixing is achieved in the reactor shown by the large dispersion number and by the CSTR in-series model.

It is pointed out that this model describes residence time distribution in a reactor with the biofilm on the media. It is postulated, though not tested, that the biofilm influences the movement of the

sodium chloride tracer through the system by causing tracer diffusion into and out of the biofilm (Riemer et al., 1980). The biofilm could therefore distort the residence time distribution in the reactor, resulting in a different degree of mixing. The same argument may be made for the water loss in the RBC which by decreasing the flowrate as water moves through the RBC could also distort the mixing regime resulting in poorer mixing.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the literature review and the experimental work of this study, the major results, together with the conclusions and recommendations drawn from them, are summarized as follows.

5.1 CONCLUSIONS

(1) For the ranges of HRT tested the percent BOD and COD removal were 86% BOD and 72% COD reductions at HRT=2 days; 83% BOD and 71% COD reductions at HRT=1.5 days; and 77% BOD and 63% COD reductions at HRT=1 day.

(2) Since most experiments were carried out at approximately 30°C high levels of evaporation occurred, because the lab scale RBC exposed a thin film of liquid to the air over an extensive surface. Water loss during runs I to III ranged between 75% and 87%. The average waterloss at 20°C (run IV) was 29%. ΔT and %RH were major parameters affecting the water loss of the RBC during this study. It was concluded that seasonal changes can have a major impact on evaporation when running an RBC system inside a temperature controlled building. Evaporation did not appear to have an effect on BOD and COD removal.

(3) Increase in flowrate (decrease in HRT) resulted in a slight decrease in percent BOD (COD) removed, an increase in organic loading rate and in BOD (COD) removal rate.

(4) For the range of temperatures tested, more BOD_5 and COD can be removed at higher temperatures. 85% BOD was removed at 31°C and 70.1% was removed at 20°C. A higher %COD/%BOD removal ratio of 0.861 at 31°C was found compared to a %COD/%BOD ratio of 0.654 at 20°C.

(5) For the ranges of treatment conditions studied, levels of dissolved oxygen, pH and MLVSS had

no distinct effect on BOD_5 and COD removal.

(6) Tests and calculations done to reveal the volatility of major volatile compounds present in the CTMP wastewater and possible BOD loss from the RBC trough to the environment caused by the high evaporation indicated that losses of acetic acid, H_2S and BOD_5 were negligible at the pH's tested.

(7) Start-up time was minimal; steady state seemed to prevail throughout the experiments.

(8) The RBC appeared to respond well to shock loadings caused by the flowrate change in going directly from run II to run III.

(9) A 'sterile' run using 50 mg/l of $HgCl_2$ revealed that mercuric chloride may inhibit bacteria, however other microorganisms such as fungi are not affected by it. Fungi appear to be able to attack COD much better than bacteria.

(10) BOD_5 oxidation lies between 60 to 65% of the ultimate BOD indicating that the oxidation of the CTMP wastewater used during this study is comparable to sewage. No nitrogenous oxygen demand was observed.

(11) The residence time distribution curve observed in the RBC reactor using a sodium chloride tracer revealed that the flow regime can be considered to be perfectly mixed.

(12) Levels of BOD_5 eliminated by the RBC treatment are comparable to those reported in the literature. At higher temperature COD removal results seemed promising compared to literature values.

(13) The HRT's required to achieve high levels of BOD removal are long suggesting that this process may be impractical for full-scale pulp mill installation.

(14) The BOD levels in the effluent are high even after correction for evaporation, thus more than one stage of treatment would be necessary to produce a dischargeable effluent.

5.2 RECOMMENDATIONS

Future research is recommended in the following areas.

(1) An increase in temperature indicated higher treatment efficiency at the temperatures tested during this study, especially for COD removal. Enclosing the RBC system to test for optimum treatment temperature may be the next logical step to do. Temperatures may be increased to levels were thermophilic bacteria become active.

(2) Using RBC's with more than one stage, separated by baffles is said to improve treatment efficiency. It is recommended to test an RBC with stages, possibly two to three. This may improve BOD_5 and COD removal further.

(3) Nitrogen levels of the RBC effluent were high during this study and it appeared that nutrient addition may be reduced. It is recommended to test if nutrients need to be added to the raw CTMP wastewater.

(4) Literature has shown that high BOD and COD reduction does not imply toxicity removal and it is suggested that the RBC effluent should be tested for toxicity.

(5) The 'sterile' run conducted in this study, as does some literature, indicates that fungi may better attack high molecular weight compounds, such as lignin. It would be of particular interest to use fungi in an RBC reactor, to see if COD could be reduced dramatically.

(6) Literature has shown that it is possible in CTMP effluent treatment to use anaerobic treatment followed by an aerobic post-treatment to reduce toxicity. It would be interesting to see how effective the RBC would be in effluent polishing after anaerobic treatment.

(7) The high levels of evaporation and the significant reductions in BOD experienced in this work with an RBC might be a way of getting rid of a lot of water in an attempt to approach a zero pulp mill effluent. If enough water could be removed perhaps the concentrated effluent could be incinerated. However, it should be kept in mind that in these experiments the temperature was kept high by adding heat. In a full-scale unit the temperature of the wastewater would decrease as a result

of evaporation.

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APPENDIX I

A.I.1 DAILY LOG OF RUN I

A.I.2 RAW DATA FROM RUN I

A.L1 DAILY LOG OF RUN I (July 20, 1990 - August 12, 1990)

Seeding of the reactor was started on July 19th, 1990. A biofilm started to grow right away, especially at the liquid surface and the media interface close to the shaft. After one day the biofilm was found to have a thickness of approximately 0.1 to 0.2 mm. The growth of the biofilm was monitored and after 3 days the biofilm had reached a thickness of approximately 0.5 to 0.8 mm. Its colour appeared whitish beige. The biomass started to slough off on day 5 (July 24, 1990), and at that time the thickness was estimated to be 0.8 to 0.9 mm for the discs closest to the wastewater inlet. The biomass thickness on the media decreased progressively towards the effluent end of the reactor to approximately 0.3 to 0.5 mm on the last few discs. The colour of the biomass on the media, by then, slowly changed to dark brown. It was hard to estimate the thickness of the biomass because of its shagginess. However, during the run the biomass started to slough off regularly at a thickness of approximately 1 mm forming large flocs in the trough. Biofilm regrew on the media quite rapidly. This phenomena occurred about once a week untill the end of the run. On day 10 (July 29th, 1990), a visible biofilm covering the plexiglass reactor blocked the view into the reactor. This biofilm increased however, the active surface area available for organic removal.

The flowrate was maintained at 7 l/day resulting in a HRT = 2 days. The temperature was set at 32 to 33⁰C, and sufficient wastewater from one batch of the QRP effluent was stored in the refrigerator to meet the requirements of run I.

After running the RBC for two days it was noticed that the effluent flowrate was much less than the influent flow rate and hardly any effluent was collected in the effluent bucket. Because of this high evaporation rate the influent and effluent volumetric flows were measured beginning on day 3 (July 23, 1990) of run I, to run IV to correct the outlet parameters for the water loss.

Measurements were taken from day 1 (July 20, 1990) and sampling was started on July 21st, 1990,

after one day of operation. A colorimetric method was used for COD measurements. Problems were encountered with this method, because of interferences caused by particles and precipitates. Underestimated measurements for high COD values were another problem known to exist in the colorimetric method. For the other three runs, a standard method, the open reflux method was used for COD analysis.

From July 30th to July 31st, 1990 the effluent volume had exceeded the influent volume and it was noticed that the glue joint at the top of the reactor between the waterbath and the reactor had a leak. The waterbath had to be shut off for regluing. On August 2nd, 1990 the reactor was reheated again. Thereafter, leakages between the waterbath and reactor occurred on August 8th, 9th, 11st and 12th, 1990. The effects of these leakages on the overall performance of the system were governed by variations in temperature (ranging from 21 to 33°C) and organic loading rate (ranging from 0.0079 to 0.0267 kg BOD/m^2/day). Finally, on August 12th, 1990 after 23 days of operation the reactor had to be shut down after leaks kept persisting.

The whole reactor was rebuilt in stainless steel after it was discovered that the acrylic material was warped. Part of the leakage problem originated, because the heat transfer between heating bath and the bio-reactor was much larger than originally thought. The high evaporation (up to 90%) in the trough resulted in a large temperature difference between the waterbath and the wastewater exceeding the maximum temperature before failure of acrylic.

The following observations were made throughout run I: (1) the colour of the effluent changed from an initial opaque milky colour of the raw wastewater to a dark reddish to purple brown colour after RBC treatment; (2) dewatering of the mixed liquor by vacuum filtration was found to be very difficult. Dewatering of the sludge taken from the discs by vacuum filtration was practically impossible. However, when the samples were subjected to 20 minutes of centrifuging, most of the water could be separated from the sludge.

A.1.2 RAW DATA FROM RUN I

Run I   DATA FOR ROTATING BIOLOGICAL CONTACTOR
2.0 days HRT

| DATE | DAY | TIME | VOLUME | | | % | | FLOWRATE | | | HRT |
| | | | in | out | net | volume | in | out | vapour | | |
		hour		liter		red.		liter/day			days
20/07/90	1										
21/07/90	2	21.75		1.70							
22/07/90	3	19.75									
23/07/90	4	28.50	11.50	3.20	8.30	72.17	9.68	2.69	6.99		1.51
24/07/90	5	21.25	8.80	2.20	6.60	75.00	9.94	2.48	7.45		1.47
25/07/90	6	29.58	8.10	3.60	4.50	55.56	6.57	2.92	3.65		2.22
26/07/90	7	21.42	6.90	2.52	4.38	63.48	7.73	2.82	4.91		1.89
27/07/90	8	27.42	8.20	1.16	7.04	85.85	7.18	1.02	6.16		2.04
28/07/90	9	18.33	5.30	3.12	2.18	41.13	6.94	4.09	2.85		2.11
29/07/90	10	31.75	8.05	2.64	5.41	67.20	6.09	2.00	4.09		2.40
30/07/90	11	25.25	7.90	5.57	2.33	29.49	7.51	5.29	2.21		1.95
31/07/90	12	23.25	5.60	8.15	-2.55	-45.54	5.78	8.41			2.53
01/08/90	13	20.42	4.50	3.24	1.26	28.00	5.29	3.81	1.48		2.76
02/08/90	14	24.00	5.80	4.60	1.20	20.69	5.80	4.60	1.20		2.52
03/08/90	15	24.50	6.70	1.40	5.30	79.10	6.56	1.37	5.19		2.23
04/08/90	16	24.50	5.20	0.84	4.36	83.85	5.09	0.82	4.27		2.87
06/08/90	17	17.00	11.00	1.14	9.86	89.64	15.53	1.61	13.92		0.94
07/08/90	18	29.33	8.75	2.12	6.63	75.77	7.16	1.73	5.43		2.04
08/08/90	19	24.25	5.80	4.20	1.60	27.59	5.74	4.16	1.58		2.55
09/08/90	20	23.58	6.30	4.10	2.20	34.92	6.41	4.17	2.24		2.28
10/08/90	21	24.17	8.35	1.86	6.49	77.72	8.29	1.85	6.44		1.76
11/08/90	22	22.17	7.00	2.80	4.20	60.00	7.58	3.03	4.55		1.93
12/08/90	23	19.25	5.20	3.55	1.65	31.73	6.48	4.43	2.06		2.25
Average						52.67	7.37	3.17	4.56		2.11
Stand. dev.						31.54	2.25	2.25	2.90		0.45

Run I
2.0 days HRT

DATE	DAY	TEMPERATURE in degree Celsius		D.O.			pH			BOD	
		in	out	in	mid mg/l	out	in	mid	out	in	out mg/l
20/07/90	1	31.5	30.5	0.20	0.70	0.50	8.26	8.32	8.35		
21/07/90	2	32.0	32.0	0.10	0.30	0.20	8.38	8.39	8.38	3100	2700
22/07/90	3	34.0	34.0	0.30	0.50	0.60	8.50	8.52	8.53	3100	1950
23/07/90	4	33.0	33.0	0.60	0.85	0.70	8.67	8.69	8.70	3100	1000
24/07/90	5	34.0	34.0	0.40	0.80	0.90	8.65	8.68	8.69	3100	1100
25/07/90	6	35.0	33.0	0.50	0.60	0.50	8.68	8.70	8.71	3400	1760
26/07/90	7	35.0	33.0	0.50	0.60	0.50	8.65	8.69	8.70	3400	2070
27/07/90	8	35.0	33.5	0.40	0.40	0.40	8.75	8.76	8.77	3400	1200
28/07/90	9	34.0	33.0	0.90	0.95	1.15	8.82	8.85	8.87	2800	1800
29/07/90	10	34.5	33.5	0.35	0.85	1.05	8.81	8.82	8.83	2800	1910
30/07/90	11	34.0	33.0	0.90	1.30	1.60	8.72	8.75	8.76	2800	1060
31/07/90	12	35.5	33.0	0.90	2.45	3.15	8.54	8.60	8.63	2800	700
01/08/90	13	22.0	21.0	1.75	2.65	4.40	8.52	8.55	8.56	2600	640
02/08/90	14	23.0	22.5	3.20	2.70	2.10	8.55	8.55	8.54	2600	400
03/08/90	15	32.0	32.0	0.60	1.20	0.60	8.73	8.72	8.71	2600	590
04/08/90	16	33.0	32.5	0.65	0.75	0.30	8.71	8.73	8.72	3010	750
06/08/90	17	33.0	33.0	1.35	1.25	0.80	8.80	8.80	8.81	3010	480
07/08/90	18	34.5	31.0	0.70	1.20	2.00	8.73	8.76	8.82	3010	710
08/08/90	19	33.0	28.0	0.50	3.20	3.20	8.44	8.68	8.77	3010	300
09/08/90	20	34.0	32.0	0.10	0.40	0.20	8.62	8.66	8.65		
10/08/90	21	34.0	33.0	0.25	0.45	0.15	8.83	8.85	8.86	3430	510
11/08/90	22	34.0	31.0	0.25	0.85	0.20	8.86	8.89	8.88	3430	530
12/08/90	23	24.0	23.0	0.90	1.00	1.00	8.85	8.88	8.88	2700	440
Average							8.66	8.69	8.70	3010	
Stand. dev.							0.16	0.14	0.14	278	

Run I
2.0 days HRT

DATE	DAY	BODred. %	BODremov rate mg/hr	BOD accum. in tank %	Org.Load. rate kg BOD/ day*m2	in	COD out mg/l	CODred. %	CODremov rate mg/l
20/07/90	1								
21/07/90	2								
22/07/90	3					4720	3240		
23/07/90	4	91.02	1139	32.26	0.0172	4720	3240	80.90	1541
24/07/90	5	91.13	1170	35.48	0.0176	4720	3660	80.61	1576
25/07/90	6	76.99	717	51.76	0.0128	4660	3660	65.09	831
26/07/90	7	77.76	852	60.88	0.0150	4660	3720	70.85	1063
27/07/90	8	95.01	966	35.29	0.0139	4660	2640	91.99	1282
28/07/90	9	62.16	503	64.29	0.0111	4920	3680	55.97	796
29/07/90	10	77.63	551	68.21	0.0097	4920	3230	78.47	979
30/07/90	11	73.31	642	37.86	0.0120	4920	2980	57.29	882
31/07/90	12	63.62	429	25.00	0.0092	4920	2430	28.12	333
01/08/90	13	82.28	471	24.62	0.0079	4520	2380	62.09	618
02/08/90	14	87.80	552	15.38	0.0086	4520	2640	53.68	586
03/08/90	15	95.26	677	22.69	0.0098	4520	2640	87.80	1085
04/08/90	16	95.97	613	24.92	0.0088	4460	2800	89.86	851
06/08/90	17	98.35	1915	15.95	0.0267	4460	1590	96.31	2779
07/08/90	18	94.28	847	23.59	0.0123	4460	1820	90.11	1199
08/08/90	19	92.78	668	9.97	0.0099	4460	2240	63.63	679
09/08/90	20								
10/08/90	21	96.69	1146	14.87	0.0163	4560	2280	88.86	1400
11/08/90	22	93.82	1016	15.45	0.0149	4560	2320	79.65	1147
12/08/90	23	88.87	648	16.30	0.0100	3840	2520	55.20	573
Average		86.04	817	31.30	0.0128	4609		72.45	1063
Stand. dev.		10.85	346	17.43	0.0044	239		17.25	522

Run I
2.0 days HRT

DATE	DAY	COD accum. in tank %	Org.Load. rate kg COD/ day*m2	in	TKN out mg/l	out correct.	in	T.PHOS. out mg/l	out correct.
20/07/90	1								
21/07/90	2								
22/07/90	3								
23/07/90	4	68.64	0.0261						
24/07/90	5	77.54	0.0268						
25/07/90	6	78.54	0.0175						
26/07/90	7	79.83	0.0206						
27/07/90	8	56.65	0.0191						
28/07/90	9	74.80	0.0195						
29/07/90	10	65.65	0.0171						
30/07/90	11	60.57	0.0211						
31/07/90	12	49.39	0.0163						
01/08/90	13	52.65	0.0137						
02/08/90	14	58.41	0.0150						
03/08/90	15	58.41	0.0170						
04/08/90	16	62.78	0.0130						
06/08/90	17	35.65	0.0396						
07/08/90	18	40.81	0.0182						
08/08/90	19	50.22	0.0146						
09/08/90	20								
10/08/90	21	50.00	0.0216						
11/08/90	22	50.88	0.0197	16.3	85.7	34.3	2.69	8.11	3.24
12/08/90	23	65.63	0.0142						
Average		59.84	0.0195						
Stand. dev.		12.21	0.0060						

Run I
2.0 days HRT

DATE	DAY	TS in	TS out mg/l	VS in	VS out mg/l	TSS in	TSS out mg/l	VSS in	VSS out mg/l
20/07/90	1								
21/07/90	2								
22/07/90	3								
23/07/90	4								
24/07/90	5								
25/07/90	6								
26/07/90	7								
27/07/90	8								
28/07/90	9								
29/07/90	10								
30/07/90	11								
31/07/90	12								
01/08/90	13								
02/08/90	14								
03/08/90	15								
04/08/90	16								
06/08/90	17								
07/08/90	18								
08/08/90	19	6200	6700	4200	1900	3600	4950	250	1400
09/08/90	20								
10/08/90	21								
11/08/90	22								
12/08/90	23								

Average
Stand. dev.

Run I
2.0 days HRT

DATE	DAY	MLVSS mg/l
20/07/90	1	
21/07/90	2	
22/07/90	3	
23/07/90	4	
24/07/90	5	
25/07/90	6	
26/07/90	7	
27/07/90	8	
28/07/90	9	
29/07/90	10	
30/07/90	11	
31/07/90	12	
01/08/90	13	
02/08/90	14	
03/08/90	15	
04/08/90	16	
06/08/90	17	
07/08/90	18	
08/08/90	19	2400
09/08/90	20	
10/08/90	21	
11/08/90	22	
12/08/90	23	

Average
Stand. dev.

APPENDIX II

A.II.1 DAILY LOG OF RUN II

A.II.2 RAW DATA FROM RUN II

A.II.1 DAILY LOG OF RUN II (November 15, 1990 - December 12, 1990)

The stainless steel reactor was operational from mid-November 1990. This new reactor had a smaller liquid volume of 12.07 litres. After achieving a good BOD and COD removal in run I at HRT = 2 days, the flowrate for run II was set at 12 l/day resulting in an HRT = 1 day, with all other parameters remaining the same as in run I.

Seeding of the reactor was started on November 15th, 1990. Within one day a biomass of 0.5 mm thickness formed on the discs. After running the system for 3 days on November 18th, 1990 the biofilm thickness was approximately 1 mm. Sloughing and regrowing of the biomass occurred the same way as in run I. Every week, the biomass thickness would increase to 3 to 4 mm before sloughing off the media, especially on the first ten discs at the influent end. It was observed that the biomass was growing much faster because of the increased organic loading rate. This fast growth rate of sludge and the very small effluent flowrate resulted in a negligible washout of biomass. The biomass concentration in the trough was increased rapidly, and consequently the dissolved oxygen concentration was close to zero throughout run II indicating possible anaerobic conditions in the trough.

Measurements were taken starting November 16th, 1990 (day 2) and sampling was started on November 17th, 1990 (day 3). Our measurements, in tune with literature values, suggested the presence of volatile compounds in the wastewater. The possibility of these volatile compounds being removed by evaporation lead to further analysis of the RBC effluent. To determine whether or not this was of importance, influent and effluent samples were analyzed for acetic acid concentration and because of the suspected anaerobic conditions in the bio-reactor tests for hydrogen sulfide (H_2S) were also performed.

On November 20th, 1990 the constant temperature bath had to be replaced by a larger unit with

higher heating capacity to keep an average temperature of 33°C. On November 27th, 1990 power failure at the University of British Columbia for 4 hours provided the opportunity to clean out 700 ml of sludge accumulated in the bio-reactor.

The following observations were made throughout run II: (1) The colour of the RBC effluent was not so dark as observed in run I and its colour was reddish brown; (2) the colour of the biomass attached to the media was brown and also seemed lighter than in run I.

The overall performance of the RBC appeared less efficient during this run as compared to run I, despite the leakage problems in run I.

A.II.2 RAW DATA FROM RUN II

Run II   DATA FOR ROTATING BIOLOGICAL CONTACTOR
1 day HRT

DATE	DAY	TIME hour	in	VOLUME out liter	net	% volume red.	in	FLOWRATE out liter/day	vapour	HRT days
15/11/90	1									
16/11/90	2	25.08	14.50	5.50	9.00	62.07	13.88	5.26	8.61	0.87
17/11/90	3	24.88	13.20	3.90	9.30	70.45	12.73	3.76	8.97	0.95
18/11/90	4	22.27	11.70	3.40	8.30	70.94	12.61	3.66	8.94	0.96
19/11/90	5	21.98	11.40	3.50	7.90	69.30	12.45	3.82	8.63	0.97
20/11/90	6	23.47	11.75	3.40	8.35	71.06	12.02	3.48	8.54	1.01
21/11/90	7	24.60	12.60	3.35	9.25	73.41	12.29	3.27	9.02	0.98
22/11/90	8	23.37	11.50	3.10	8.40	73.04	11.81	3.18	8.63	1.02
23/11/90	9	24.27	12.00	2.10	9.90	82.50	11.87	2.08	9.79	1.02
24/11/90	10	22.27	11.00	3.75	7.25	65.91	11.85	4.04	7.81	1.02
25/11/90	11	25.20	12.30	3.40	8.90	72.36	11.71	3.24	8.48	1.03
26/11/90	12	24.95	11.75	2.90	8.85	75.32	11.30	2.79	8.51	1.07
27/11/90	13	21.50	8.90	2.00	6.90	77.53	9.93	2.23	7.70	1.22
28/11/90	14	20.62	10.40	2.40	8.00	76.92	12.10	2.79	9.31	1.00
29/11/90	15	27.38	13.30	3.70	9.60	72.18	11.66	3.24	8.41	1.04
30/11/90	16	28.00	14.60	1.70	12.90	88.36	12.51	1.46	11.06	0.97
01/12/90	17	18.07	8.60	0.75	7.85	91.28	11.42	1.00	10.43	1.06
02/12/90	18	25.38	13.20	1.10	12.10	91.67	12.48	1.04	11.44	0.97
03/12/90	19	23.22	10.75	0.90	9.85	91.63	11.11	0.93	10.18	1.09
04/12/90	20	25.72	12.40	1.60	10.80	87.10	11.57	1.49	10.08	1.04
05/12/90	21	18.32	8.30	1.40	6.90	83.13	10.87	1.83	9.04	1.11
06/12/90	22	23.30	11.70	1.70	10.00	85.47	12.05	1.75	10.30	1.00
07/12/90	23	23.12	11.60	1.90	9.70	83.62	12.04	1.97	10.07	1.00
Average						77.97	11.92	2.65	9.27	1.02
Stand. dev.						8.59	0.76	1.13	0.98	0.07

Run II
1 day HRT

DATE	DAY	TEMPERATURE			D.O.				pH			
		in	out	in	mid	out	in	mid	out	infl.	effl.
		degree	Cels.		mg/l						
15/11/90	1	18.0	17.0	0.25	0.10	0.20	8.02	8.08	8.09		
16/11/90	2	32.0	32.0	0.20	0.25	0.10	7.75	8.44	8.45		8.39
17/11/90	3	31.0	31.0	0.10	0.15	0.15	8.04	8.61	8.64		8.67
18/11/90	4	30.0	30.5	0.20	0.15	0.30	8.35	8.74	8.75		8.68
19/11/90	5	31.0	31.5	0.20	0.40	0.50	8.50	8.76	8.79		8.80
20/11/90	6	32.0	31.5	0.10	0.05	0.10	8.29	8.80	8.80		8.84
21/11/90	7	32.0	31.0	0.40	0.30	0.25	7.58	8.83	8.83		8.81
22/11/90	8	33.0	31.5	0.40	0.30	0.20	8.48	8.83	8.83		8.82
23/11/90	9	33.0	31.0	0.30	0.25	0.20	7.55	8.81	8.80		8.78
24/11/90	10	32.5	31.5	0.10	0.15	0.25	7.68	8.83	8.83		8.76
25/11/90	11	33.0	31.0	0.40	0.35	0.30	7.54	8.83	8.83		8.82
26/11/90	12										
27/11/90	13	33.5	32.0	0.30	0.30	0.25	8.88	8.87	8.89		
28/11/90	14	31.0	32.0	0.35	0.25	0.20	8.81	8.81	8.80		8.72
29/11/90	15	31.0	31.0	0.10	0.20	0.15	8.77	8.81	8.82		8.87
30/11/90	16	35.0	35.0	0.30	0.25	0.20	8.94	8.92	8.87		
01/12/90	17	35.0	36.0	0.15	0.25	0.30	9.06	9.07	9.07		9.08
02/12/90	18	33.5	34.5	0.55	0.60	0.50	8.93	8.96	8.95		
03/12/90	19	32.0	33.5	0.05	0.10	0.05	8.99	8.98	8.98		9.13
04/12/90	20	32.0	33.5								
05/12/90	21	32.0	33.5	0.40	0.40	0.30	9.08	9.11	9.10	6.49	8.99
06/12/90	22	34.0	34.0	0.30	0.50	0.50	8.92	8.93	8.93		
07/12/90	23	33.0	33.0	0.20	0.30	0.30	8.96	8.98	8.95	6.34	9.01
Average		32.45	32.40	0.26	0.27	0.25	8.43	8.81	8.81	6.42	
Stand. dev.		1.28	1.51	0.13	0.14	0.13	0.55	0.22	0.21	0.08	

Run II
1 day HRT

DATE	DAY	in	BOD out mg/l	BODred. %	BODremov rate mg/hr	BOD accum. in tank %	Org.Load. rate kg BOD/ day*m2	Filtered in	out mg/l	BOD red. %
15/11/90	1									
16/11/90	2	3400	1800	79.92	1571	52.94	0.0270			
17/11/90	3	3100	2000	80.94	1331	64.52	0.0226	3000	1600	84.24
18/11/90	4	3500	3100	74.26	1366	88.57	0.0252			
19/11/90	5	3500	3000	73.68	1338	85.71	0.0249			
20/11/90	6	4500	4600	70.42	1586	102.22	0.0309			
21/11/90	7	4500	4500	73.41	1692	100.00	0.0316	4250	4200	73.73
22/11/90	8	3900	3700	74.43	1428	94.87	0.0263			
23/11/90	9									
24/11/90	10	5400	4350	72.54	1935	80.56	0.0366			
25/11/90	11	4550	4250	74.18	1647	93.41	0.0305	4450	4050	74.84
26/11/90	12									
27/11/90	13									
28/11/90	14	4300	3550	80.95	1756	82.56	0.0297			
29/11/90	15	4150	3600	75.87	1529	86.75	0.0276	4050	3100	78.71
30/11/90	16									
01/12/90	17	2600	2750	90.78	1123	105.77	0.0170			
02/12/90	18									
03/12/90	19	3000	3150	91.21	1267	105.00	0.0190			
04/12/90	20									
05/12/90	21	2800	4800	71.08	902	171.43	0.0174	2350	3800	72.72
06/12/90	22									
07/12/90	23	2700	4200	74.52	1010	155.56	0.0186	2300	3850	72.58
Average		3685		77.21	1432	97.99	0.0257	3400		76.14
Stand. dev.		859		6.23	274	29.36	0.0056	972		4.16

Run II
1 day HRT

DATE	DAY	in	COD out mg/l	CODred. %	CODremov rate mg/hr	COD accum. in tank %	Org.Load. rate kg COD/ day*m2	Filtered in	COD out mg/l	COD red. %
15/11/90	1									
16/11/90	2	7300	5150	73.24	3091	70.55	0.0579			
17/11/90	3	7300	8500	65.60	2541	116.44	0.0531	5800	6750	65.62
18/11/90	4	8000	9400	65.85	2768	117.50	0.0576			
19/11/90	5	8000	11150	57.21	2374	139.38	0.0569			
20/11/90	6	7850	11650	57.06	2242	148.41	0.0539			
21/11/90	7	7850	12400	58.00	2332	157.96	0.0551	7200	11600	57.16
22/11/90	8	8000	11600	60.91	2398	145.00	0.0540			
23/11/90	9									
24/11/90	10	8450	11500	53.60	2237	136.09	0.0572			
25/11/90	11	8350	13250	56.14	2288	158.68	0.0559	7000	10600	58.14
26/11/90	12									
27/11/90	13									
28/11/90	14	7850	12400	63.55	2516	157.96	0.0543			
29/11/90	15	7750	11150	59.98	2258	143.87	0.0516	6500	9650	58.70
30/11/90	16									
01/12/90	17	7550	15600	81.98	2946	206.62	0.0493			
02/12/90	18									
03/12/90	19	8350	22800	77.14	2982	273.05	0.0530	5800	15250	77.99
04/12/90	20									
05/12/90	21	8500	22700	54.95	2116	267.06	0.0528	6650	17800	54.85
06/12/90	22									
07/12/90	23	8400	19950	61.10	2575	237.50	0.0578	6850	18750	55.17
Average		7973		63.09	2511	165.07	0.0547	6543		61.09
Stand. dev.		422		7.93	294	55.00	0.0025	556		7.65

Run II
1 day HRT

DATE	DAY	in	Acetic out mg/l	Acid out correct.	red. %	BOD Acet. in	Acid out mg/l	COD Acet. in mg/l	Acid out mg/l
15/11/90	1								
16/11/90	2								
17/11/90	3								
18/11/90	4								
19/11/90	5	463.40	123.63	37.96	91.81	417.06	111.27	478.85	127.75
20/11/90	6								
21/11/90	7								
22/11/90	8								
23/11/90	9								
24/11/90	10	413.13	87.70	29.90	92.76	371.82	78.93	426.90	90.62
25/11/90	11								
26/11/90	12								
27/11/90	13								
28/11/90	14	442.71	115.35	26.62	93.99	398.44	103.82	457.47	119.20
29/11/90	15								
30/11/90	16								
01/12/90	17	382.79	100.25	8.74	97.72	344.51	90.23	395.55	103.59
02/12/90	18								
03/12/90	19								
04/12/90	20								
05/12/90	21	408.79	33.03	5.57	98.64	367.91	29.73	422.42	34.13
06/12/90	22								
07/12/90	23								
Average		422.16				379.95		436.24	
Stand. dev.		31.36				28.22		32.41	

Run II
1 day HRT

DATE	DAY	in	TKN out mg/l	out correct.	Filt. out mg/l	TKN out correct.	in	T.PHOS. out mg/l	out correc.	Filt. T.PHOS. out mg/l
15/11/90	1									
16/11/90	2									
17/11/90	3									
18/11/90	4									
19/11/90	5									
20/11/90	6									
21/11/90	7									
22/11/90	8									
23/11/90	9									
24/11/90	10									
25/11/90	11									
26/11/90	12									
27/11/90	13									
28/11/90	14									
29/11/90	15									
30/11/90	16									
01/12/90	17									
02/12/90	18									
03/12/90	19									
04/12/90	20									
05/12/90	21	16.4	391	66.0	221	37.3	3	25	4.2	12
06/12/90	22									
07/12/90	23									

Average
Stand. dev.

Run II
1 day HRT

DATE	DAY	Filt. T.PHOS. out correc.	in	TS out mg/l	in	VS out mg/l	in	TSS out mg/l	in	VSS out mg/l
15/11/90	1									
16/11/90	2									
17/11/90	3									
18/11/90	4									
19/11/90	5									
20/11/90	6									
21/11/90	7									
22/11/90	8									
23/11/90	9									
24/11/90	10									
25/11/90	11									
26/11/90	12									
27/11/90	13									
28/11/90	14									
29/11/90	15									
30/11/90	16									
01/12/90	17									
02/12/90	18		2000	15400	900	10350	5000	13900	800	9050
03/12/90	19									
04/12/90	20									
05/12/90	21	2.0	2000	12500	900	7500	4850	11850	900	4350
06/12/90	22									
07/12/90	23									
Average			2000	13950	900	8925	4925	12875	850	6700
Stand. dev.			0	1450	0	1425	75	1025	50	2350

Run II
1 day HRT

DATE	DAY	MLVSS mg/l	MLTSS mg/l	in	Sulfate SO4 out mg/l	correct. out	in	Sulfite SO3 out mg/l	Sulfite correct. out
15/11/90	1								
16/11/90	2								
17/11/90	3								
18/11/90	4								
19/11/90	5								
20/11/90	6								
21/11/90	7								
22/11/90	8								
23/11/90	9								
24/11/90	10								
25/11/90	11								
26/11/90	12								
27/11/90	13								
28/11/90	14		6000						
29/11/90	15		8800						
30/11/90	16		9750						
01/12/90	17	9100	10350						
02/12/90	18		10600						
03/12/90	19		8450						
04/12/90	20		10700						
05/12/90	21	10500	11950	430	2750	463.86	69.5	59.5	10.0
06/12/90	22								
07/12/90	23			440	3450	565.09	61.5	48.0	7.9
Average		9800	9575	435			65.5		
Stand. dev.		700	1704	5			4.0		

Run II
1 day HRT

DATE	DAY	Sulfide	
		S	
		in	out
			mg/l
15/11/90	1		
16/11/90	2		
17/11/90	3		
18/11/90	4		
19/11/90	5		
20/11/90	6		
21/11/90	7		
22/11/90	8		
23/11/90	9		
24/11/90	10		
25/11/90	11		
26/11/90	12		
27/11/90	13		
28/11/90	14		
29/11/90	15		
30/11/90	16		
01/12/90	17		
02/12/90	18		
03/12/90	19		
04/12/90	20		
05/12/90	21	3.87	6.65
06/12/90	22		
07/12/90	23	3.22	5.02
Average		3.55	
Stand. dev.		0.33	

APPENDIX III

A.III.1 DAILY LOG OF RUN III

A.III.2 RAW DATA FROM RUN III

A.III.1 DAILY LOG OF RUN III (December 7, 1990 - December 28, 1990)

After completing run II, 2 litres of excess biomass were removed from the reactor and the tubing for the inlet and the outlet was replaced. Then the flowrate was started for run III. Because of the excess biomass growth caused by the high organic loading rate of run II, the flowrate for this run was set at 8 l/day resulting in an HRT = 1.5 days. All other parameters were kept the same as in run I and II.

Measurements were taken starting December 8th, 1990 and sampling was started on the same day. It was hoped that because of the increase in HRT the D.O. concentration would also increase, but this was not the case. It was then decided to measure the oxidation reduction potential to verify if conditions were indeed anaerobic as was suspected. All other measurements performed were the same as in run II.

The evaporation rate was higher during this run as expected, considering the decrease in the flowrate. Relative humidity measurements were taken every five days during this run to correlate the evaporation to various parameters.

The following observations were made throughout run III: (1) The colour of the effluent and of the attached biomass did not change from run II; (2) the growth and sloughing of biomass did not considerably change from run II.

On December 28th, 1990 all data needed for run III had been collected and the reactor was shut down and cleaned out. Shortly after a 'sterile run' was started. This experiment is described and discussed in section 4.3.1 to section 4.3.3.

A.III.2 RAW DATA FROM RUN III

Run III   DATA FOR ROTATING BIOLOGICAL CONTACTOR
1.5 days HRT

DATE	DAY	TIME hour	VOLUME in	VOLUME out liter	net	% volume red.	in	FLOWRATE out liter/day	vapour	HRT days
07/12/90	1									
08/12/90	2	24.63	12.60	2.00	10.60	84.13	12.28	1.95	10.33	0.98
09/12/90	3	18.03	8.10	1.00	7.10	87.65	10.78	1.33	9.45	1.12
10/12/90	4	21.28	9.30	1.00	8.30	89.25	10.49	1.13	9.36	1.15
11/12/90	5	24.33	10.40	1.10	9.30	89.42	10.26	1.09	9.17	1.18
12/12/90	6	26.00	11.10	1.00	10.10	90.99	10.25	0.92	9.32	1.18
13/12/90	7	29.33	12.20	1.50	10.70	87.70	9.98	1.23	8.76	1.21
14/12/90	8	17.05	7.10	0.90	6.20	87.32	9.99	1.27	8.73	1.21
15/12/90	9	31.00	12.40	1.50	10.90	87.90	9.60	1.16	8.44	1.26
16/12/90	10									
17/12/90	11	23.33	9.30	1.10	8.20	88.17	9.57	1.13	8.44	1.26
18/12/90	12	26.17	11.40	1.45	9.95	87.28	10.45	1.33	9.12	1.16
19/12/90	13	21.50	8.20	1.20	7.00	85.37	9.15	1.34	7.81	1.32
20/12/90	14	21.75	8.20	1.20	7.00	85.37	9.05	1.32	7.72	1.34
21/12/90	15	23.58	8.10	1.00	7.10	87.65	8.24	1.02	7.23	1.47
22/12/90	16	22.58	8.80	1.10	7.70	87.50	9.35	1.17	8.18	1.29
23/12/90	17	27.72	10.30	1.40	8.90	86.41	8.92	1.21	7.71	1.35
24/12/90	18	23.93	8.70	1.20	7.50	86.21	8.73	1.20	7.52	1.38
25/12/90	19	26.97	9.70	1.30	8.40	86.60	8.63	1.16	7.47	1.40
26/12/90	20	24.17	9.00	1.20	7.80	86.67	8.94	1.19	7.75	1.35
27/12/90	21	20.40	7.60	0.90	6.70	88.16	8.94	1.06	7.88	1.35
28/12/90	22	23.22	8.70	1.10	7.60	87.36	8.99	1.29	8.94	1.34
Average						87.36	9.63	1.23	8.47	1.33
Stand. dev.						1.49	0.92	0.20	0.83	0.08

Run III
1.5 days HRT

DATE	DAY	TEMPERATURE in degree	out Celsius	in	D.O. mid mg/l	out	in	mid	O.R.P. out mV	infl.	effl.
07/12/90	1										
08/12/90	2	32.0	32.0	0.35	0.30	0.20					
09/12/90	3	31.0	31.0	0.40	0.30	0.30					
10/12/90	4	31.0	32.0	0.20	0.25	0.30					
11/12/90	5	31.0	31.0	0.30	0.30	0.30					
12/12/90	6	31.0	31.0	0.20	0.30	0.30					
13/12/90	7	31.0	31.0								
14/12/90	8	30.0	31.0	0.20	0.10	0.20	-270	-265	-260	-210	-179
15/12/90	9	30.5	31.0	0.30	0.25	0.20	-380	-340	-325	-275	-327
16/12/90	10										
17/12/90	11	31.0	30.0	0.30	0.25	0.20	-350	-310	-340	-200	-336
18/12/90	12	30.0	32.0	0.20	0.15	0.25	-355	-390	-330	-201	-339
19/12/90	13	29.0	29.0	0.50	0.40	0.50	-345	-370	-320	-214	-309
20/12/90	14	29.0	29.0	0.60	0.40	0.60	-350	-400	-310		
21/12/90	15	31.0	31.0	0.40	0.50	0.50	-330	-390	-375	-223	-330
22/12/90	16	30.0	31.5	0.20	0.30	0.20	-355	-400	-330	-242	-180
23/12/90	17	31.5	31.5	0.20	0.20	0.20	-285	-270	-275	-246	-214
24/12/90	18	31.0	32.0	0.10	0.20	0.20	-250	-240	-225		
25/12/90	19	28.0	29.0								
26/12/90	20	30.5	31.5	0.30	0.40	0.30	-260	-255	-250	-265	-290
27/12/90	21	32.5	31.0	0.20	0.30	0.30	-380	-380	-340	-226	-167
28/12/90	22	31.0	30.0	0.20	0.20	0.20	-380	-390	-300	-231	-272
Average		30.60	30.88	0.29	0.28	0.29	-330	-338	-306	-230	-268
Stand. dev.		1.05	0.99	0.13	0.10	0.12	47	59	41	24	66

Run III
1.5 days HRT

DATE	DAY	pH in	mid	out	infl.	effl.	BOD in	out mg/l	BODred. %	BODremov. rate mg/hr
07/12/90	1									
08/12/90	2	8.98	8.96	8.94						
09/12/90	3	9.04	9.03	9.03	6.37	9.03	3400	5200	81.12	1239
10/12/90	4	9.07	9.03	9.01	6.18	9.03	3450	6300	80.36	1212
11/12/90	5	9.02	9.03	9.04	6.38	8.99				
12/12/90	6	9.05	9.00	8.98	6.53	8.95	2800	4800	84.56	1011
13/12/90	7									
14/12/90	8	8.98	8.97	8.96	6.40	8.91	3900	4750	84.56	1373
15/12/90	9	9.04	9.06	9.04	6.45	8.97				
16/12/90	10									
17/12/90	11	8.96	8.97	8.95	6.52	8.97	2750	3700	84.09	922
18/12/90	12	8.97	8.72	8.98	6.53	8.95				
19/12/90	13	8.87	8.55	8.87	6.55	8.95	2900	4500	77.29	855
20/12/90	14	8.95	8.65	8.99						
21/12/90	15	8.95	8.69	8.92	6.36	8.97	3000	3900	83.95	865
22/12/90	16	8.95	8.35	8.9	6.26	8.91				
23/12/90	17	8.98	8.97	8.95	6.30	9.00	2800	2900	85.92	894
24/12/90	18	8.93	8.94	8.95						
25/12/90	19									
26/12/90	20	8.97	8.95	8.94	6.15	9.01	2500	2900	84.53	787
27/12/90	21	8.99	9.00	9.01	6.35	9.01				
28/12/90	22	8.51	8.83	8.93	6.22	8.97	2750	3350	82.47	850
Average		8.96	8.87	8.97	6.37		3025		82.89	1001
Stand. dev.		0.12	0.19	0.05	0.13		404		2.47	191

Run III
1.5 days HRT

DATE	DAY	BOD accum. in tank %	Org.Load. rate kg BOD/ day*m2	in	Filtered BOD out mg/l	red. %	in	COD out mg/l	CODred. %
07/12/90	1								
08/12/90	2						8450	21800	59.05
09/12/90	3	152.94	0.0209				8050	20350	68.79
10/12/90	4	182.61	0.0207	2900	4650	82.76	8500	22350	71.73
11/12/90	5						8600	21900	73.07
12/12/90	6	171.43	0.0164	2400	4050	84.80	8600	21900	77.06
13/12/90	7						8350	22450	66.94
14/12/90	8	121.79	0.0223				8400	20150	69.59
15/12/90	9						7500	20500	66.94
16/12/90	10								
17/12/90	11	134.55	0.0150				8000	21400	68.36
18/12/90	12						7700	19550	67.71
19/12/90	13	155.17	0.0152	2500	3900	77.17	7700	17100	67.50
20/12/90	14								
21/12/90	15	130.00	0.0141				7350	15700	73.63
22/12/90	16						6750	16100	70.19
23/12/90	17	103.57	0.0143	2450	2850	84.19	7700	16200	71.40
24/12/90	18								
25/12/90	19								
26/12/90	20	116.00	0.0128				7700	12650	78.10
27/12/90	21								
28/12/90	22	121.82	0.0141	2350	3100	81.02	8000	14500	73.92
Average		138.99	0.0166	2520		81.99	7959		70.99
Stand. dev.		24.26	0.0032	196		2.74	518		3.44

Run III
1.5 days HRT

DATE	DAY	CODremov. rate mg/hr	COD accum. in tank %	Org.Load. rate kg COD/ day*m2	in	Filtered COD out mg/l	red. %	Acetic in	Acid out mg/l
07/12/90	1								
08/12/90	2	2553	257.99	0.0593					
09/12/90	3	2488	252.80	0.0496					
10/12/90	4	2664	262.94	0.0509	7050	20100	69.34		
11/12/90	5	2686	254.65	0.0504					
12/12/90	6	2829	254.65	0.0504	6800	18500	75.49	491.50	21.33
13/12/90	7	2325	268.86	0.0476					
14/12/90	8	2434	239.88	0.0480	7450	18200	69.03		
15/12/90	9	2008	273.33	0.0411					
16/12/90	10								
17/12/90	11	2180	267.50	0.0437	6000	14400	71.61	469.00	22.69
18/12/90	12	2271	253.90	0.0460	6650	13900	73.41		
19/12/90	13	1982	222.08	0.0403					
20/12/90	14								
21/12/90	15	1859	213.61	0.0346	6800	15900	71.13	421.05	26.01
22/12/90	16	1846	238.52	0.0361					
23/12/90	17	2043	210.39	0.0392	6800	15550	68.92	431.38	35.29
24/12/90	18								
25/12/90	19								
26/12/90	20	2239	164.29	0.0393	6800	12250	75.98		
27/12/90	21							433.28	20.82
28/12/90	22	2216	181.25	0.0411	6600	12100	73.62		
Average		2289	238.54	0.0449	6772		72.06	449.24	
Stand. dev.		291	31.01	0.0063	362		2.56	26.63	

Run III
1.5 days HRT

DATE	DAY	Acetic Acid out correct.	red. %	BOD Acet.Acid in	out mg/l	COD Acet.Acid in	out mg/l	in	TKN out mg/l	out correct.
07/12/90	1									
08/12/90	2									
09/12/90	3									
10/12/90	4									
11/12/90	5									
12/12/90	6	1.92	99.61	442.35	19.20	507.88	22.04			
13/12/90	7									
14/12/90	8									
15/12/90	9									
16/12/90	10									
17/12/90	11	2.68	99.43	422.10	20.42	484.63	23.45			
18/12/90	12									
19/12/90	13									
20/12/90	14									
21/12/90	15	3.21	99.24	378.95	23.41	435.09	26.88			
22/12/90	16							16.2	159	19.9
23/12/90	17	4.80	98.89	388.24	31.76	445.76	36.47			
24/12/90	18									
25/12/90	19									
26/12/90	20									
27/12/90	21	2.47	99.43	389.95	18.74	447.72	21.51			
28/12/90	22									
Average				404.31		464.21				
Stand. dev.				23.96		27.51				

Run III
1.5 days HRT

DATE	DAY	Filtered TKN			T.PHOS.		Filtered T.PHOS.			TS
		out mg/l	out correct.	in	out mg/l	out correct.	out mg/l	out correct.	in	out mg/l
07/12/90	1									
08/12/90	2									
09/12/90	3									
10/12/90	4									
11/12/90	5									
12/12/90	6									
13/12/90	7									
14/12/90	8									
15/12/90	9									
16/12/90	10									
17/12/90	11									
18/12/90	12									
19/12/90	13									
20/12/90	14									
21/12/90	15									
22/12/90	16	141	17.6	6.12	9.76	1.22	4.22	0.53	6900	22250
23/12/90	17									
24/12/90	18									
25/12/90	19									
26/12/90	20								7350	22450
27/12/90	21									
28/12/90	22									
Average									7350	22350
Stand. dev.									225	100

Run III
1.5 days HRT

DATE	DAY	VS in	VS out mg/l	TSS in	TSS out mg/l	VSS in	VSS out mg/l	MLVSS mg/l	Sulfate SO4 in	Sulfate SO4 out mg/l	correct. out
07/12/90	1										
08/12/90	2										
09/12/90	3										
10/12/90	4										
11/12/90	5										
12/12/90	6										
13/12/90	7										
14/12/90	8										
15/12/90	9										
16/12/90	10										
17/12/90	11										
18/12/90	12										
19/12/90	13										
20/12/90	14										
21/12/90	15										
22/12/90	16	5050	7350	900	2450	900	2350	11850	440	4000	500
23/12/90	17										
24/12/90	18										
25/12/90	19										
26/12/90	20	5400	10850	1100	6250	1000	5200	9450			
27/12/90	21								470	4190	496
28/12/90	22										
Average		5225	9100	1000	4350	950	3775	10650	455		
Stand. dev.		175	1750	100	1900	50	1425	1200	15		

Run III
1.5 days HRT

DATE	DAY	in	Sulfite SO3 out mg/l	correct. out	in	Sulfide S out mg/l
07/12/90	1					
08/12/90	2					
09/12/90	3					
10/12/90	4					
11/12/90	5					
12/12/90	6					
13/12/90	7					
14/12/90	8					
15/12/90	9					
16/12/90	10					
17/12/90	11					
18/12/90	12					
19/12/90	13					
20/12/90	14					
21/12/90	15					
22/12/90	16	59.0	53.5	6.7	3.50	2.38
23/12/90	17					
24/12/90	18					
25/12/90	19					
26/12/90	20					
27/12/90	21	56.0	40.0	4.7	3.37	1.8
28/12/90	22					
Average		57.5			3.44	
Stand. dev.		1.5			0.07	

APPENDIX IV

A.IV.1 DAILY LOG OF RUN IV

A.IV.2 RAW DATA FROM RUN IV

A.IV.1 DAILY LOG OF RUN IV (May 1, 1991 - May 21, 1991)

After evaluating the data gathered up to this date it was evident that one more run was needed, this time with a temperature close to room temperature. After examining the data it was found that reasonably good organic removal was achieved during run III at HRT = 1.5 days. The flowrate for run IV was therefore set at 8 l/day (HRT = 1.5 days), temperature at 20°C constant in the bioreactor, with all other parameters remaining the same as in run I, II, and III.

The reactor was seeded and started up on May 1st, 1991. On the first day biomass started to grow on the discs but mostly at the liquid level and media interface, close to the shaft. After 2 days on May 2nd, 1991 the biomass covered all the discs and its thickness was approximately 0.3 mm. The colour of the biomass was brownish beige. The biomass grew well and by May 6th, 1991 (after 6 days) the biofilm had reached a thickness of about 1 mm. On May 11th, 1991 the biomass on the first 5 discs (on the influent end) had a thickness of approximately 2 mm which decreased progressively to about 0.8 mm thickness at the last disc (effluent end). On May 17th, 1991 it was noted that while the first 6 discs had biomass of beige white colour, the other 17 discs had biomass of more brownish beige colour. No sloughing of biomass from the discs occurred until May 24th, 1991, three weeks after start-up. After 24 days, bridging of biomass had started and progressed to cover the first half of the discs close to the shaft. The thickness of the biomass being 2-3 mm at the influent side, decreasing to about 1 mm on the discs at the effluent side. The thickness of the biomass at that point was very hard to estimate because of its shaggy surface.

Measurements were taken starting May 1st, 1991 and sampling was started on May 11th, 1991. For this run the following measurements were taken daily: Flow volume in and out, temperature in the reactor, room temperature, %RH, D.O., and pH. After evaluating the data obtained in the previous runs, it was observed that steady state had been reached approximately after 2 days. However, the

literature indicates that steady state for aerobic treatment systems should have been reached after 10 to 14 days. Based on this information sampling was started after 10 days of running the reactor. The analysis for the following parameters was done every second day for steady state data: BOD_5 and COD; and TS, VS, VSS, and MLVSS. Samples were taken beginning May 11th, 1991 until May 21st, 1991.

At this lower temperature lesser evaporation occurred than during the other runs and the bacterial wash out increased with the increasing effluent flowrate.

The following observations were made during this run: (1) The effluent colour was light reddish brown; (2) the biomass on the discs had a noticeably stronger texture than was observed during run I, II, and III and this might have contributed to the fact that sloughing occurred occurred after 24 days.

In general, the operation of the RBC during this run required very little attention and the run was much smoother than the other three runs.

A.IV.2 RAW DATA FROM RUN IV

Run IV   DATA FOR ROTATING BIOLOGICAL CONTACTOR
1.5 days HRT

DATE	DAY	TIME hour	in	VOLUME out liter	net	% volume red.	in	FLOWRATE out liter/day	vapour	HRT days
01/05/91	1									
02/05/91	2	24.30	10.55	7.50	3.05	28.91	10.42	7.41	3.01	1.16
03/05/91	3	25.63	10.80	7.40	3.40	31.48	10.11	6.93	3.18	1.19
04/05/91	4	24.37	10.30	7.40	2.90	28.16	10.14	7.29	2.86	1.19
05/05/91	5	22.83	8.30	5.50	2.80	33.73	8.73	5.78	2.94	1.38
06/05/91	6	24.28	9.10	6.70	2.40	26.37	9.00	6.62	2.37	1.34
07/05/91	7	25.57	9.60	6.40	3.20	33.33	9.01	6.01	3.00	1.34
08/05/91	8	21.32	8.30	5.90	2.40	28.92	9.34	6.64	2.70	1.29
09/05/91	9	24.00	8.80	6.50	2.30	26.14	8.80	6.50	2.30	1.37
10/05/91	10	24.17	9.40	6.90	2.50	26.60	9.33	6.85	2.48	1.29
11/05/91	11	27.75	11.00	8.00	3.00	27.27	9.51	6.92	2.59	1.27
12/05/91	12	19.75	7.30	5.10	2.20	30.14	8.87	6.20	2.67	1.36
13/05/91	13	24.07	8.90	6.50	2.40	26.97	8.87	6.48	2.39	1.36
14/05/91	14	23.57	8.20	6.00	2.20	26.83	8.35	6.11	2.24	1.45
15/05/91	15	22.42	7.40	5.10	2.30	31.08	7.92	5.46	2.46	1.52
16/05/91	16	23.58	8.70	6.10	2.60	29.89	8.85	6.21	2.65	1.36
17/05/91	17	24.50	9.00	6.20	2.80	31.11	8.82	6.07	2.74	1.37
18/05/91	18	24.58	8.90	6.50	2.40	26.97	8.69	6.35	2.34	1.39
19/05/91	19	24.25	8.40	6.20	2.20	26.19	8.31	6.14	2.18	1.45
20/05/91	20	25.13	8.70	6.40	2.30	26.44	8.31	6.11	2.20	1.45
21/05/91	21	23.53	9.30	6.90	2.40	25.81	9.49	7.04	2.45	1.27
Average						28.62	9.04	6.46	2.59	1.39
Stand. dev.						2.42	0.64	0.49	0.29	0.09

Run IV
1.5 days HRT

| DATE | DAY | TEMPERATURE | | | REL.HUM. | | D.O. | | | pH |
| | | in | out | room | RH | in | mid | out | in | mid |
		degree	Celsius		%		mg/l			
01/05/91	1	20.0	20.0	19.5	39.0	6.50	6.30	6.70	8.46	8.50
02/05/91	2	19.5	20.0	19.9	27.6	0.60	1.60	2.30	8.52	8.60
03/05/91	3	20.0	20.0	20.0	26.3	1.60	2.10	3.00	8.54	8.60
04/05/91	4	20.0	20.0	19.5	41.5	2.90	3.10	3.70	8.60	8.65
05/05/91	5	20.0	20.0	19.2	46.7	2.90	2.80	3.30	8.57	8.57
06/05/91	6	20.0	20.5	18.9	56.2	3.20	2.50	2.60	8.58	8.58
07/05/91	7	20.5	20.0	19.5	52.0	1.80	2.30	2.40	8.56	8.56
08/05/91	8	19.5	20.0	19.5	42.1	1.50	3.20	1.90	8.62	8.63
09/05/91	9	19.5	20.0	18.6	42.1	0.80	2.60	3.20	8.50	8.56
10/05/91	10	20.0	20.2	19.6	41.5	0.50	1.40	1.50	8.50	8.51
11/05/91	11	20.0	20.0	19.5	50.7	0.30	0.50	0.80	8.54	8.56
12/05/91	12	20.0	20.0	19.3	46.1	0.80	1.60	1.80	8.54	8.54
13/05/91	13	20.0	20.0	19.1	50.7	0.40	1.30	1.30	8.61	8.58
14/05/91	14	20.0	20.0	20.1	42.9	0.80	2.50	1.80	8.58	8.57
15/05/91	15	20.0	20.2	19.5	39.4	0.40	2.50	2.20	8.57	8.56
16/05/91	16	20.0	20.0	19.5	52.4	1.50	3.50	3.10	8.63	8.66
17/05/91	17	20.0	20.2	19.0	49.1	2.20	2.60	1.80	8.61	8.60
18/05/91	18	20.0	20.2	19.8	50.7	1.80	4.50	4.70	8.80	8.81
19/05/91	19	20.0	20.2	19.2	61.0	0.70	1.60	2.10	8.61	8.61
20/05/91	20	20.0	20.3	19.3	59.6	1.80	3.00	3.10	8.60	8.61
21/05/91	21	19.9	20.2	18.8	47.8	1.10	2.30	2.60	8.59	8.60
Average		19.95	20.10		46.32	1.42	2.42	2.47	8.58	8.59
Stand. dev.		0.22	0.14		8.72	0.88	0.88	0.91	0.06	0.06

Run IV
1.5 days HRT

DATE	DAY	out	pH infl.	in	BOD out mg/l	BOdred. %	BODremov rate mg/hr	BOD accum. in tank %	Org.Load. rate kg BOD/ day*m2
01/05/91	1	8.51	5.62						
02/05/91	2	8.62	5.65						
03/05/91	3	8.62	5.48						
04/05/91	4	8.66	5.45						
05/05/91	5	8.58	5.37						
06/05/91	6	8.58	5.53						
07/05/91	7	8.56	5.49						
08/05/91	8	8.61	5.62						
09/05/91	9	8.58	5.70						
10/05/91	10	8.49	5.57						
11/05/91	11	8.51	5.55	3600	1700	65.66	937	47.22	0.0196
12/05/91	12	8.54	5.57						
13/05/91	13	8.56	5.61	3550	1750	64.00	840	49.30	0.0180
14/05/91	14	8.51	5.61						
15/05/91	15	8.56	5.56	3550	1200	76.70	899	33.80	0.0161
16/05/91	16	8.65	5.57						
17/05/91	17	8.57	5.58	4300	2000	67.96	1073	46.51	0.0217
18/05/91	18	8.80	5.57						
19/05/91	19	8.61	5.52	3250	1250	71.61	806	38.46	0.0154
20/05/91	20	8.60	5.55						
21/05/91	21	8.61	5.49	2900	1000	74.42	853	34.48	0.0157
Average		8.59	5.56	3525	1483	70.06	901	41.63	0.0177
Stand. dev.		0.06	0.07	423	354	4.58	88	6.28	0.0023

Run IV
1.5 days HRT

DATE	DAY	in	COD out mg/l	CODred. %	CODremov rate mg/l	COD accum. in tank %	Org.Load. rate kg COD/ day*m2	in	TS out mg/l
01/05/91	1								
02/05/91	2								
03/05/91	3								
04/05/91	4								
05/05/91	5								
06/05/91	6								
07/05/91	7								
08/05/91	8								
09/05/91	9								
10/05/91	10								
11/05/91	11	7250	5900	40.82	1173	81.38	0.0394	7250	6925
12/05/91	12								
13/05/91	13	8000	6200	43.40	1284	77.50	0.0406		
14/05/91	14								
15/05/91	15	8500	6100	50.54	1418	71.76	0.0385		
16/05/91	16								
17/05/91	17	8150	6100	48.44	1450	74.85	0.0411		
18/05/91	18								
19/05/91	19	7950	5850	45.69	1258	73.58	0.0378		
20/05/91	20								
21/05/91	21	7900	5750	46.00	1436	72.78	0.0428	7225	6650
Average		7958	5983	45.81	1337	75.31	0.0400	7238	6788
Stand. dev.		518	160	3.16	104	3.26	0.0017	13	138

Run IV
1.5 days HRT

DATE	DAY	VS in	VS out mg/l	TSS in	TSS out mg/l	VSS in	VSS out mg/l	MLVSS mg/l
01/05/91	1							
02/05/91	2							
03/05/91	3							
04/05/91	4							
05/05/91	5							
06/05/91	6							
07/05/91	7							
08/05/91	8							
09/05/91	9							
10/05/91	10							
11/05/91	11	5225	4000	1000	2300	900	2200	3600
12/05/91	12							
13/05/91	13							
14/05/91	14							
15/05/91	15							
16/05/91	16							
17/05/91	17							
18/05/91	18							
19/05/91	19							
20/05/91	20							
21/05/91	21	5275	4000	900	2200	900	2000	4000
Average		5250	4000	950	2250	900	2100	3800
Stand. dev.		50	0	25	50	0	100	200

APPENDIX V

A.V.1 RAW DATA FROM 'STERILE' RUN

A.V.2 RESULTS FROM MICROBIAL PLATING

A.V.3 RAW DATA FROM START-UP RUN

WITHOUT MICROBIAL INOCULUM

A.V.2 RAW DATA FROM 'STERILE' RUN

DATA FOR ROTATING BIOLOGICAL CONTACTOR

Sterile Runs

RUNS	DATE	TIME		VOLUME			%		FLOWRATE			HRT
		hour	in	out liter	net		volume red.	in	out liter/day	of gas		days

1.0 days HRT:

	02/01/91	6.25	3.0	0.2	2.80	93.33	11.52	0.77	10.75	1.05
Average							11.52	0.77		

1.5 days HRT:

	04/01/91	17.73	6.2	0.2	6.00	96.77	8.39	0.27	8.12	1.44
Average							8.39	0.27		

2.0 days HRT:

	06/01/91	19.50	5.2	0.15	5.05	97.12	6.40	0.18	6.22	1.89
Average							6.40	0.18		

Sterile Runs

RUNS	DATE	TEMPERATURE in out degree Cels.		in	mid	pH out	infl.	effl.	BOD in	out mg/l
1.0 days HRT:										
	02/01/91	30.1	30.0	7.10	7.15	7.20	6.42	7.32	3650	4550
									3300	4000
Average									3475	4275
1.5 days HRT:										
	04/01/91	30.0	31.5	7.20	7.21	7.30	6.42	7.67	3650	5550
									3300	4000
Average									3475	4775
2.0 days HRT:										
	06/01/91	31.0	31.5	7.35	7.40	7.55	6.41	7.97	3650	5350
									3300	6550
Average									3475	5950

Sterile Runs

RUNS	DATE	BODred. %	COD in	COD out mg/l	CODred %	Acetic Acid in mg/l	out	out correct.	red. %
1.0 days HRT:									
	02/01/91	91.69	6900	8450	91.84	426.93	608.30	40.55	90.50
		91.90	8000	7650	93.61	463.49	577.96	38.63	91.67
Average		91.80	7450	8050	92.73	445.21	593.13	39.59	91.09
1.5 days HRT:									
	04/01/91	95.10	6900	11450	94.65	426.93	784.78	25.32	94.07
		96.10	8000	11950	95.19	463.49	773.25	24.88	94.63
Average		95.60	7450	11700	94.92	445.21	779.02	25.10	94.35
2.0 days HRT:									
	06/01/91	95.77	6900	10650	95.55	426.93	998.05	28.07	93.26
		94.42	8000	14800	94.80	463.49	892.00	25.09	94.59
Average		95.10	7450	12725	95.18	445.21	945.03	26.57	93.93

Sterile Runs

RUNS	DATE	BOD AceticAcid in	out mg/l	COD AceticAcid in	out mg/l	in	Sulfide S out mg/l	correct out

1.0 days HRT:

	02/01/91	384.24	547.47	441.16	628.58	3.58	5.40	0.36
		417.14	520.16	478.94	597.23			
Average		400.69	533.82	460.05	612.91			

1.5 days HRT:

	04/01/91	384.24	706.30	441.16	810.94	3.58	6.54	0.21
		417.14	695.93	478.94	799.03			
Average		400.69	701.12	460.05	804.99			

2.0 days HRT:

	06/01/91	384.24	898.25	441.16	1031.32	3.58	6.22	0.18
		417.14	802.80	478.94	921.73			
Average		400.69	850.53	460.05	976.53			
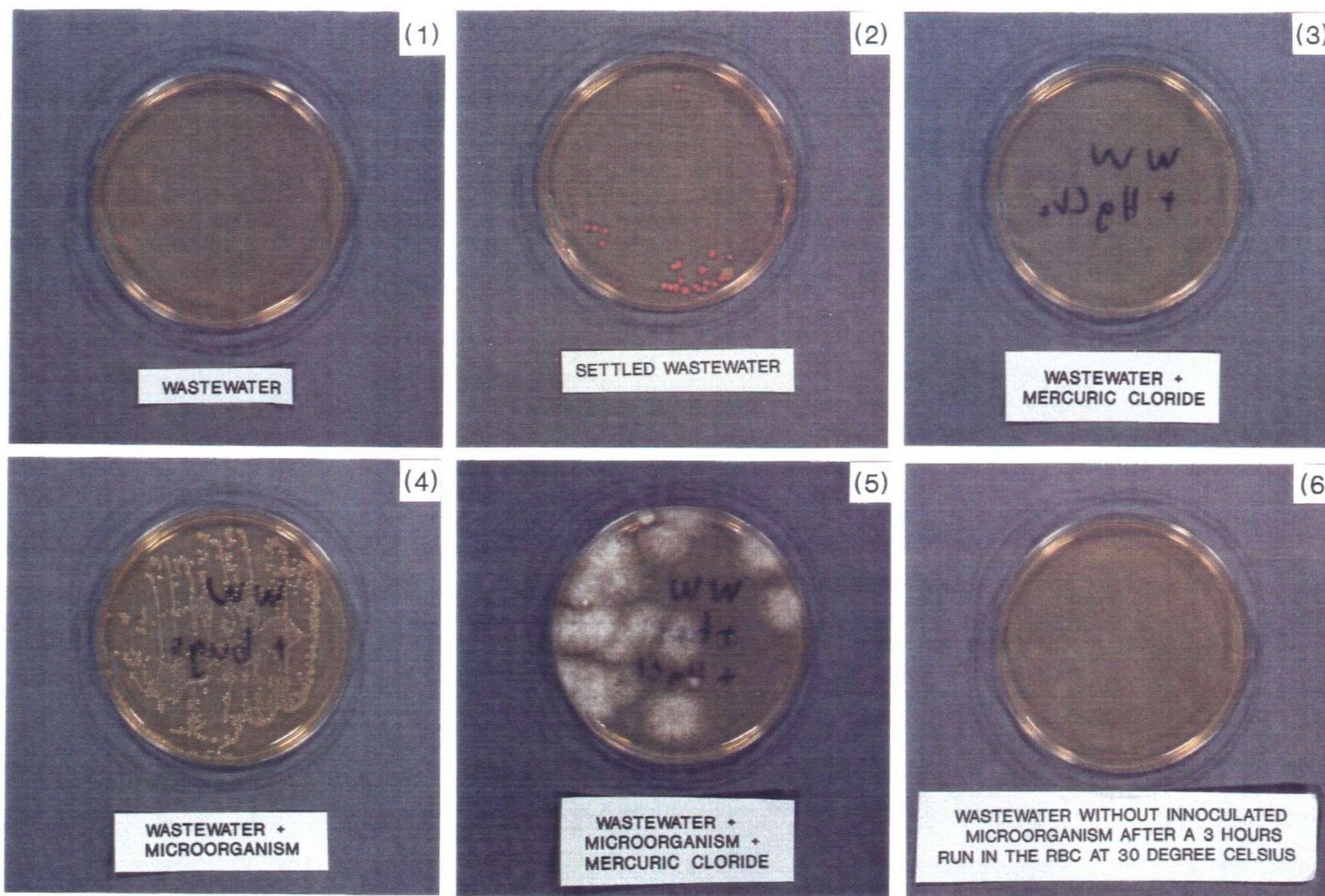
FIGURE A.V.1   Bacterial plating under different conditions.

A.V.3 RAW DATA FROM START-UP RUN WITHOUT MICROBIAL INOCULUM

Start-up run using CTMP wastewater
without microorganism innoculum
Date of Experiment: 30 April 1991

TIME	hour	DO mg/l	pH	TEMP. deg.C	BODin mg/l	BODout mg/l	BODout correct. mg/l	%BODred	MLVSS mg/l
13:00	0.0	7.70	5.91	28.0	3600	4200	3486	3.17	450
13:30	0.5	7.10	6.35	30.0	3600	4100	3403	5.47	600
14:00	1.0	6.70	6.32	30.5	3600	4100	3403	5.47	500
14:30	1.5	6.40	6.46	30.5	3600	3800	3154	12.39	550
15:00	2.0	6.20	6.40	31.0	3600	3900	3237	10.08	400
15:30	2.5								
16:00	3.0	6.15	6.25	31.0	3600	4000	3320	7.78	550
Average				30.2					508
Stand. dev.				1.0					67

APPENDIX VI

A.VI.1 RAW DATA FROM TRACER TEST

A.VI.2 F-CURVE

A.VI.1 RAW DATA FROM TRACER TEST

| TIME		C/Co	OUTLET CONDUCT.	EVAPO. CORRECT.	CONDUCT. noBACKGR. NOISE (C)	INLET CONDUCT (Co)	TEMP.
days	hours		mS	mS	mS	mS	degree C

Hydraulic Characteristics of the RBC reactor:
Tracer Test
Date of Experiment: 25 May - 30 May 1991
Average Evaporation during Experiment: 24.7%

TIME		C/Co	OUTLET CONDUCT.	EVAPO. CORRECT.	OUTLET CONDUCT. noBACKGR. NOISE (C)	INLET CONDUCT (Co)	TEMP.
days	hours		mS	mS	mS	mS	degree C
	0.00	0.000	4.44	3.56	0.000	25.5	18.9
	0.50	0.008	4.65	3.73	0.168		19.6
	0.82	0.013	4.80	3.85	0.289		19.4
	0.89	0.017	4.89	3.92	0.361		19.6
	1.00	0.019	4.96	3.98	0.417		19.3
	1.47	0.031	5.28	4.23	0.674		19.5
	1.48	0.032	5.30	4.25	0.690		19.5
	2.00	0.040	5.53	4.43	0.874		19.6
	3.00	0.054	5.90	4.73	1.171		19.7
	3.28	0.057	6.00	4.81	1.251	24.8	19.7
	3.50	0.070	6.35	5.09	1.532		19.4
	4.00	0.074	6.46	5.18	1.620		19.6
	4.50	0.083	6.70	5.37	1.812		19.7
	5.00	0.093	6.96	5.58	2.021		19.7
	5.50	0.102	7.22	5.79	2.229		19.8
	6.00	0.111	7.45	5.97	2.414		19.8
	6.50	0.121	7.72	6.19	2.630		19.8
	7.00	0.131	7.99	6.41	2.847		19.8
	7.50	0.141	8.28	6.64	3.079		19.7
	8.00	0.150	8.53	6.84	3.280		19.7
	8.50	0.159	8.75	7.02	3.456		19.6
	9.00	0.168	9.02	7.23	3.673		19.6
	9.50	0.176	9.22	7.39	3.833	25.8	19.6
	10.00	0.199	9.86	7.91	4.346		19.5
	11.00	0.210	10.15	8.14	4.579		19.4
	12.00	0.228	10.63	8.52	4.964		19.2
	13.00	0.242	11.03	8.85	5.285		19.4
	14.00	0.262	11.57	9.28	5.718		19.5
	15.00	0.280	12.06	9.67	6.111		19.2
	16.00	0.319	13.10	10.51	6.945		19.3
	17.00	0.335	13.55	10.87	7.306		19.3
	18.00	0.346	13.85	11.11	7.546		19.2
	19.00	0.358	14.18	11.37	7.811		19.2
	20.00	0.374	14.60	11.71	8.148		19.3
	21.00	0.386	14.92	11.96	8.404		19.2
	22.00	0.399	15.30	12.27	8.709		19.3

TIME days	TIME hours	C/Co	OUTLET CONDUCT. mS	EVAPO. CORRECT. mS	CONDUCT. noBACKGR. NOISE (C) mS	INLET CONDUCT (Co) mS	TEMP. degree C
1	23.00	0.410	15.59	12.50	8.941		19.1
	24.00	0.420	15.85	12.71	9.150	25.1	19.6
	25.00	0.434	16.25	13.03	9.471		19.7
	26.00	0.449	16.65	13.35	9.792		19.7
	27.00	0.466	17.11	13.72	10.160		19.9
	28.00	0.479	17.45	13.99	10.433		19.7
	29.00	0.489	17.73	14.22	10.658		20.0
	30.00	0.504	18.14	14.55	10.986		20.0
	31.00	0.519	18.54	14.87	11.307		20.0
	32.00	0.531	18.87	15.13	11.572		20.1
	33.00	0.543	19.20	15.40	11.836		19.8
	34.00	0.558	19.60	15.72	12.157	25.1	19.6
	35.00	0.565	19.80	15.88	12.318		19.6
	36.00	0.580	20.20	16.20	12.638		19.6
	37.00	0.594	20.60	16.52	12.959		19.7
	38.00	0.605	20.90	16.76	13.200		19.6
	39.00	0.620	21.30	17.08	13.520		19.5
	40.00	0.628	21.50	17.24	13.681		19.5
	41.00	0.639	21.80	17.48	13.921		19.5
	42.00	0.650	22.10	17.72	14.162		19.6
	43.00	0.655	22.25	17.84	14.282		19.6
	44.00	0.663	22.45	18.00	14.443		19.6
	45.00	0.674	22.76	18.25	14.691		19.6
	46.00	0.679	22.90	18.36	14.804		19.8
2	47.00	0.686	23.10	18.52	14.964		19.7
	49.00	0.701	23.50	18.85	15.285		19.6
	51.00	0.708	23.70	19.01	15.445	25.4	19.7
	53.00	0.720	24.00	19.25	15.686		19.6
	59.00	0.764	25.20	20.21	16.648		19.6
3	70.00	0.845	27.40	21.97	18.412		19.8
	72.00	0.856	27.70	22.21	18.653		19.9
	75.00	0.867	28.00	22.45	18.893		20.2
	77.00	0.878	28.30	22.69	19.134		20.5
	79.00	0.885	28.50	22.85	19.294		19.2
	94.00	0.966	30.70	24.62	21.059		19.3
4	95.00	0.966	30.70	24.62	21.059		19.5
	97.00	0.973	30.90	24.78	21.219		19.8
	100.00	0.992	31.40	25.18	21.620	25.1	19.6
	101.00	0.988	31.30	25.10	21.540		19.3
	109.00	0.999	31.60	25.34	21.780		19.4
5	119.00	1.003	31.70	25.42	21.860		19.5
	121.00	0.995	31.50	25.26	21.700		19.5
	123.00	0.999	31.60	25.34	21.780		19.7
	125.00	1.003	31.70	25.42	21.860		19.7

Average 25.26
Stand. dev. 0.33

Figure A.VI.1   F—CURVE