REVIEW NOTICE

Comparison Between Aerobic and Anaerobic Treatment Costs of Chemi-Thermomechanical Pulping Effluents

A Report For

Environment Canada
Conservation and Protection
Wastewater Technology Centre

by

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Environmental Engineers & Scientists

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ABSTRACT

A technical and economic comparison was carried out between aerobic and anaerobic processes for the treatment of CTMP effluents. The treatment processes considered were: aerated lagoons with and without post clarification, activated sludge and high rate anaerobic treatment followed by an aerated polishing lagoon. The upflow anaerobic sludge blanket was selected as representative of anaerobic treatment processes.

The comparison was based on meeting an effluent quality of 7.5 kg BOD/ADt, 10 kg TSS/ADt and satisfying a 96 hour LC_{50} of 100%. The evaluation indicated that for high strength wastes, aerated lagoons could not meet the TSS effluent quality without incorporation of post clarification facilities.

The economic evaluation showed that aerated lagoons were least costly in terms of capital plus operating and maintenance costs for low strength wastes, while a high rate anaerobic treatment process followed by an aerated polishing lagoon was most cost effective for high strength wastes. Activated sludge systems were the most costly alternative in all instances.

Based on the findings of the economic evaluation, the high rate anaerobic treatment process followed by an aerobic polishing lagoon was determined to be the lowest cost alternative (capital plus operations and maintenance) for six of the seven Canadian CTMP mills considered.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Wastewater treatment, where practiced in the pulp and paper industry, includes one or more of the following:

a) Primary treatment for suspended solids removal;
b) Aerobic treatment such as aerated lagoons and activated sludge systems;
c) Anaerobic treatment consisting mostly of high rate processes.

Chemical treatment has found little application because of difficulties in handling the resultant gelatinous sludge. Its limited use has been primarily as a pre-treatment step to reduce colour and/or reduce the toxicity of a wastestream. Aerobic treatment has traditionally been the treatment of choice at most Canadian pulp mills where secondary treatment is practiced. Anaerobic treatment had, until recently, received little attention because wastes from pulp mills were deemed to be too dilute to render this method of treatment cost effective. The increased use of internal recirculation of process water and the advent of TMP and CTMP pulping technologies has resulted in the production of more concentrated effluents which are more amenable to anaerobic treatment. This has generated extensive interest on the part of governmental agencies, private enterprise and academia to develop anaerobic treatment processes to handle these wastes.

Some mills operate more than one type of pulping process. Others are fully integrated mills. Thus, waste treatment considerations differ significantly between mills. This report addresses itself solely to the treatment of CTMP effluents recognizing the limitations of such an approach. The forms of treatment currently practiced at Canadian CTMP (and similar-type mills) are presented in Table 1.

TABLE 1 WASTEWATER TREATMENT PRACTICES AT SELECTED CANADIAN CTMP AND SIMILAR MILLS

Location	Status	Treatment
Baie Comeau, Quebec	existing	primary clarification
Bathurst, N.B.	existing	upflow anaerobic sludge blanket, aerated lagoon
Beaupre, Quebec	existing	primary clarification
Crofton, B.C.	existing	extended aeration activated sludge (on part of wastestream)
Gold River, B.C.	U/C	aerated lagoon (for CTMP only)
Jonquierre, Quebec	existing	primary clarification
Port Mellon, B.C.	proposed	pure O_2 activated sludge
Quesnel, B.C.	existing	primary clarification, upflow anaerobic sludge blanket, aerated lagoon
Taylor, B.C.	U/C	aerated lagoon
Temiscaming, Quebec	existing	dissolved air floatation
Whitecourt, Alberta	existing	aerated lagoon

U/C: Under construction

* Aerated lagoon already exists

1.1 Study Objectives

The overall objective of this study is to compare treatment costs between selected aerobic and anaerobic/aerobic processes in the treatment of CTMP effluents. Other objectives include a review and comparison between aerobic and anaerobic treatment processes.

2 CHARACTERIZATION OF CTMP WASTES

A comprehensive characterization of CTMP wastes is beyond the scope of this report. Table 2 summarizes the range of typical values for selected parameters.

CTMP wastes, like other pulp and paper wastes, are deficient in nitrogen and phosphorus, and supplemental addition of these two elements is normally practiced as part of biological treatment. The nutrients are needed for microbial growth (i.e., the formation of new bacterial biomass).

TABLE 2 TYPICAL RANGE OF WASTE CHARACTERISTICS FOR SELECTED PARAMETERS

Parameter	Unit	Range
Flow	m^3/ADt	18 - 25
BOD	mg/L	1,400 - 4,000
	kg/ADt	35 - 80
COD	mg/L	4,000 - 12,000
	kg/ADt	75 - 250
TSS	mg/L	140 - 800
	kg/ADt	3 - 15
Resin Acids	mg/L	20 - 70
Fatty Acids	mg/L	60 - 100
Hydrogen Peroxide	mg/L	0 - 200
Fish Toxicity	96 hr LC_{50}	1 - 2 %
pH		6.0 - 9.5

3 AEROBIC BIOLOGICAL TREATMENT

Properly designed aerobic biological treatment processes can generally achieve relatively high BOD, TSS and toxicity reduction. It is now well established that natural wood extractives are readily biodegradable aerobically (Mueller et al., 1976; McLeay, 1986). Other toxicants found in pulp mill wastes, such as juvabiones (a constituent of fir) are also detoxified readily under aerobic conditions (Leach et al., 1976).

3.1 Aerated Lagoons

Aerated lagoons are the simplest types of biological systems to construct and operate. They will only be reviewed in a cursory manner here.

Properly designed and well maintained aerated lagoons are capable of achieving a high reduction in BOD levels and in the extractives content of pulping wastes. One bench scale study has found that a 5 to 7 day hydraulic detention time (HRT) is sufficient to detoxify TMP/CTMP pulping waste under ideal conditions (Servizi and Gordon, 1985).

The technical literature on the performance of aerated lagoons in the treatment of CTMP wastes is very limited. Wilson et al. (1985) reported on the Bathurst mill which consists of a combined NSSC/CTMP waste, and thus is not representative of a typical CTMP waste. The TMP/CTMP mill in Quesnel has used a 5 to 7 day aerated lagoon with two cells for the treatment of its waste. The treated effluent consistently exceeded its BOD, TSS and toxicity limits. This has been attributed to insufficient aeration capacity (Beak, 1986).

Liquid temperature has a major impact on lagoon performance. Winter operation can be a problem where the detention time is excessive (due to loss of liquid temperature). This has seldom been a problem in Canada with kraft mills due to the insulating abilities of frozen foam and the relatively short hydraulic retention times. The problem can arise with mechanical and chemi-mechanical effluents that do not foam to any signficant degree. Low winter liquid temperatures have been observed at the Stephenville mill in Newfoundland. The Quesnel River Pulp mill lagoon effluent temperature, on the other hand, is only about 5°C lower in the winter than in the summer (it drops from about 33°C to around 28°C). It should be noted that the detention time in the lagoon is insufficient to detoxify the effluent and that subsurface aeration is practiced.

A major consideration in the use of aerated lagoons is the availability of suitable soils and sufficient, relatively flat, land on which to construct them. Subject to this constraint, aerated lagoons have traditionally represented the most cost-effective form of aerobic treatment. The power requirements, however, are generally of the same order of magnitude as activated sludge systems.

Several new CTMP mills have adopted aerated lagoons for treatment of their effluent. They include Whitecourt (10 day HRT), Taylor (10 day HRT) and the Gold River expansion (7 day HRT). A proposed CTMP mill (by Alberta Newsprint Company) is considering the use of aerated lagoons (10 day HRT). None of the mills have incorporated post clarification facilities for suspended solids reduction.

In spite of the adoption of aerated lagoons for these new CTMP mills, it is not clear if the cost effectiveness of the lagoon system versus combined anaerobic/aerobic systems had been fully confirmed. Several factors have to be taken into consideration when dealing with CTMP mill effluents:

a) CTMP wastes have a significantly higher organic concentration than the traditional pulp mill wastes. As a result, the power requirements to treat an equal volume of CTMP effluent can be several orders of magnitude higher than for the more traditional types of pulp and paper effluents.

b) The higher waste strength also results in a higher total suspended solids (TSS) concentration in the effluent due to: (1) increased mixing horsepower (which prevents settling); and (2) increased solids production per unit volume of waste. The increased TSS loading could result in the need for post clarification facilities.

c) Traditionally, the nutrient requirements of lagoons have been significantly lower than for activated sludge systems. This has been attributed to the settling of suspended biological solids within the lagoon. Upon decomposition of these solids, the nutrients (N and P) are solubilized and reintroduced into the liquid phase thus minimizing the need for N and P addition. The higher energy levels maintained in lagoons treating CTMP effluents results in minimal settling of suspended solids within the lagoon (most solids remain in suspension). This in turn increases the nutrient addition requirements for the lagoon system and brings it in line with the nutrient requirements associated with activated sludge systems.

d) The higher effluent suspended solids concentrations resulting from the treatment of CTMP wastes will, in turn, lead to higher nitrogen and phosphorus loading on the receiving environment; biosolids contain about 10% nitrogen and 1.5% phosphorus by weight.

3.2 Activated Sludge

Several variations of the activated sludge process have been used in treating pulp and paper wastes. These include: conventional activated sludge, extended aeration, deep tank (up to 20m liquid depth), and pure oxygen systems. It is well established that activated sludge systems can achieve high BOD and TSS removal from pulp and paper wastes. Some uncertainty remains as to the ability of the process to achieve a reliable degree of detoxification. A 2.5 day detention time activated sludge pilot-plant was unable to detoxify an NSSC/CTMP waste (Wilson et al., 1985). Some authors believe that detoxification of pulp mill wastes is largely dependent on the aerobic retention time, and as such, lagoons (with their long hydraulic retention times) are superior to activated sludge systems (with their short hydraulic retention times) (Wilson et al., 1985).

The only activated sludge treatment plant serving a

CTMP effluent in Canada is at the Crofton mill in B.C. The furnish is predominantly hemlock with a low resin acid content. It treats a flow of about 5,500 m^3/d with a BOD loading of 1,400 mg/L. The plant operates with minimal problems and meets its toxicity objectives of 100% LC_{50} (the relatively low waste BOD and resin acid content may contribute to this good performance). The waste is cooled from 66°C to 35°C ahead of the treatment plant.

The Port Mellon CTMP mill in B.C. is reportedly considering the use of a pure oxygen activated sludge system. The oxygen will be generated on-site for bleaching purposes and will thus be available for the treatment plant at a relatively low cost.

The only known deep tank activated sludge system treating pulp and paper waste is at the Port Angeles ammonia base sulphite mill in Washington State. The plant has been in operation since 1979. The tanks are 20m deep and the process achieves 99% soluble BOD reduction. The total annual costs (including depreciation plus operations and maintenance) reportedly amount to $12 million, representing a cost of $65/tonne of pulp produced. In the opinion of the author, the savings achieved with deep tanks in terms of improved oxygen transfer efficiencies are offset by the added power needed to introduce air at a liquid depth of 20m. The major advantage of deep tanks over conventional activated sludge is in reduced land area requirements.

4 HIGH RATE ANAEROBIC TREATMENT

Anaerobic biodegradation of organic substrates is more complex than aerobic processes. Unlike aerobic biodegradation which can be achieved by a single bacterial species, anaerobic biodegradation requires at least two and up to four different groups of bacterial species, most of which are obligate anaerobes. The processes are (see Figure 1):

a) Hydrolysis, by means of extracellular enzymes, which breaks down insoluble compounds into shorter chain soluble amino acids and sugars;
b) Fermentation which produces acetic acid, hydrogen and other short chain fatty acids from the soluble acids and sugars formed by hydrolysis; and
c) Methanogenesis which produces methane gas from acetic acid, methanol, formic acid and hydrogen/carbon dioxide.

For most soluble substrates, the rate limiting step during anaerobic biodegradation is the final stage of methane production. For more complex mixtures, such as pulp and paper wastes containing high concentrations of cellulose and lignin, the first step of hydrolysis is the rate limiting step.

Anaerobic treatment processes can be operated in the temperature range of 20 to 55^{o}C, although they are most commonly operated in the range of 30-35^{o}C (mesophilic range).

Theoretically, anaerobic biodegradation of carbohydrates produces a gas containing equal quantities of carbon dioxide and methane. Dissolution of carbon dioxide in the liquid results in a methane yield accounting for 60-70% of the gas generated (Webb, 1983).

4.1 Background to High Rate Anaerobic Treatment

The use of anaerobic biodegradation in the treatment of municipal sludge is a low rate process and is well established. It generally consists of a flow through reactor where the solids

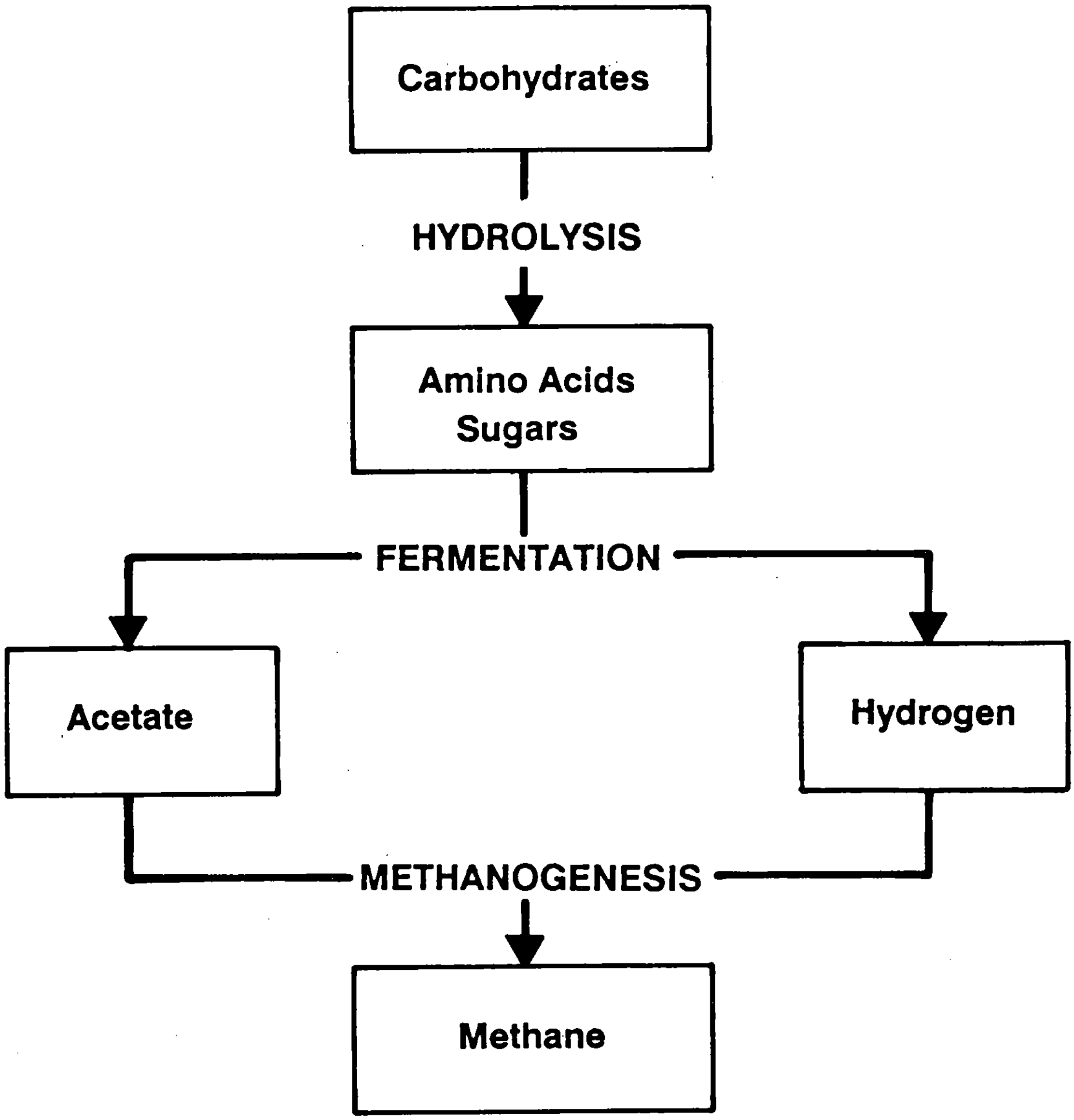


FIGURE 1

SIMPLIFIED PATHWAY OF ANAEROBIC BIODEGRADATION

retention time equals the hydraulic retention time. Its major limitation for use with high strength industrial wastes has been the long retention times (over 30 days). This limitation has been overcome by the recent development of treatment systems similar in concept to the activated sludge process where the solids retention time is much larger than the hydraulic retention time. Typically, these new anaerobic processes can have solids retention times of several hundred days with very short hydraulic retention times, ranging from several hours to several days. These newly developed processes are referred to as high rate systems in contrast to the traditional low rate system.

High rate anaerobic treatment (HRAT) systems represent an emerging technology, especially in their application to the pulp and paper industry.

Most HRAT systems currently in use or under consideration for pulp and paper waste treatment are proprietary in nature. Little technical information is released by the proponents regarding internal configuration, process details or the nature and extent of operational problems.

The first HRAT process treating a paper mill effluent, consisting of an upflow sludge blanket, commenced operation in late 1983 at the Roermond paper mill in the Netherlands. Since then several full scale installations have been constructed or are currently under construction for the treatment of CTMP wastes. These include: two pulp mills in Sweden, one producing a combined CTMP/bleached kraft pulp and the other a combined CTMP/bleached sulphite pulp; a CTMP mill in New Zealand; and two mills in Canada, the TMP/CTMP mill in Quesnel, B.C., and the CTMP/NSSC mill in Bathurst, N.B.

4.1.1 Acidification Tank. Most HRAT systems incorporate an 'acidification' tank ahead of the bioreactor. Its presence offers several advantages:

a) Improved process control in terms of pH, temperature and nutrients;
b) Degradation of reactive and unstable compounds that are toxic

to the methanogens (such as hydrogen peroxide and oxygen);

c) Hydrolysis of some complex organics into volatile fatty acids;

d) Faster recovery from toxic effects;

e) Some buffering ability with respect to hydraulic and organic shocks;

f) Buffering of temperature extremes.

A major disadvantage of the acidification tank is its added cost.

4.1.2 Types of HRAT Processes. Numerous HRAT processes have been developed, both at the pilot and full-scale level. They differ mostly in the mode by which the biomass is retained within the reactor. Most fall under four major categories (see Figure 2):

a) Fixed film processes;

b) Suspended growth processes;

c) Combination of fixed film/suspended growth processes;

d) Fluidized bed processes.

4.2 Fixed Film Processes

These are mostly upflow or downflow filters. The packing consists of fixed media of variable type and design. The process is suitable for the treatment of dilute soluble wastes but less suitable for the treatment of wastes containing hard to digest suspended solids which settle and interfere with the reactor operation (Van den Berg and Kennedy, 1983). One of the advantages of such systems over suspended growth systems is in their ability to retain biosolids under adverse conditions (suspended growth systems are prone to washout).

4.2.1 Upflow Fixed Film Reactor. This system was developed in the mid- 1960's. Waste enters at the bottom of the reactor and flows upward through the packing which provides a surface upon

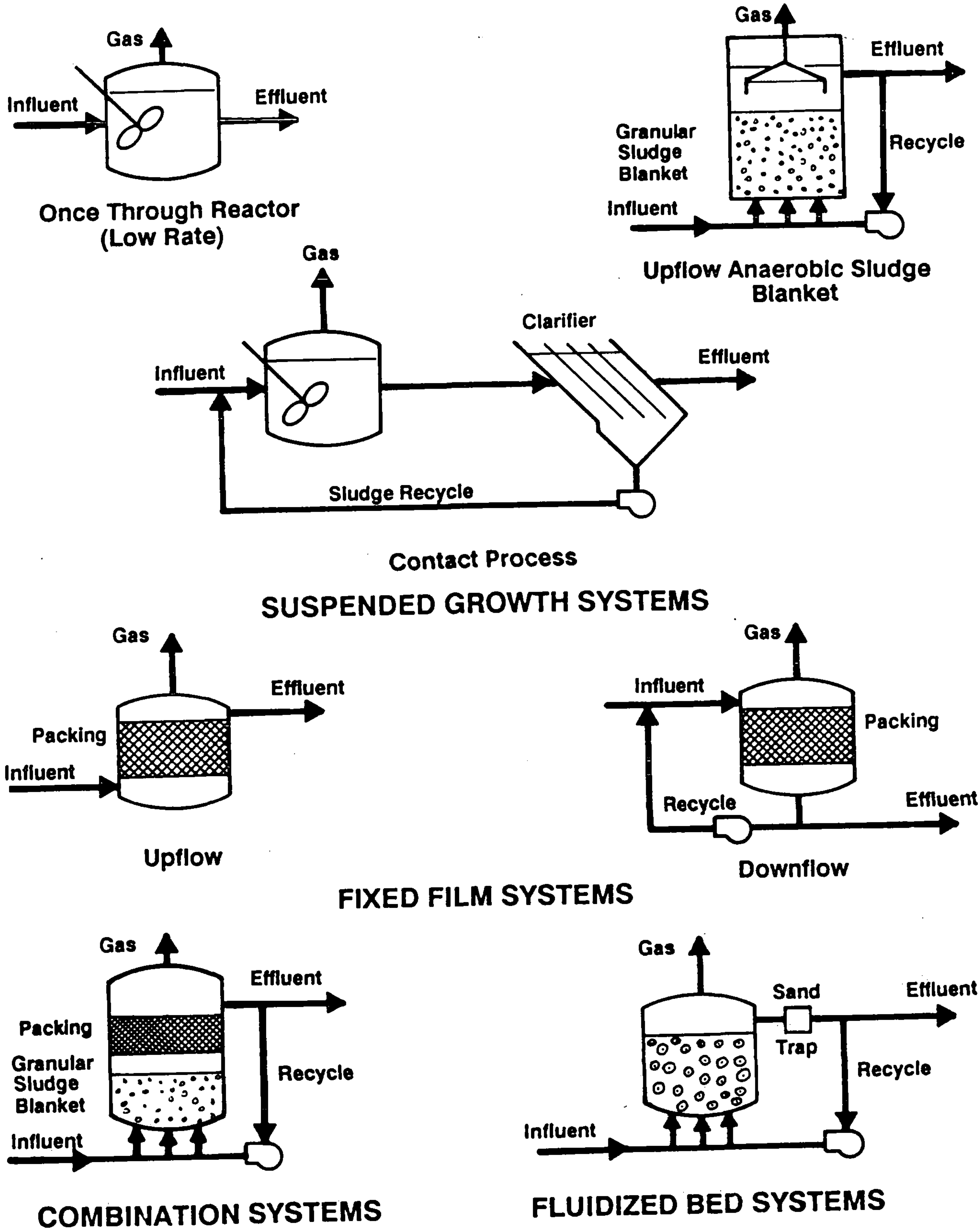


FIGURE 2
SCHEMATIC OF ANAEROBIC TREATMENT PROCESSES

which the biomass can attach itself. Studies, however, have determined that most of the biomass is present in suspended form within the voids and tends to collect at the bottom of the reactor causing plugging problems (Van den Berg and Kennedy, 1983). Since in reality the reactor operates in a suspended growth mode, the configuration of the liquid distribution system in the bottom of the reactor is critical in obtaining optimum performance. Other problems include short-circuiting and channeling.

Biomass International of England is marketing an upflow anaerobic reactor, but no application on pulp mill wastes has been reported. The Celrobic process, marketed by Badger Engineering, was developed and successfully operated by the Celanese Corporation for petrochemical wastes at Bishop, Texas. It consists of flow equalization and a packed tower anaerobic filter followed by aerobic polishing. No application on pulp and paper wastes has been reported.

4.2.2 Downflow Fixed Film Reactor. This system has been extensively studied by the Canadian National Research Council, and was developed to overcome the plugging problems associated with the upflow reactor. The suspended growth is supposed to be eliminated by the downward movement of the liquid which should continuously flush out any suspended growth that may start forming. Furthermore, the need for an elaborate distribution system is eliminated as the escaping gas bubbles provide ample mixing of the incoming waste within the reactor. This refinement has not eliminated the problem of plugging of the packing. Most speakers at a conference in Toronto in November, 1986 dealing specifically with anaerobic fixed film reactors identified plugging as a major, and as yet unresolved, problem with both types of reactors.

ADI in Fredricton, N.B. developed the ADI downflow and horizontal fixed film filters that use rock media or geotextile. Bench and pilot scale units have been developed and at least three treatability studies were carried out on pulp and paper wastes. The loading rates range between 4 and 9 kg $COD/m^3.d$

(Landine et al., 1986).

Another commercial example of the downflow plastic media anaerobic filter is the Bacardi/Ultrasystems process developed for the treatment of rum stillage waste. No application has been reported in the treatment of pulp and paper wastes.

In spite of extensive research, anaerobic filters have not found much acceptance in the pulp and paper industry and no full-scale installations currently exist.

4.3 Suspended Growth Processes

These consist of anaerobic contact reactors and upflow anaerobic sludge blanket (UASB) reactors. The former is similar to the activated sludge process in that a clarifier is used to recycle the biomass to the anaerobic reactor. The latter consists of a single reactor which combines biodegradation with settling.

Suspended growth systems avoid the main problems with anaerobic filters, namely plugging of the packing.

4.3.1 Anaerobic Contact Reactor. The Anamet process is an example of an anaerobic contact reactor. This combined anaerobic-aerobic treatment process was developed by A.C. Biotechnics (formerly AB Sorigona) of Sweden for use in the food and fermentation industry (the firm is now owned by Purac). The process was introduced to the pulp and paper industry in 1980. Little is known about the anaerobic reactor details although it appears to consist of a non-granulated suspended growth biomass. A lamella clarifier is used to settle the sludge and return it to the bioreactor.

Four full-scale installations treating pulp waste currently exist. One of them is treating the waste from the CTMP mill at Ostrand in Sweden. Another is at Ornskoldsvik in Sweden. It treats the combined waste from a sulphite mill (sulphite spent liquor evaporator condensate) and a cellulose derivative manufacturing plant. It has a capacity of 13,000 m^3/d and is designed to remove 88% of the BOD_7. The plant consists of an equalization tank, two anaerobic reactors in series, two lamella clarifiers and an aeration step. The sulphur content of the influent averages 1,000 mg/L. Hydrogen sulphide toxicity is prevented by continuous scrubbing by the aid of a gas recirculation system. The plant was brought into operation during the first half of 1985. The COD loading ranged between 3-4 $kg/m^3.d$ while the removal efficiencies averaged 60% and 97% for COD and BOD_7 respectively (Sarner, 1986).

A full scale Anamet system is under construction at the Sitka sulphite mill in Alaska. It will be operational in late 1988 or early 1989. It is designed to handle an average flow of 13,600 m^3/d and an average COD loading of 170 t/d. It is guaranteed to achieve 75% BOD removal and to produce 0.13 m^3 of methane/kg COD applied.

A 10 m^3 pilot-scale unit operated at the CTMP Bathurst mill for about a year. It was loaded at 4 kg $COD/m^3.d$ and achieved about 60% BOD reduction and 40% COD reduction with supplemental nutrient addition and a reactor temperature of 37^oC.

One of the apparent limitations of the anaerobic contact reactor process is its relatively low COD loading rate which is generally under 5 kg $COD/m^3.d$. This results in large reactor size. Also, the reactor's performance depends on that of the clarifier.

4.3.2 UASB Reactor. In the UASB process, solids separation and anaerobic biodegradation are achieved within the same reactor. A critical element in the successful application of this process was the development of a sludge blanket with good settling properties. Suspended growth biomass in anaerobic systems does not generally settle well.

In 1980, Lettinga and co-workers reported on the development of a granular sludge with good settling characteristics. The loading rate on a reactor with granulated sludge can be four to five times higher than for non granulated sludge (Habets and Knelissen, 1985). The granular sludge cannot be achieved with all types of waste (Van den Berg and Kennedy, 1983). It has been reported that supplemental calcium addition may be beneficial to develop the granulation of the sludge with pulp wastes. Granular sludge build-up is a slow process that is adversely affected by process upsets. Scum and floating mat accumulation at the top of the reactor require constant removal and can cause major loss of biomass inventory leading to failure of the system (Hall <u>et al.</u>, 1986). UASB systems seem, however, to be able to operate without pH adjustment once they reach 'steady state' conditions. Several commercial designs have been developed.

The Biopaq system, developed in the Netherlands by Paques BV and currently marketed in North America by Paques Lavalin, is an example of a UASB reactor. The reactor contains at its top a three phase settler for separating sludge, effluent and gas. The upflow velocity within the reactor is in the range of 1.2 m/hr. A pre-acidification tank is normally located ahead of the reactor. Its purpose was discussed earlier. It is also claimed that the pre-acidification stage results in more consistent and higher pH levels in the main reactor, reducing the potential for process upsets. The sludge bed ranges between 40-60% of overall reactor depth with a TSS content of about 80 kg/m^3 of reactor volume. Effluent recycle, needed only for high strength wastes, is practiced to dilute the incoming waste and to return some of the alkalinity which is produced in the reactor as a result of the fermentation process.

The first full scale installation was at the paper mill at Papierfabriek Roermond in the Netherlands which processes wastepaper. The treatment plant started operation in October 1983 following laboratory and pilot-scale studies. It consists of a 1,000 m^3 UASB reactor preceded by a 400 m^3 buffer basin. Anaerobic treatment is followed by an existing activated sludge system. Suspended solids levels in the lower part of the anaerobic reactor reached 5%. Complete granulation of the sludge was achieved within five months of start-up. Operation of the activated sludge plant has improved following the addition of the anaerobic unit ahead of it; sludge bulking problems were eliminated. Furthermore, it has been found that the combined anaerobic/aerobic treatment sequence provided a higher degree of treatment than aerobic treatment alone (Habets and Knelissen, 1985).

Several other full scale installations have been reported in addition to a number of pilot scale studies conducted world-wide, some on CTMP wastes. One full-scale installation, at the Quesnel River TMP/CTMP mill, was put into operation in late 1988.

A 20m^3 pilot-scale unit operated at the NSSC mill in Sturgeon Falls from May 1986 to mid 1987. Nutrient addition in the form of urea and phosphoric acid was practiced. The raw waste contained about 12,000 mg BOD/L and 24,000 mg COD/L. Removal rates were 50-60% for COD and 80-90% for BOD. Influent TSS levels were in the range of 300 to 500 mg/L; effluent TSS levels were around 900 mg/L, probably mostly biomass. Loss of biomass was a serious problem throughout the study although accumulation seems to have been finally achieved towards the end of the study (Hall, 1987).

The Biothane reactor is another example of a UASB reactor. It was developed by CSM, a Dutch sugar beet firm, for the treatment of food processing wastes. The concept is similar to that of the Biopaq reactor. It also includes an acidification/equalization tank ahead of the main reactor. It operates on the principle of the formation of a granular biomass with a three phase separation of the liquid, sludge and gas. The solids concentration in the sludge blanket can be as high as 10%. The system has been used by several industries, but its use in the pulp and paper industry is still limited. The first full-scale application is at the Bathurst CTMP/NSSC mill in New Brunswick which is currently undergoing start-up.

Prior to construction a one year pilot plant study using a 6 m^3 reactor was undertaken. The pilot plant was loaded at 10 kg COD/m^3.d and achieved 80% BOD removal and 45% COD removal. A biomass concentration of 20-25 kg VSS/m^3 was maintained in the reactor.

Other pilot plant operations have been undertaken; a sulphite evaporator mill in Wisconsin, and a tissue paper waste in Germany.

4.4 Combination Fixed Film/Suspended Growth Processes

These processes are hybrids that apparently combine the advantages of fixed film and suspended growth systems in one reactor. Normally, the bottom portion where the waste is introduced consists of a UASB section while the top part contains a plastic fixed film media.

The Taman process, a hybrid reactor, was developed by Tampella Anjala paper mill in Finland (Tampella-anaerobic). It consists of a multi-stage reactor containing separate fermentation and methane formation stages and is a combination fixed film/suspended growth system.

Following hydrogen peroxide removal, the waste is conducted through a pre-clarifier into the acid fermentation unit. From there the homogenized waste is introduced to the methane stage. The anaerobic process is followed by an aerated lagoon.

Few details of the system configuration have been released by its developers. The first full-scale pulp mill installation was at the Anjala pressure groundwood and TMP mill in 1985.

Biotim, a Belgian firm, produces a complete range of HRAT systems. Their only full-scale installation at a pulp mill is a recently constructed hybrid process at Caxton Paper in New Zealand. It is a two stage treatment process consisting of a first stage detoxification reactor followed by a hybrid type UASB reactor containing a polyurethane carrier at the surface.

The pilot-scale unit developed at the Wastewater Technology Centre in Burlington, Ontario is a hybrid. It consists of a UASB in the lower section and a fixed media in the upper section with provision for effluent recycle. It has operated, until late summer 1988, in Kapuskasing on a combined TMP/ groundwood/ magnesium sulphite mill effluent.

4.5 Fluidized Bed Processes

In the fluidized bed process wastewater flows upward through a medium, usually sand, at a velocity sufficient to expand the bed beyond the point at which the frictional drag is equal to the net downward force exerted by gravity. Thus the media particles are individually and hydraulically supported, providing a vast surface area for biological growth. It is claimed that the biomass concentration that can develop is five to ten times greater than in a suspended growth system, resulting in significant reduction of reactor hydraulic retention times (Sutton and Huss, 1984). In addition, the biomass aggregate settles readily due to the weight of the sand.

The process requires recycling of the effluent to maintain the bed fluidized and the use of a sand-biomass separator to recover the sand from the wasted sludge.

The Anitron system was developed by Dorr-Oliver when it purchased its licence in 1976. The process was originally developed for the treatment of food processing wastewater and was later adapted for use with pulp and paper wastes. Pilot scale studies include: a sulphite pulping waste (Sutton and Li, 1981); effluent from the Sturgeon Falls NSSC mill; and the Consolidated Bathurst CTMP mill. Apparently, the unit did not perform well and difficulty was experienced in biomass attachment to the sand particles.

The Enso-Fenox process was developed in Finland and has been studied for a period of 1.5 years at the laboratory and pilot-scale levels in the treatment of TMP/CTMP wastes. Over 80% BOD removal was usually achieved during that time (Salkinoja-Salonen et al., 1985). The parent company entered into a marketing agreement with Paques BV in late 1986 with the objective of marketing the Biopaq system in Finland. As a result, the fate of the Enso-Fenox system is unknown.

The Biobed process was developed in the Netherlands by Gist-Brocades and consists of two reactors, an acidification reactor followed by a methanisation reactor. The first full-scale installation was in 1984 at a yeast factory. To-date no full scale installations at pulp and paper mills have been reported. A pilot scale unit was operated at the Bathurst CTMP mill for a short period of time.

4.6 HRAT Systems Installed at Pulp Mills

Table 3 presents a list of the status of worldwide, full-scale HRAT installations at pulp mills. Due to the multitude of commercial manufacturers and the intense interest in this process, the list is, perforce, incomplete.

TABLE 3 SUMMARY OF HIGH RATE ANAEROBIC TREATMENT SYSTEMS USED IN THE TREATMENT OF PULP MILL EFFLUENTS

Developer	Stage of Development	Pulp Mill Installations	
		Existing	Under Construction
<u>Fixed Film</u>			
Biomass International	full-scale	-	-
ADI	pilot-scale	-	-
Bacardi/Ultrasystems	full-scale	-	-
<u>Suspended Growth - Contact Reactors</u>			
Purac	full-scale	four	one
<u>Suspended Growth - UASB</u>			
Paques	full-scale	two	-
Biothane	full-scale	one	one
<u>Fixed Film/Suspended Growth</u>			
Taman	full-scale	one	-
Biotim-A	full-scale	-	one
<u>Fluidized Bed</u>			
Dorr Oliver	full-scale	-	-
Enso-Fenox	pilot-scale	-	-
Gist-Brocades	full-scale	-	-

4.7 Advantages of Anaerobic Treatment

Anaerobic treatment offers several advantages over aerobic treatment. These include:

a) Lower energy demand since no oxygen is needed for treatment purposes.
b) Lower sludge production. Anaerobic processes produce between 0.05 and 0.1 g of biomass/g of COD removed.
c) Production of methane gas which can be recovered (the theoretical gas yield is 0.35 m^3 methane per kg of COD consumed).
d) Lower nutrient requirements (i.e., nitrogen and phosphorus) since the biomass production is significantly lower than with aerobic treatment.
e) Ability to withstand extended periods of starvation (up to one year) with only modest loss of activity.
f) Ability to operate effectively at high temperatures.

The first four advantages, and especially the third one, can result in significant cost savings to an industry. The savings associated with the production of methane gas, for example, can offset part of the operational cost of the treatment plant. Approximately 1 kW of aeration power can be saved per 20 kg of BOD degraded anaerobically (Cocci et al., 1985).

4.8 Disadvantages of Anaerobic Treatment

While the benefits of anaerobic treatment of CTMP wastes are significant, it is important to be aware of its limitations and the nature of problems that can arise. Disadvantages of the anaerobic treatment process include:

a) Inability to degrade high molecular weight organics: Lignins of a molecular mass higher than about 850 are not degraded anaerobically. This is a major reason for the relatively moderate COD reduction rates (of 50-60%), and high BOD reductions (of up to 95%) with pulp mill wastes (Eriksson, 1985).

b) Need for post-treatment by aerobic processes: Unlike aerobic treatment, anaerobic treatment by itself is insufficient to detoxify a waste and meet stringent effluent standards. It has to be followed by an aerobic treatment step (Eriksson, 1985; Habets and Knelissen, 1985; Norrman et al., 1983; Orivuori, 1985; Gunnarsson and Rosen, 1985; Luonsi et al., 1986; Springer, 1986). A detention time of 3 to 5 days in an aerated lagoon at 20°C was recommended to detoxify an NSSC/ CTMP wastestream following anaerobic treatment (Wilson et al., 1985), although a 24 hour aerated lagoon was finally constructed. The use of anaerobic treatment, however, appears to reduce the subsequent aerobic retention time needed to achieve detoxification and also reduces the energy needs for aeration.

c) Slow start-up: Start up periods may be in excess of 100 days. Habets and Knelissen (1985) reported on a 6-month long start-up period with a UASB reactor. Concurrently, recovery time from operational upsets is long (Springer, 1986). Start- up can be accelerated by the seeding with a large quantity of biomass from a similar treatment process.

d) Need for high biomass separation efficiency: Due to the low biomass yield under anaerobic growth conditions, it is necessary to retain the active biomass in the reactor and prevent its washout (especially important for suspended growth systems). Slow loss of biomass over an extended period of time can be difficult to recognize until process performance is affected.

e) Need for pH control: The methanogens are sensitive to low pH levels (i.e., hydrogen ions) whereas the acidogens are less sensitive, and tend to produce acids which depress the pH of the liquid. As a result, most anaerobic systems require provision for pH control usually in the form of caustic addition. Operating experience with pilot-scale HRAT units at some mills has shown that the need for caustic addition drops dramatically once steady state conditions are achieved.

f) Odour generation: Anaerobic systems have greater tendency than aerobic systems for odour generation. The problem is caused mostly by the presence of sulphur in the waste (mainly as sulphate and thiosulphate). With anaerobic treatment most of the oxidized forms of sulphur are reduced to hydrogen sulphide. Some of the hydrogen sulphide is removed with the other gases; methane and carbon dioxide. Scrubbing and/or burning of the collected gases will greatly reduce any hydrogen sulphide problem associated with anaerobic treatment. The hydrogen sulphide which remains in solution is discharged with the treated effluent from the anaerobic reactor and can also cause odour problems. The odour threshold for hydrogen sulphide in air is extremely low (0.00047 mg/L).

g) Formation of calcium carbonate crystals: Wastes containing in excess of 500 mg/L calcium can cause operational problems due to crystallization of calcium carbonate (Ruffer and Boeck, 1986).

h) Corrosion Problems: This is caused by hydrogen sulphide generation during anaerobic treatment. This gas is converted to sulphuric acid in the presence of oxygen at the gas liquid interface within some types of anaerobic reactors. The acid can cause severe corrosion problems if not properly addressed in the construction of the reactors (Maat et al., 1987).

i) Sensitivity to toxic materials: For CTMP wastes, the following constituents have been identified as being inhibitory to anaerobic bacteria:

- Wood extractives, especially resin acids;
- Hydrogen peroxide which is used as a bleaching agent;
- Diethylenetriaminepenta-acetic acid (DTPA), a strong chelating agent used for stabilizing hydrogen peroxide;
- Tannins and lignins;
- Sulphate and other oxidized sulphur compounds which are reduced anaerobically to sulphide, a substance very toxic

to the methanogens.

j) Lack of proven operating experience: The first full scale anaerobic treatment installation at a paper mill was commissioned in late 1983. This represents just under five years operating experience for that system and significantly shorter periods for all other full-scale installations that have come on stream since. There are no reported full-scale installations treating CTMP wastes anywhere in the world, although several are coming on stream this year. Two full-scale systems are in operation treating TMP wastes alone or in combination with other pulping wastes. In view of the recent introduction of this technology to the pulp and paper industry (especially CTMP mills), operational reliability aspects cannot be fully assessed at this stage.

4.9 Effect of Toxicants Found in CTMP Effluents on Anaerobic Systems

DTPA has been found to inhibit bacterial activity. This may be partially due to its ability to bind micronutrients needed for microbial growth (Beak, 1986).

Hydrogen peroxide is a very strong oxidizing agent that is rapidly degraded. It is not toxic to aerobic bacteria because they produce an enzyme, catalase, that actively decomposes it. Obligate anaerobes, on the other hand, do not possess this enzyme and as such are very sensitive to the presence of hydrogen peroxide. The problem associated with the presence of hydrogen peroxide in the waste and means of removing it has been reviewed by Welander and Andersson (1985) and Beak (1986). Some mills have adopted minimal treatment strategies for dealing with it while others have installed elaborate pretreatment reactors to degrade it. Hydrogen peroxide, being an unstable compound, degrades naturally given sufficient time.

Welander and Andersson (1985) reported a two-stage system where the first stage, with a 10 hour retention time, was capable of degrading influent hydrogen peroxide levels of 200 mg/L. Higher peroxide levels, up to 1,200 mg/L were successfully reduced by the addition of another reactor (2 hour retention) ahead of the acidogenic stage. The additional reactor had to be constantly fed with active biomass to achieve the high removal rates since the biomass within the reactor was completely inhibited by hydrogen peroxide. Earlier studies had shown that methanogenic bacteria were severely inhibited by the introduction of small quantities of hydrogen peroxide into a single stage reactor.

Hydrogen peroxide degradation studies were undertaken at the Chemical Engineering Department of the University of British Columbia in early 1987. The waste originated from the CTMP process at Quesnel River Pulp. Hydrogen peroxide was added to the waste and the rate of degradation observed. The results showed that complete degradation was achieved in under 15 minutes for hydrogen peroxide levels of up to 200 mg/L (the highest concentration of chemical added).

Tannins originate mostly from bark and inhibit methanogenic activity. The performance of a pilot-scale anaerobic reactor treating TMP waste was reduced due to the presence of tannins in the waste (Maat et al., 1987).

Methanogenesis is inhibited by the presence of sulphur in two ways. Sulphide acts as a direct inhibitor of methanogenic activity. Many authors quote a maximum tolerable level of 200 mg S/L for non-acclimated biomass (Webb, 1983; Springer, 1986). Also, the sulphate reducing bacteria compete directly with the methane forming bacteria for the hydrogen ion. This results in a reduction of the methane yield. The reduced sulphide compound will subsequently exert an oxygen demand under aerobic conditions (Ferguson and Benjamin, 1985; Webb, 1983; Hall and Cornacchio, 1987).

The presence of high sulphur levels in the waste does not necessarily result in inhibition of methanogenesis. Several methods have been successfully developed to control hydrogen sulphide toxicity in anaerobic reactors. They include: (1) hydrogen sulphide precipitation by heavy metal addition; (2) continuous gas scrubbing to remove hydrogen sulphide from the reactor; (3) pH control at values of 8 or above to reduce free hydrogen sulphide (the toxic constituent). All three methods have been successfully implemented at the pilot and full-scale level (Ruffer and Boeck, 1986); (4) maintaining COD:SO_4-S ratios in excess of 100:1 to prevent sulphide inhibition. Ratios as low as 30:1 have also been claimed to achieve this end (Sarner, 1986).

In addition to the aforementioned methods for controlling sulphide toxicity, it is now well established that the methanogens can acclimate to a number of inhibitory compounds including hydrogen sulphide up to concentrations of 800 mg S/L (Orivuori, 1985; Eis et al., 1983).

Adaptation of the methanogens to other toxic constituents found in CTMP wastes was reported by Welander and Andersson (1985). Methanogenic activity was initially completely inhibited by the presence of resin acids and DTPA. After several months of adaptation, methanogenic activity resumed and it was noted that a shift in methanogenic species had occurred.

5 IMPACT OF REGULATIONS ON CTMP WASTE TREATMENT

The options for the treatment of CTMP mill effluents are largely related to the degree of treatment to be achieved. This, in turn, is dependent on local regulations. A cursory overview of regulations in selected Canadian jurisdictions and elsewhere is presented in Table 4.

No standards dealing specifically with CTMP mill wastewater appear to have been developed in any jurisdiction to-date. A strict comparison of regulations between jurisdictions is clearly not possible. The comparison is based, wherever possible, on the 'closest-type' categories of regulated mills. These are as follows:

- Federal (Canadian): New mechanical mills;
- Quebec: Chemical/mechanical pulping;
- British Columbia: Mechanical mills (Level A - new mills);
- United States: Groundwood/thermomechanical mills;

The U.S. regulations appear to be the strictest, but they deal with a different and less concentrated-type wastewater (CTMP mill wastewater is generally at least 100% more concentrated than groundwood/TMP wastewaters). Furthermore, as noted, the U.S. regulations allow substantial deviation in any one day period per month.

The Quebec regulations, promulgated in 1981, were intended for the implementation of primary treatment processes only (ie., relatively high BOD and low TSS). They provide for daily effluent quality variations of up to twice the monthly allowance. Phase 1 of the Quebec BOD regulations became effective on January 1, 1989. The A-Level B.C. Objectives were based on the implementation of secondary level treatment (ie, biological aerobic).

The Federal regulations contain limitations for suspended solids levels and not BOD. BOD was excluded because at the time the regulations were promulgated in 1971, no representative values could be found. The regulations do not specify an averaging period, and it is presumed that they are

TABLE 4 EFFLUENT LIMITATIONS IN SELECTED JURISDICTIONS

Jurisdiction	BOD kg/ADt	TSS kg/ADt	Fish Toxicity 96 hr LC_{50} % v/v	Dissolved Oxygen mg/L
Federal Regulations		10.5	see note	
Alberta (Whitecourt)	7.5	30.0	100	2.0
British Columbia	7.5	10.0	100	2.0
Ontario	30/16.5	10.0	100	
Quebec				
- maximum day (summer)	15.0	12.0		
- 30-day av. (summer)	10.0	6.0		
- 30-day av. (winter)	20.0	6.0		
United States				
- maximum 30-day BPT	5.0	9.6		
- maximum 30-day NSPS	2.5	4.6		
- maximum day BPT	9.6	17.05		
- Maximum day NSPS	4.6	8.7		

NOTES:

Federal:
1) Fish toxicity based on 80% survival in 65% effluent concentration.
2) TSS levels exclude biosolids generated during biological treatment.
3) TSS loading based on: debarking, pulping, bleaching and pulp sheet formation.

Alberta/ Whitecourt: TSS levels set at 10.0 kg/ADt after primary treatment, and 30.0 kg/ADt after treatment in aerated basin. Other controlled parameters: Resin acid less than 2 mg/L; colour less than 45 kg/ADt.

B.C.: Based on Level 'A' effluent quality for mechanical mills.

Ontario:
1) Currently there are no BOD, TSS or toxicity limits in Ontario. Discharge permits are prepared on a mill by mill basis.
2) Levels shown are proposed by MISA expert committee for Kraft mills. No sublethal effects allowed beyond mixing zone. BOD not exceed 30 kg/ADt for bleached pulp and 16.5 kg/ADt for unbleached pulp.

Quebec:
1) For new chemical mechanical pulping excluding other operations such as debarking and bleaching. Bleaching adds from 17 to 35% to the allowable BOD and TSS effluent loading.
2) Summer levels are now being adopted year-round.

U.S.:
1) For groundwood/thermomechanical mills.
2) BPT: Best practical technology.
3) NSPS: New Source Performance Standards.

annual allowances since they were developed on the basis of annual averages. The Federal regulations, however, focus on effluent toxicity and rely on the use of fish bioassay to determine the acceptability of an effluent for discharge.

Discharge limits set recently for new CTMP mill effluents in Alberta and British Columbia are presented in Table 5. It is notable that the permits set either very high or no limits on total suspended solids discharge in the final effluent. The solids are deemed to consist mostly of bacterial biomass (biosolids) resulting from biological treatment. This lack of concern with the suspended solids content of the effluent appears to be limited to biosolids produced in aerated lagoons and reflects a general belief that the biosolids do not impact adversely on fish nor on the receiving environment.

TABLE 5 DISCHARGE LIMITS FOR SELECTED CANADIAN CTMP MILLS

Parameter	Unit	Quesnel B.C.	Taylor B.C.	Whitecourt Alberta
Fish Toxicity	96 hr LC_{50}	100%	100%	100%
BOD_5	kg/ADt	7.5	7.5	7.5
TSS	kg/ADt			
- After primary		8.5	8.5	10.0
- After secondary		no limit	no limit	30.0
D.O.	mg/L	2.0	2.0	2.0
pH		6.5-8.5	6.5-8.0	6.5-8.5
Temperature	^{o}C	35	35	40
Resin Acids	mg/L	-	-	2.0
Colour	kg/ADt	-	-	45.0

It is interesting to note that these biosolids are of a similar nature to the biosolids produced in other forms of biological treatment (ie, activated sludge processes), yet current regulations prohibit the discharge of any appreciable amount of biosolids from other types of treatment processes into the receiving environment. These biosolids are referred to as biological sludges and are handled and disposed of at great cost. They are considered to be one of the most problematic aspects of plant operation. The cost of solids handling usually represents at least one third of the total treatment cost.

With the continued trend toward more stringent effluent limitations, it is probable that the discharge of large quantities of biosolids will be restricted at some time in the future. Under such conditions, aerated lagoons used in the treatment of high strength pulp and paper wastes may be required to reduce the amount of biosolids discharged in the effluent. This would involve biosolids collection, digestion (if necessary), dewatering and disposal.

6 COMPARISON BETWEEN TREATMENT PROCESSES USED IN CTMP WASTE TREATMENT

6.1 Types of Treatment Processes Considered

The treatment processes considered for comparison purposes are (see Figure 3):

a) Aerated lagoons without post clarification;
b) Aerated lagoons with post clarification;
c) Activated sludge;
d) High rate anaerobic treatment (HRAT) preceded by dissolved air floatation and followed by aerated lagoons.

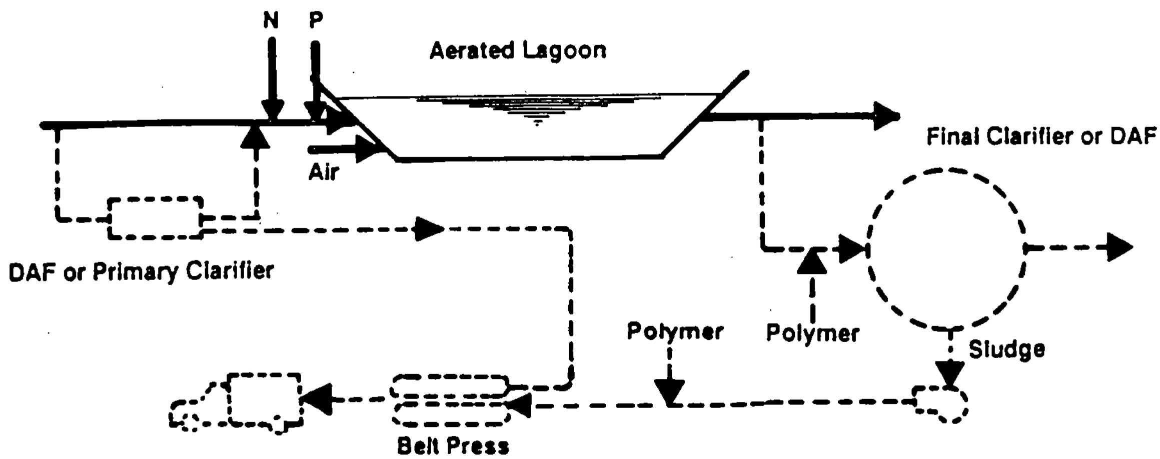
The above process combinations, with the exception of aerated lagoons with post clarification, constitute the virtual totality of treatment processes currently in use, or under consideration, for the treatment of CTMP effluents.

6.2 General Comparison Between Treatment Systems

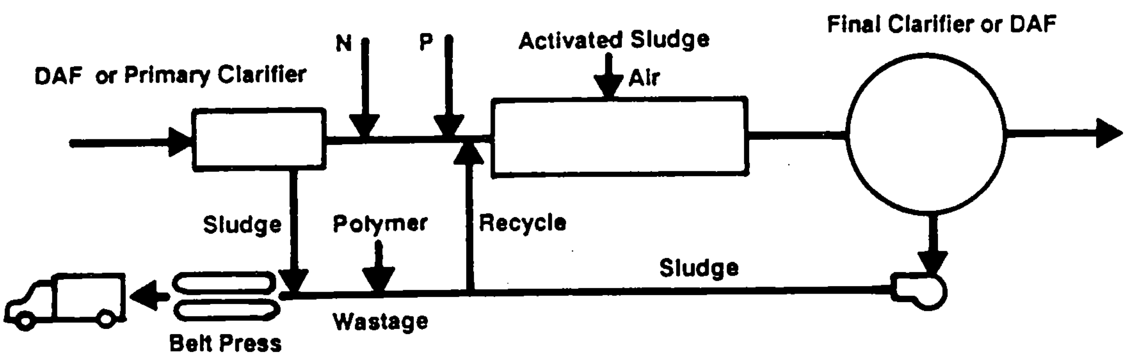
Table 6 compares these treatment processes with respect to fifteen parameters. The treatment processes are ranked on a scale of 1 to 3 for each parameter. Aerated lagoons rank best while activated sludge rank worst. HRAT/aerated polishing lagoon systems fall in between the two extremes. Such generalized comparisons are qualitative in nature and offer little assistance in a decision making process. A more meaningful comparison would have to be quantitative and based largely on total costs.

6.3 Basis for Cost Comparison

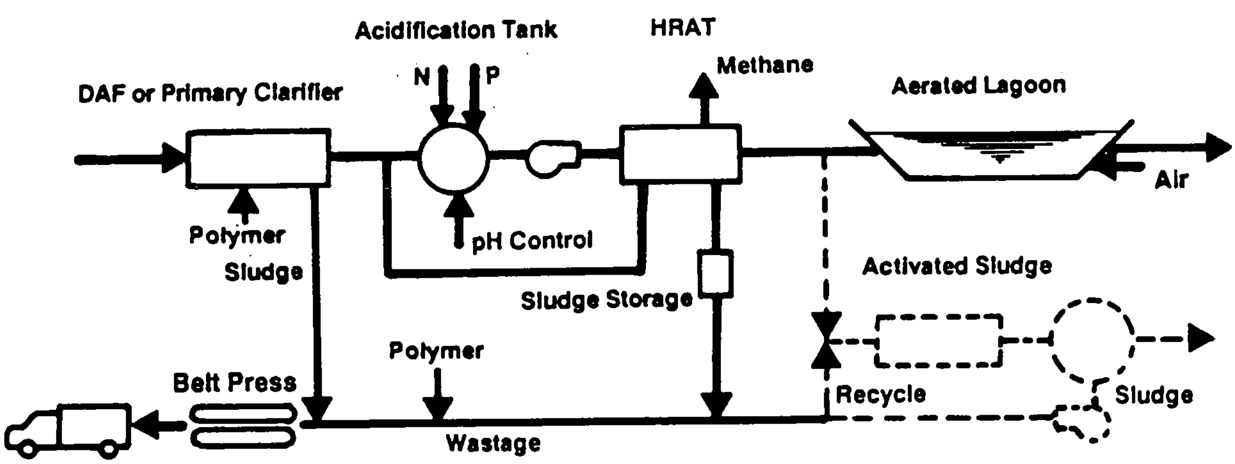
The decision to adopt a particular type of treatment process rather than an equally feasible alternative is largely based on cost considerations. Many parameters considered in Table 6 impact on the total cost. Thus a cost comparison would provide for a more meaningful measure of comparison between alternatives.



AERATED LAGOON



ACTIVATED SLUDGE



HIGH RATE ANAEROBIC TREATMENT/AEROBIC POLISHING

FIGURE 3

SCHEMATIC OF TREATMENT ALTERNATIVES

Site specific aspects such as effluent discharge permits, land availability, nature of terrain, cost of power, and the presence of pure oxygen on site also impact on the cost. None of these site specific considerations can be dealt with in this report. In spite of this limitation, some reasonable estimate can be made of the overall cost of each process to allow for meaningful comparisons. At the very least, such 'generic' cost comparisons could be used as a base from which to prepare site specific estimates.

The criteria on which the costing comparison is based follows. It covers both capital and operating costs.

TABLE 6 SUMMARY COMPARISON BETWEEN TREATMENT TECHNOLOGIES USED IN CTMP WASTE TREATMENT

Parameter	Aerated Lagoon	Activated Sludge	HRAT/ Aerated Lagoon
Land requirement	3	1	2
Complexity of operation	1	3	3
Energy demand	3	3	1
Detoxification ability	2	2	1
Nutrient addition	2	3	1
Need for pilot testing	1	2	3
Sludge production	2	3	1
Sensitivity to toxicants	1	2	3
Proven operating history	1	2	3
pH control	1	1	3
Odour generation potential	1	1	3
Shock load handling	1	3	2
TSS reduction	3	2	1
High temperature shocks	1	3	2
Recovery from upsets	1	3	3

Rating: 1 - best 3 - worst

6.3.1 Influent/Effluent Criteria. The influent and effluent criteria adopted for cost estimating purposes are presented in Table 7.

The size of mills considered ranges from an output of 250 to 1,000 ADt of pulp. This adequately covers most CTMP mills currently in operation in Canada.

Most CTMP mills generate between 18 and 25 m^3 of effluent per ADt of pulp produced. To facilitate comparisons, a uniform effluent flow of 20 m^3/ADt was adopted.

The BOD concentration of CTMP wastes generally ranges between 2,000 and 4,000 mg/L. This is much higher than that of

TABLE 7 INFLUENT AND EFFLUENT CRITERIA ADOPTED FOR COSTING PURPOSES

Parameter	Unit	Limits
Size of Mill	ADt of pulp	250 - 1,000
Wastewater:		
- Flow	m^3/ADt	20
	m^3/d	5,000 - 20,000
- BOD Loading	mg/L	1,000 - 4,000
	t/d	5 - 80
- TSS Loading	mg/L	200 - 800
	t/d	1 - 16
- COD:BOD		2.8
- Temperature	^oC	35
- N Content	mg/L	0
- P Content	mg/L	0
Effluent Discharge Standards:		
- BOD	kg/ADt	7.5
- TSS	kg/ADt	10.0
- Fish Toxicity	96 hr LC_{50}	100 %

most other types of pulping processes. To cover a range that could be useful to other types of mills, the comparison used here spans from concentrations of 1,000 mg/L to 4,000 mg/L.

The effluent discharge standards adopted in Table 7 reflect strict effluent standards that are likely to become the norm in the 1990's. Effluent criteria dealing with organochlorines have not been addressed since CTMP mills do not practice chlorine bleaching.

Effluent criteria play a major role in the selection of a treatment process train. This is graphically demonstrated in Figure 4 which reflects the TSS level associated with influent BOD levels ranging from 1,000 to 4,000 mg/L BOD and TSS levels amounting to 20% of the BOD. Based on the adopted criteria, ten day aerated lagoons alone (which appear to be the 'norm' for CTMP mills) are inadequate to treat high strength CTMP wastes (ie, BOD above 1,000 mg/L) without additional post-treatment (and possibly pre-treatment) for the reduction of TSS (and possibly BOD) to levels below 10 kg/ADt. Pre-treatment could be in the form of an HRAT system, while post-treatment could be in the form of polymer aided post-clarification, complete with solids handling, dewatering and disposal. For BOD levels of up to 1,000 mg/L, post clarification facilities are not required to achieve the desired effluent quality of 10 kg TSS/ADt.

The adoption of a ten day aerated lagoon as the basis for costing purposes is not intended to suggest that a ten day detention time is sufficient to detoxify the waste and reduce its BOD to the desired level. It merely reflects the practice in Canada to-date in sizing such facilities to treat CTMP effluents. The use of longer hydraulic detention times could reduce the solids loading in the effluent and the concomitant need for post clarification facilities.

6.3.2 Unit Processes Criteria. The unit process criteria adopted for each treatment process are presented in Table 8.

An important consideration that impacts on the cost and decision making process is the proven operating history of a

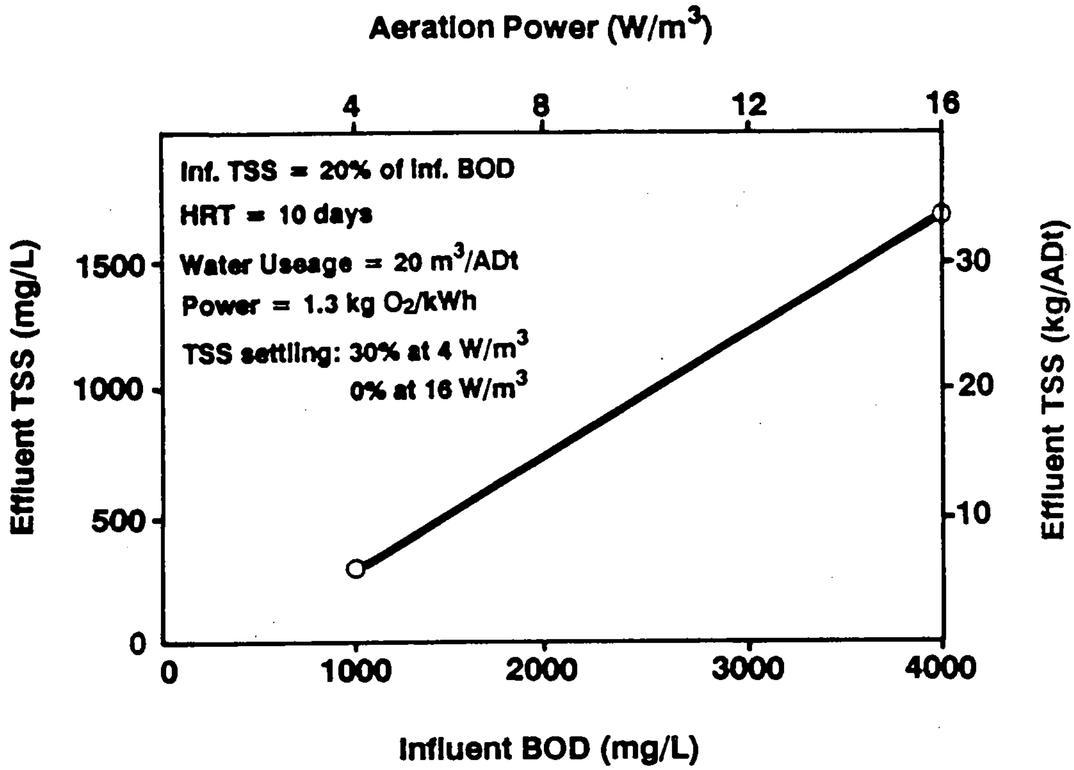


FIGURE 4

PREDICTED SUSPENDED SOLIDS LEVELS IN AERATED LAGOON EFFLUENT

process. HRAT systems have the shortest proven operating history. In recognition of that fact and to render comparisons meaningful, a conservative value was used in estimating methane generation. A value of 0.27 m^3/kg COD removed was used instead of the traditional 0.35 m^3/kg COD removed, which represents the maximum theoretical yield. This reduction of 27% would allow for periods of operational upset.

TABLE 8 DESIGN CRITERIA FOR UNIT PROCESSES

Parameter	Unit	Aerated Lagoon No Post Settling	Aerated Lagoon With Post Settling	Activated Sludge	HRAT/ Aerated Lagoon
Dissolved Air Floatation:					
- Loading rate	kg TSS/m^2.h	N.A.	N.A.	5.0	5.0
- Polymer dosage	mg/L	N.A.	N.A.	N.A.	15
BOD:N:P		100:5:1	100:5:1	100:5:1	100:1:0.2
MLSS	mg/L	400-1,700	400-1,700	4,000	80,000/635
Sludge Production	t/t BOD	0.4	0.4	0.4	0.1/0.4
Sludge Dewatering:					
- Rate	kg VSS/m.h	N.A.	170	170	325/N.A.
- Polymer dosage	kg/t	N.A.	5	5	2/N.A.
Hydraulic reten. time	d	10	10	0.6-2.7	0.5-1.0/3
Solids retention time	d	10	10	15	100/3
Aeration Power	kg O_2/kWh	2	2	2	N.A./2
Final Clarifier Loading Rate	m/h	N.A.	2.1	0.8	N.A.
Caustic Addition	mg/L NaOH	N.A.	N.A.	N.A.	200/N.A.
Methane Generation	m^3/kg COD	N.A.	N.A.	N.A.	0.27/N.A.
Manpower		0.5-1.0	0.5-2.5	4-6	4-6

N.A. Not applicable

NOTES: 1) Range of values cover flow variation from 5,000 to 20,000 m^3/d

2) Slashes in column 6 separates the value of the HRAT system from the aerated lagoon

In addition to the aforementioned, the following process-specific considerations were adopted for the HRAT system:

a) Use of UASB reactors (they have been adopted in Canada to the exclusion of all other types of HRAT systems).
b) COD loading rate in anaerobic bioreactor: 15 kg COD/m^3 of reactor volume.
c) 60% COD removal.
d) Equalization/preacidification tank sized for 6 hours retention.
e) One sludge storage tank sized at 10% of the total UASB reactor(s) volume.
f) Chemical feed system for pH control.
g) Gas collection system.
h) Odour control scrubber.

6.3.3 Items Excluded From Capital Costs. The capital cost estimates exclude the following components:

a) Cost of land;
b) Site specific terrain considerations;
c) Rock excavation;
d) Pre-settling tanks (for lagoon option only);
e) Disposing of dewatered waste biological sludge;
f) In-mill modifications;
g) Transport of wastestreams to treatment facility;
h) Emergency storage basins;
i) Owners costs (administration of works);
j) Pilot-scale testing;
k) Effluent outfall.

Of the eleven items excluded from the capital cost considerations, the first four all result in greater cost to the aerated lagoon option, while the remaining items (with the exception of pilot scale testing), are common to all. Pilot scale testing is considered necessary for HRAT systems but not necessarily for the other treatment systems.

6.3.4 Unit Costs For Operations and Maintenance. The unit operations and maintenance costs are presented in Table 9.

TABLE 9 BASIS FOR OPERATIONS AND MAINTENANCE COSTS

Parameter	Cost Allowance
Manpower	$50,000 annually, including benefits/person
Power	4.5 cents/kWh
Spare parts	2% of capital cost
Chemicals:	
- Ammonia	$250/t
- Phosphoric acid	$1.00/kg as 75% phosphoric acid
- Sodium hydroxide	$200/t as 50% NaOH solution
- Polymer	$2.00/kg liquid polymer (50-60% concent.)
- Methane	$3.60/GJ equivalent natural gas value

The operations and maintenance cost summary for each alternative is presented in Table 10.

6.3.5 Items Excluded From the Operations and Maintenance Costs. The operations and maintenance cost estimates exclude the following:

- Ultimate disposal of biological sludges;
- Administration personnel and expenses.

6.4 Cost Comparisons

A summary comparison of the capital, operating and total annual costs is presented in Table 11. Figure 5 compares only the total annual costs for the range of flows and BOD loadings considered. It is interesting to note that for a given flow rate the total annual costs of the HRAT/aerated lagoon system increases only marginally with increasing waste strength.

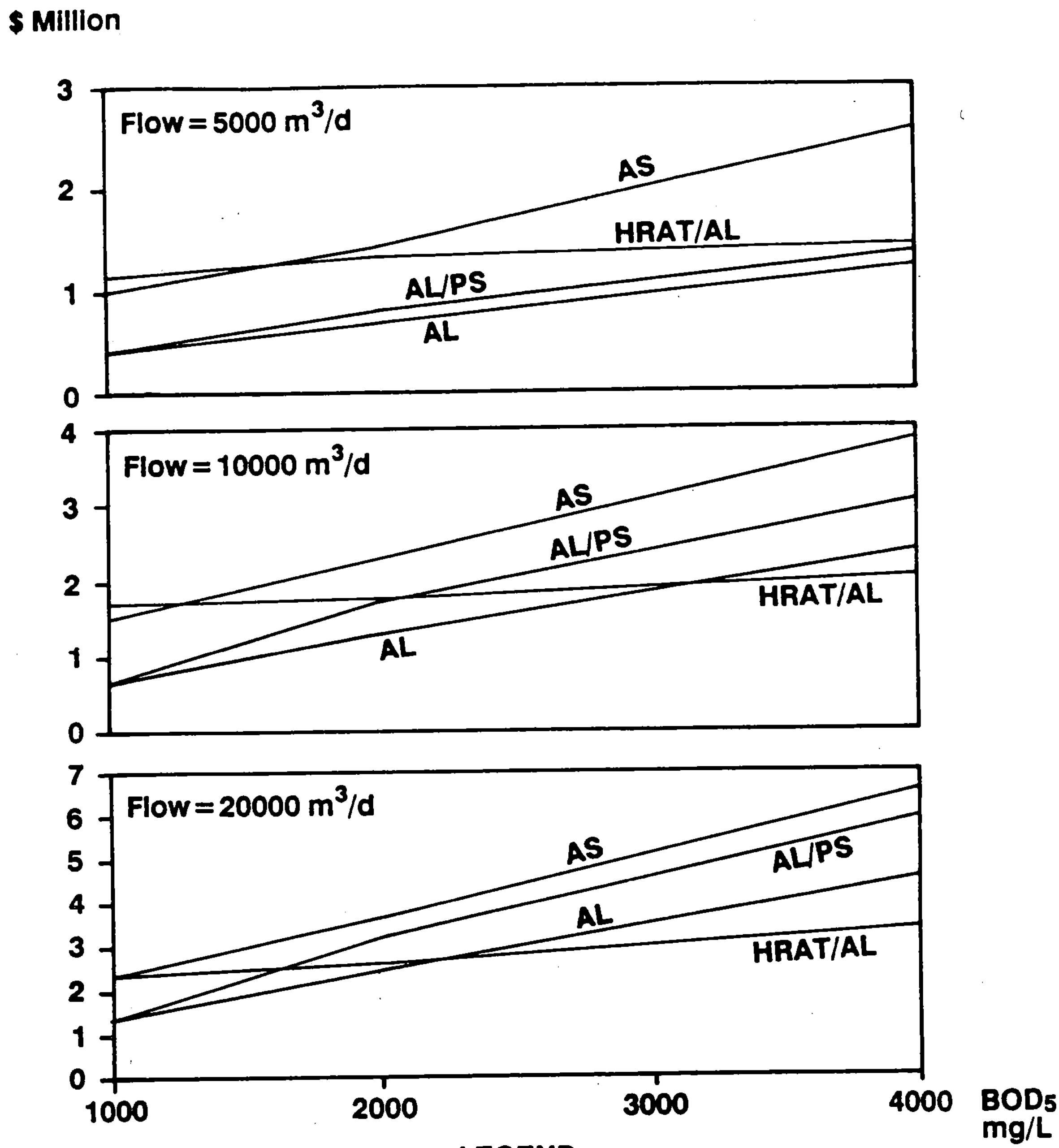
TABLE 10 OPERATIONS AND MAINTENANCE COST SUMMARY ($ '000)

Cost Item	5,000 m^3/d			10,000 m^3/d			20,000 m^3/d		
	BOD (mg/L)			BOD (mg/L)			BOD (mg/L)		
	1000	2000	4000	1000	2000	4000	1000	2000	4000
AERATED LAGOON - NO POST SETTLING									
Power	75	150	300	156	309	618	312	624	125
Ammonia	14	27	55	46	91	183	91	183	365
Phosphoric acid	11	22	44	37	73	146	73	146	292
Polymer - DAF									
Polymer - Sludge				40	78	155	78	155	310
Sodium hydroxide									
Spare parts	31	58	105	65	124	227	111	206	404
Manpower	25	25	25	75	75	75	75	75	125
TOTAL	156	282	529	419	750	1404	740	1389	2747
AERATED LAGOON - WITH POST SETTLING									
Power	75	150	300	156	309	618	312	624	125
Ammonia	14	27	55	46	91	183	91	183	365
Phosphoric acid	11	22	44	37	73	146	73	146	292
Polymer - DAF									
Polymer - Sludge									
Sodium hydroxide									
Spare parts	31	58	105	47	90	168	79	153	294
Manpower	25	25	25	25	25	25	50	50	50
TOTAL	156	282	529	311	588	1140	605	1156	2252
ACTIVATED SLUDGE									
Power	75	150	300	156	309	618	312	624	125
Ammonia	14	27	55	46	91	183	91	183	365
Phosphoric acid	11	22	44	37	73	146	73	146	292
Polymer - DAF									
Polymer - Sludge	17	34	68	34	68	135	68	135	270
Sodium hydroxide									
Spare parts	74	98	143	120	166	249	192	274	452
Manpower	200	200	200	200	250	250	250	300	300
TOTAL	391	531	810	593	957	1581	986	1662	2930
HRAT WITH POST SETTLING LAGOONS									
Power	6	18	47	12	35	92	18	69	183
Ammonia	5	9	18	9	18	37	18	37	73
Phosphoric acid	4	8	15	8	15	29	15	29	58
Polymer - DAF	50	50	50	100	100	100	200	200	200
Polymer - Sludge	5	9	18	9	18	36	18	36	72
Sodium hydroxide	73	73	73	146	146	146	292	292	292
Spare parts	104	134	166	158	188	256	220	292	462
Manpower	200	200	200	250	250	250	300	300	300
TOTAL	447	501	587	692	770	946	1081	1255	1640

TABLE 11 CAPITAL AND OPERATING COST SUMMARY ($ million)

Cost Item	Flow = 5,000 m^3/d			Flow = 10,000 m^3/d			Flow = 20,000 m^3/d		
	BOD mg/L			BOD mg/L			BOD mg/L		
	1,000	2,000	4,000	1,000	2,000	4,000	1,000	2,000	4,000
AERATED LAGOONS - NO POST SETTLING									
Capital Cost	1.55	2.34	3.93	2.89	4.47	7.63	5.24	8.40	14.70
A.C.C.	0.25	0.37	0.62	0.46	0.71	1.21	0.83	1.33	2.33
Annual O & M	0.16	0.31	0.61	0.28	0.59	1.16	0.53	1.14	2.25
Total Annual Cost	0.41	0.68	1.23	0.74	1.30	2.37	1.36	2.47	4.58
AERATED LAGOONS - WITH POST SETTLING									
Capital Cost	N.R.	2.34	3.93	N.R.	6.17	10.33	N.R.	11.34	20.17
A.C.C.	N.R.	0.37	0.62	N.R.	0.98	1.64	N.R.	1.80	3.20
Annual O & M	N.R.	0.42	0.74	N.R.	0.75	1.39	N.R.	1.40	2.75
Total Annual Cost	N.R.	0.79	1.36	N.R.	1.73	3.03	N.R.	3.20	5.95
ACTIVATED SLUDGE									
Capital Cost	3.70	4.90	7.16	6.00	8.30	12.45	9.60	13.70	22.60
A.C.C.	0.59	0.78	1.52	0.95	1.32	2.17	1.52	2.17	3.58
Annual O & M	0.39	0.53	0.81	0.59	0.96	1.58	0.99	1.66	2.93
Total Annual Cost	0.98	1.31	2.33	1.54	2.28	3.75	2.51	3.83	6.51
HRAT WITH POST AEROBIC LAGOONS									
Capital Cost	5.20	6.70	8.30	7.90	9.40	12.80	11.00	14.60	23.10
A.C.C.	0.82	1.06	1.32	1.25	1.49	2.03	1.74	2.31	3.66
Annual O & M	0.45	0.50	0.58	0.70	0.77	0.94	1.09	1.26	1.62
Methane Credit	(0.12)	(0.23)	(0.47)	(0.23)	(0.47)	(0.93)	(0.47)	(0.93)	(1.86)
Total Annual Cost	1.15	1.33	1.43	1.72	1.79	2.04	2.36	2.64	3.42

A.C.C. Amortized capital cost (at 10% interest for 10 years)
N.R. Not Required



LEGEND

AL - Aerated lagoon - no post settling

AL/PS - Aerated lagoon with post settling

AS - Activated sludge

HRAT/AL - HRAT/Aerated lagoon

FIGURE 5
TOTAL ANNUAL COST COMPARISON

This is attributed to the higher methane generation rates associated with increased waste strength which offsets both the added capital and operating costs. It is clear from Figure 5 that no single treatment process is most cost effective over the entire range studied.

Figure 6 identifies the overall most cost effective treatment process for any flow/waste combination within the range considered (the range was extrapolated to a BOD strength of 5,000 mg/L).

Aerated lagoons are most cost effective at low organic loadings and flows. HRAT/aerobic polishing systems are most cost effective at the higher strengths and flows. Activated sludge systems are not cost effective within the range studied. Implementation of post clarification for aerated lagoons considerably reduces the cost effective range of lagoon systems and renders HRAT/aerated lagoon options more attractive over a wider range of flow/strength combinations.

Figure 7 identifies the most cost effective form of treatment for seven selected Canadian CTMP mills based on the findings of this study. Three of the mills clearly fall within the area where the HRAT/aerobic lagoon system is most cost effective. Another three mills are within the band where the aerated lagoon without post clarification is most cost effective. Aerated lagoons in this band cannot meet the earlier stated objective of 10 kg TSS/ADt without provision of post clarification facilities. Should post clarification be included, all three remaining mills would be more cost effectively treated by an HRAT/aerated lagoon system. The seventh mill is clearly in a zone where aerated lagoons are most cost effective. It should be remembered that site specific considerations would impact on the above conclusions.

Figure 8 compares the total annual costs of all treatment processes in terms of dollars per tonne of pulp produced for the range of flows and organic strength considered.

The total annual cost differential between the two least costly alternatives for the flow and BOD loading range studied is presented in Figure 9. At a BOD level of 1,000 mg/L, the aerated lagoon option results in annual savings of $750,000 to $1,000,000. At BOD levels of 4,000 mg/L, the HRAT/Aerated lagoon option ranges from annual savings of $560,000 (at a flow of 10,000 m^3/d) to $2.5 million (at a flow of 20,000 m^3/d).

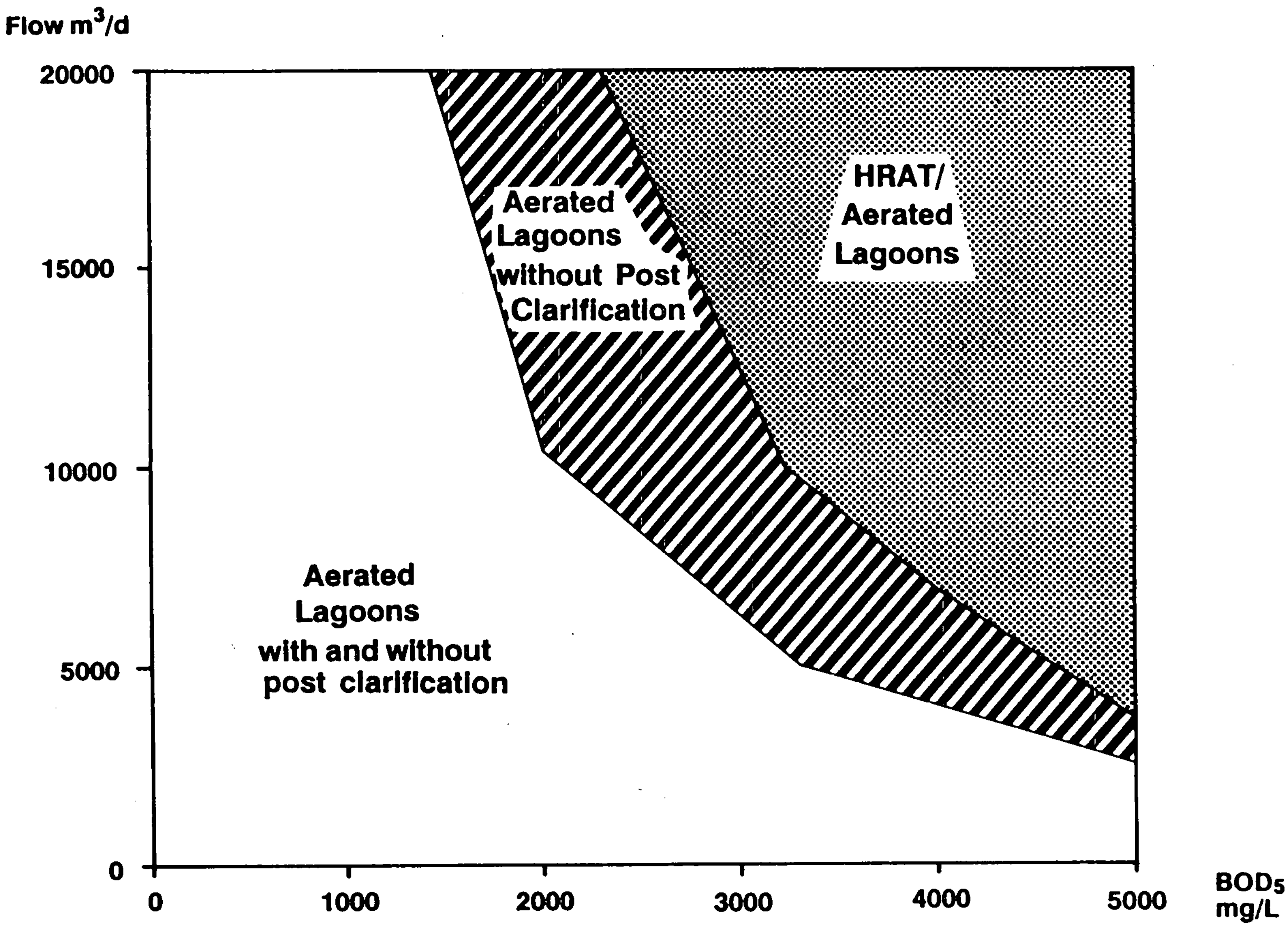


FIGURE 6

OVERALL MOST COST EFFECTIVE TREATMENT PROCESS

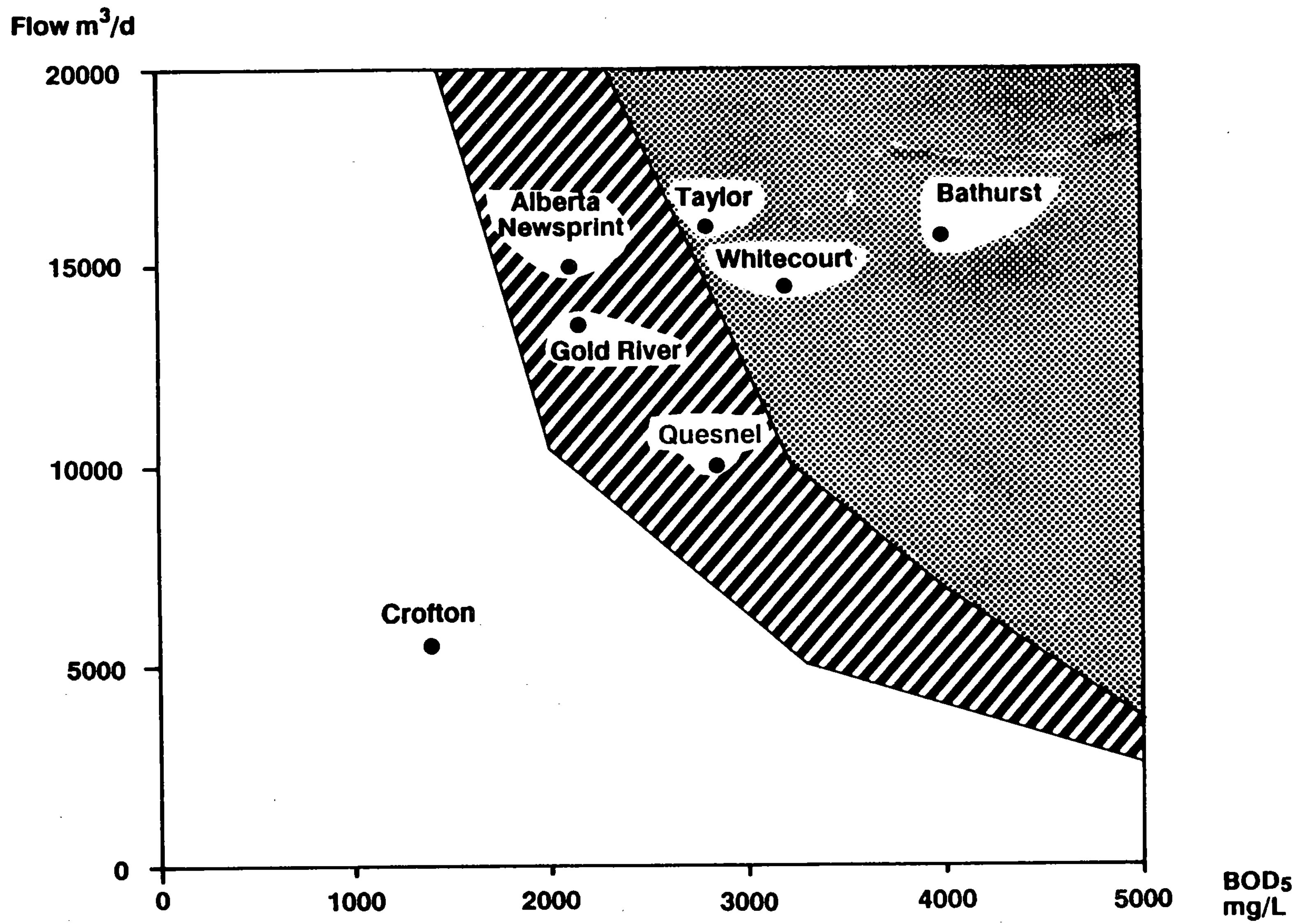


FIGURE 7

MOST COST EFFECTIVE TREATMENT PROCESS FOR SEVEN CANADIAN CTMP MILLS

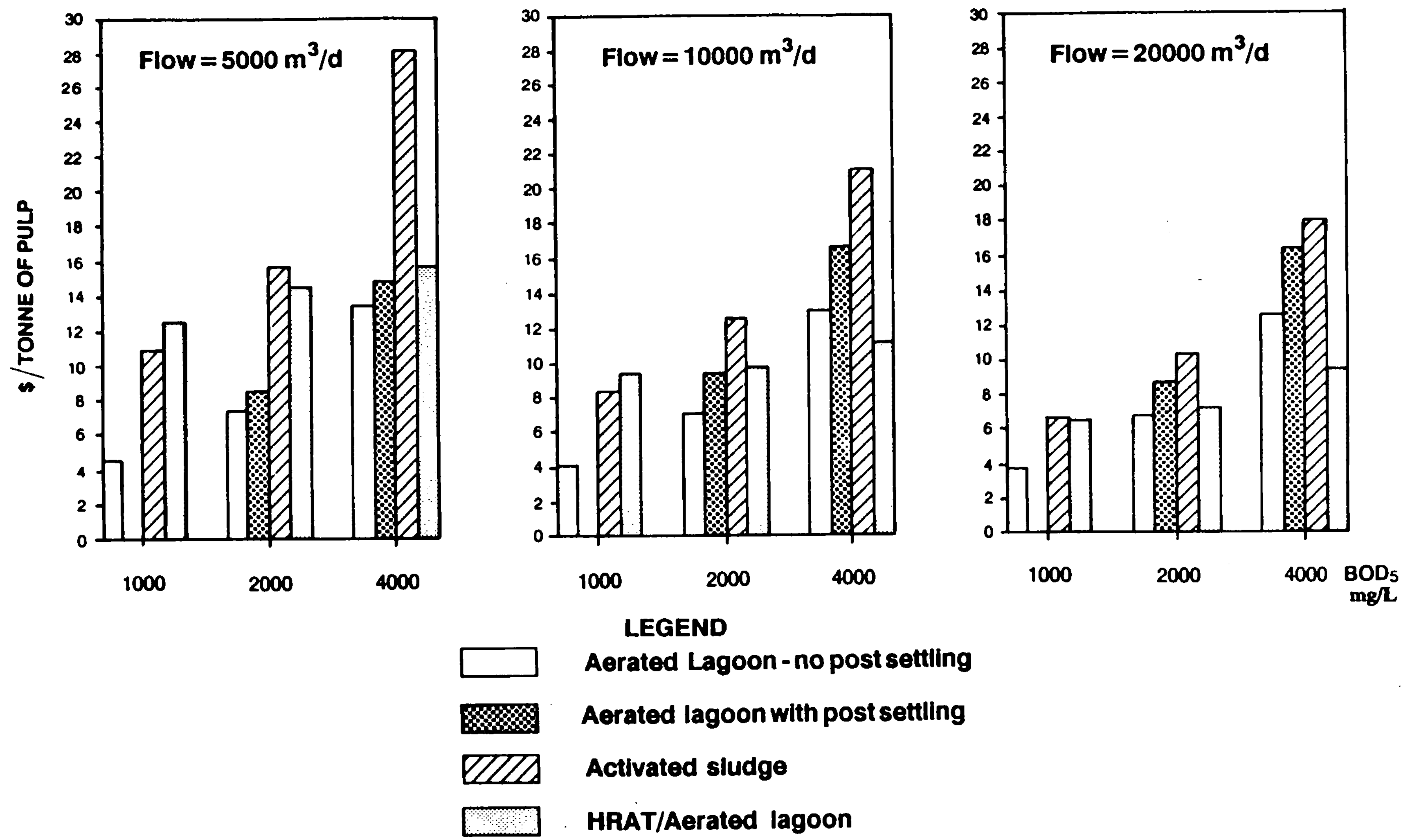


FIGURE 8

TOTAL ANNUAL COST PER TONNE OF PULP PRODUCED

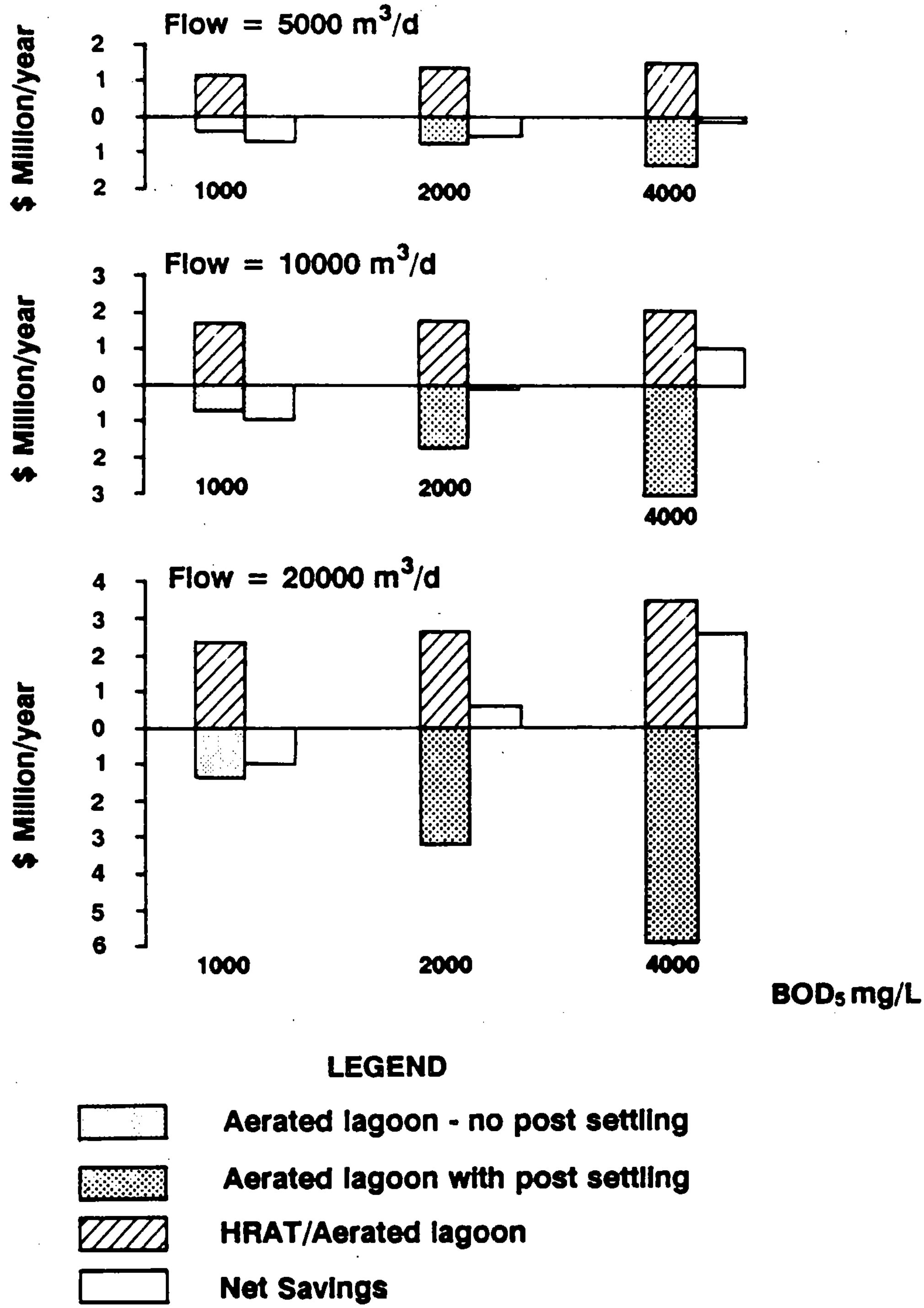


FIGURE 9
ANNUAL COST DIFFERENTIAL BETWEEN THE TWO LEAST COSTLY ALTERNATIVES

7 CONCLUSIONS

a) High rate anaerobic treatment is an emerging technology which has good potential for treating CTMP wastewater.

b) Anaerobic treatment cannot detoxify CTMP wastewater and has to be followed by a post aerobic treatment step.

c) Properly designed and operated aerated lagoons can be used for the treatment of CTMP wastewater provided solids handling facilities are installed.

d) Cost comparisons indicate that aerated lagoons are the most cost effective form of treatment for CTMP wastes with BOD levels of up to around 1,000 mg/L. At higher strengths, high rate anaerobic treatment followed by aerated polishing lagoon represents the most cost effective method of treatment. Activated sludge systems are not cost effective within the range studied.

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