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1984 TRIANGLE CONFERENCE ON ENVIRONMENTAL TECHNOLOGY
DUKE UNIVERSITY

A REVIEW OF ANAEROBIC TREATMENT OF HIGH STRENGTH WASTEWATER STREAMS

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INTRODUCTION

Wastewater streams with high concentrations of soluble organics and low concentrations of solids have historically been treated in aerobic reactors such as activated sludge or trickling filters. In the past, energy costs associated with aerobic treatment has been low and disposal of sludge resulting from the process has been easy. However, in recent years, power costs have risen dramatically and sludge disposal has become much more difficult and costly. These changes have significantly reduced the comparative economy of aerobic treatment and caused industry to re-examine other treatment technologies.

Anaerobic biological treatment of wastewaters has gained considerable recognition in recent years. In some cases, the anaerobic processes currently being used have been shown to be more cost effective treatment alternatives than the more commonly used aerobic treatment processes, particularly where highly concentrated organic wastes are concerned.

Anaerobic treatment is being repeatedly proposed as an alternative to aerobic treatment for high-strength effluents, those having COD concentrations greater than or equal to 1000 mg/L. Use of an anaerobic treatment alternative offers many advantages, including reduced energy requirements. Also, because methane is produced during this process, anaerobic treatment can often be a net energy producer. Biomass production is generally between 10 and 20 percent of that of activated sludge. Anaerobic treatment also greatly reduces the requirements for nitrogen and phosphorus, imposes minimum constraints of food to microorganism (F/M) control, and generally has a lower sensitivity toward heavy metal poisoning.

This paper presents an overview of anaerobic treatment technology and provides results for different wastewaters treated by some of the anaerobic treatment process configurations in use today.

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BACKGROUND

Anaerobic biological treatment has mainly been used for primary and excess sludges at municipal wastewater treatment plants. In this treatment process, anaerobic and faculative microorganisms are used to break down organic material to form biomass, carbon dioxide, and methane. The methane fermentation process is a two-stage process, as shown in Figure 1. In the first stage, which is referred to as "acid fermentation", complex waste components, including fats, proteins, and polysaccharides, are broken down into organic acids by acid-forming bacteria. During this stage of the process, organic material is converted to organic acids, alcohols, and new bacterial cells with little reduction of BOD or COD. In the second-stage, referred to as "methane fermentation", the organic acids and alcohols are metabolized by several species of anaerobic bacteria to methane, carbon dioxide, and water.

Environmental Factors

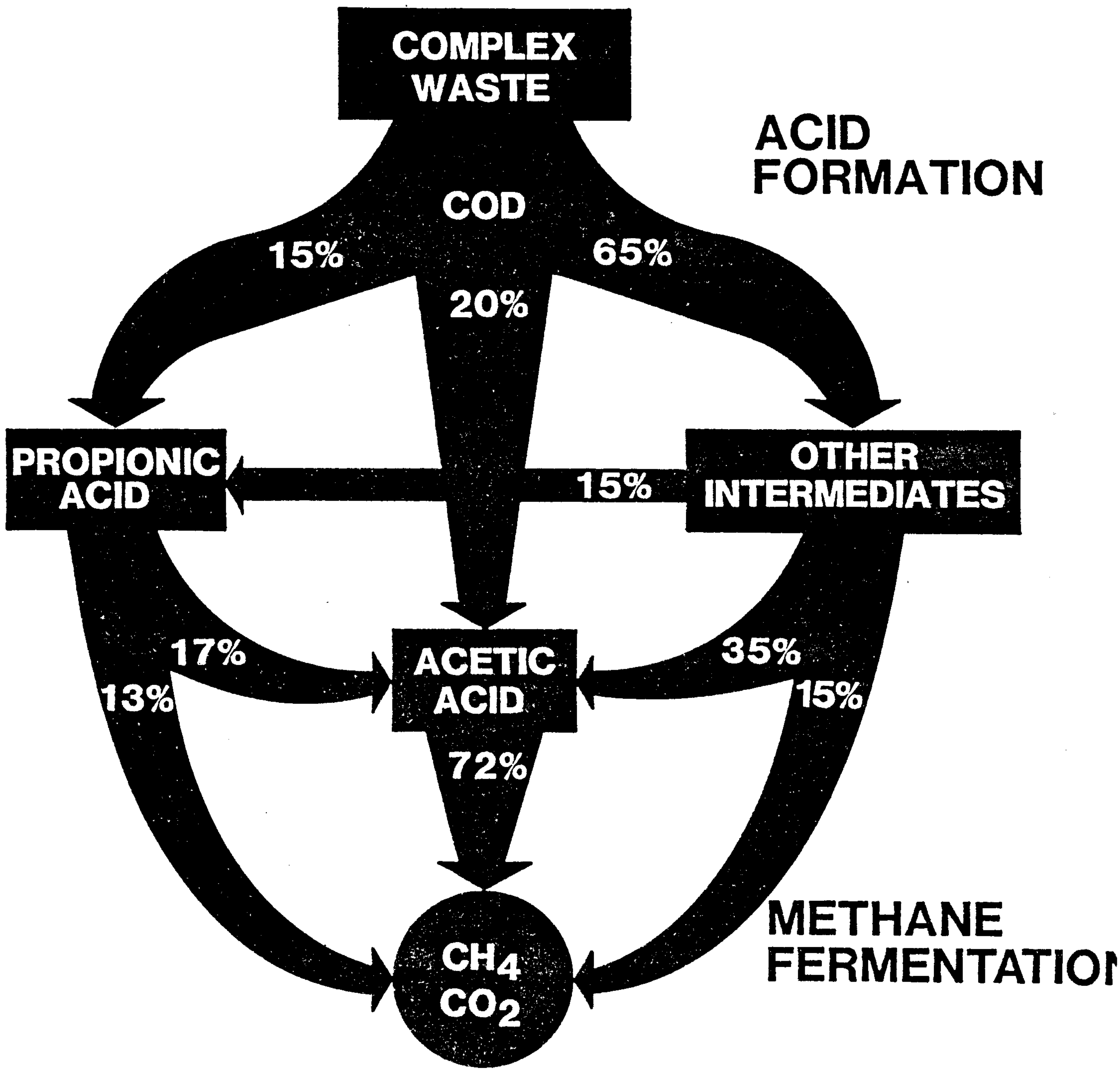
During the methane fermentation process, the methane bacteria are limited in the quantity of energy they can obtain from substrate fermentation, because the majority of the substrate energy is lost in the methane gas producted. As a result, the rate of growth is restricted. In addition, the rate of substrate use per unit of organism is relatively low. The combination of these two factors tends to restrict the overall rate of substrate use by methane bacteria. Therefore, optimum environmental conditions are necessary for satisfactory rates of methane fermentation to occur. However, methane fermentation in acid bogs and at relatively low temperatures indicate that methane bacteria can survive under much less than optimum conditions.

Optimum methane fermentation has generally been found to occur between the pH range of 6.0 to 8.5(1) but drops rapidly outside this range. Values of pH below 6 or above 8.5 have been found to be restrictive and somewhat toxic to methane bacteria. For proper pH control, sufficient alkalinity is essential because it acts as a buffer to the system. Alkalinity is produced from the breakdown of organic material and, at typical fermentation pH around 7.0, is present primarily in the form of bicarbonates.

The optimum temperature for methane fermentation is in the range of 30 to 35°C. As the temperature drops below this range for a given hydraulic retention time (HRT), the quantity of substrate removed from the system decreases. Unless HRT is increased at temperatures below 20°C, anaerobic treatment is usually not feasible because biomass will be removed from the system faster than it is being produced and eventually all the biomass will be lost. If

FIGURE 1

PATHWAYS IN METHANE FERMENTATION OF COMPLEX WASTES



this occurs, the effluent substrate concentration will be the same as the influent concentration, because no microorganisms will be present to use the organic matter.

Nutrient requirements for methane fermentation are relatively small. Continuous fermentation for periods in excess of one year has been obtained with the following substrates as the sole source of organic carbon: glucose, starch, cellulose, nutrient broth, leucine, oleic acid, palmitric acid, octanoic acid, butyric acid, propionic acid, and acetic acid.(4) Other additions were the normal inorganic nutrients, nitrogen and phosphorous, and other usually required trace inorganic ions.

The complete absence of oxygen is necessary to achieve methane fermentation. Highly purified cultures of methane bacteria are extremely sensitive to even small quantities of oxygen and great care should be used in its exclusion.

Anaerobic vs. Aerobic Treatment

Anaerobic biological treatment has not generally been used to treat high strength organic wastewaters. Anaerobic treatment processes are initially slow to start up and are less stable to operating fluctuations than aerobic treatment processes. Suspended solids in an anaerobic treatment effluent do not settle as well as those in an aerobic system; therefore, anaerobic effluents typically have higher suspended solids and organic concentrations than aerobic effluents. Because of these reasons, pollutants controlled by secondary treatment standards have historically been treated in aerobic rather than anaerobic systems. However, as indicated earlier in this paper, aerobic systems are becoming less attractive for the treatment of high strength wastes because of the rising costs of power and sludge disposal.

Anaerobic wastewater treatment offers the following significant advantages over aerobic treatment for high strength industrial wastewaters:

- Low energy requirements
- Production of energy in the form of methane
- Reduced nutrient requirements
- Reduced sludge production

Significantly less energy is required for anaerobic treatment of organic waste. Aerobic treatment requires approximately one hp-hour to reduce 1.6 pounds of BOD, while anaerobic treatment can remove as much as 14 pounds of BOD for the same power requirements.(2)

The energy savings realized with anaerobic treatment are further enhanced when methane produced in the process is burned to provide process energy. The theoretical volume of methane gas produced for each pound of COD converted is 5.6 cubic feet with an energy value of 5600 Btu. The theoretical methane yield for typical food processing waste, in which BOD is approximately 60 percent of COD, is 9.3 cubic feet per pound of BOD removed.(2)

Many high strength industrial wastewater streams have insufficient nitrogen and phosphorous concentrations to support aerobic biological growth. However, these streams can often successfully support anaerobic biological growth which requires fewer nutrients and results in less sludge formation as BOD is metabolized. In an aerobic process, 40 to 70 percent of the BOD metabolized may be converted into sludge mass, whereas an anaerobic process will produce only 5 to 10 percent.

Wastewater Candidates for Anaerobic Treatment

Anaerobic treatment was previously regarded as an odorous and unreliable treatment process. However, today it is receiving greater acceptance, especially under the following circumstances:

- The wastewater contains high concentrations of biodegradable material (COD $\geq$1000 mg/L).
- The wastewater has a low suspended solid concentration.
- The wastewater temperature is high (from 30 to 35°C) or a low value of excess heat is available.
- The recovered gas can possibly be used for direct steam generation without storage.

Because the anaerobic treatment process is sensitive, all environmental factors previously discussed must be considered carefully before an anaerobic treatment process is selected. Variations in either organic or hydraulic loading over short periods of time may cause operational problems. In addition, anaerobic treatment is generally not suitable for treating waste from seasonal processes, such as small cannery operations, because of the long startup time required.

ANAEROBIC TREATMENT PROCESSES

The relationship between microorganism growth rate and biological solids retention time (BSRT) for an anaerobic treatment process with no recycle stream is given by the following equation:

$$1/u = BSRT$$

where u is the specific biological growth rate (days $^{-1}$). With no recycle stream, the HRT within the process will equal the BSRT. If the HRT decreases, a BSRT will be reached at which biomass is removed from the system faster than it is being produced. Therefore, if a process is operating at a BSRT below this minimum value, the slow growing anaerobic bacteria will washout. To prevent washout, a minimum BSRT must be maintained such that microorganism growth rate exceeds the washout rate determined by HRT. These conditions can be achieved by using large reactor volumes.

In recent years, a great deal of research and development into anaerobic waste treatment processes have taken place, resulting in the development and successful application of a number of high rate anaerobic treatment process configurations. The common factor among these processes is a high biomass concentration which allows long BSRTs to be maintained even with low HRTs. These process configurations include:

- o Anaerobic contact process
- o Anaerobic filters
- o Anaerobic fluidized bed
- o Anaerobic attached-film expanded-bed (AAFEB)
- o Upflow anaerobic sludge blanket reactor (UASB)

Anaerobic Contact Process

An anaerobic contact process consists of a heated digestion tank followed by a settling tank which removes the active biological suspended solids from the effluent flow and returns them to the digestion tank to increase the solids contact. Richter(7) reported that the process involves two parts: a contact portion where the raw waste is intimately mixed with a previously developed anaerobic sludge culture, and a separation portion where the activated sludge particles are separated from the treated liquor and recycled to the contact unit.

Typical industrial wastes treated with an anaerobic contact process are listed in Table 1 along with expected treatment performances for various conditions. The anaerobic contact process is employed in a combined anaerobic-aerobic treatment process known as the ANAMET® process, shown in Figure 2.

FIGURE 2

ANAMET PROCESS

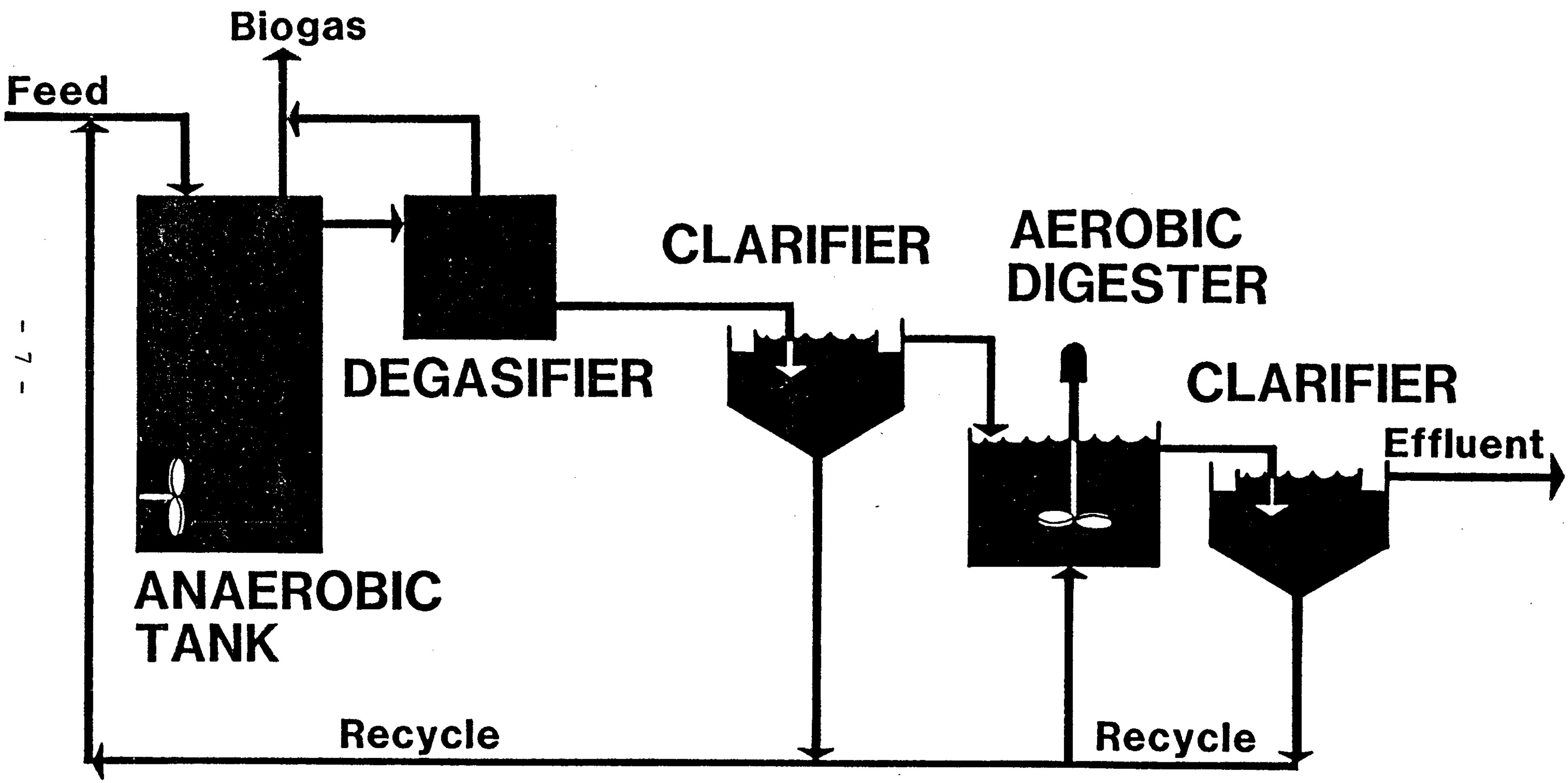


TABLE 1 [1]

Example Performance For The Anaerobic Contact Process

Waste		Hydraulic Retention Time (days)	Digestion Temperature (°C)	BOD$_5$ Raw Waste mg/L	BOD$_5$ lb/1000 ft^3/day added	BOD$_5$ Percent Removed
Maize starch		3.3	23	6,280	110	88
Whiskey distillery		6.2	33	25,000	250	95
Cotton Kiering		1.3	30	1,600	74	67
Citrus		1.3	33	4,600	214	87
Brewery		2.3		3,900	127	96
Starch gluten		3.8	35	14,000[a]	100[a]	80[a]
Wine		2.0	33	23,400[a]	730[a]	85[a]
Yeast		2.0	33	11,900[a]	372[a]	65[a]
Molasses		3.8	33	32,800[a]	546[a]	69[a]
	(	1.3	33	2,000	110	95
	(	0.5	33	1,380	156	91
Meat packing	(	0.5	35	1,430	164	95
	(	0.5	29	1,310	152	94
	(	0.5	24	1,110	131	91

[a] Volatile suspended solids, rather than BOD$_5$

Wastewater enters an anaerobic reactor which is maintained at a temperature range of 35 to 37°C. BOD in the influent is metabolized and sludge, methane, and carbon dioxide are produced. After leaving the anaerobic reactor, the treated wastewater enters a sludge separator, where most of the solids are separated and recycled to the anaerobic reactor. This recycle stream allows a high microorganism concentration to be maintained in the reactor, thereby reducing process retention time.

The second stage in an ANAMET process is a conventional activated sludge plant where further degradation of the waste occurs. Excess sludge from the aerobic treatment process is digested in the anaerobic reactor which reduces the total excess sludge production and results in a higher yield of methane.

Typically, BOD_5-treatment efficiencies between 80 to 90 percent are achieved in the anaerobic stage. The rest of the organic material is degraded 80 to 90 percent in the aerobic stage, resulting in a total BOD_5 reduction between 95 and 99 percent.(3) Table 2 summarizes results for different wastewaters treated in ANAMET pilot plants.

Anaerobic Filters

The anaerobic filter is filled with a medium such as rocks or plastic rings and is similar in appearance to an aerobic trickling filter. However, wastewater is distributed across the filter bottom, and flow is upward through the media so that it is completely submerged. Substrate removal in the anaerobic filter is primarily through the growth of microbial films attached to the filter media. To prevent solids accumulation and plugging of the filter, sludge withdrawal pipes are generally provided.

In the early 1970s, Centennial Mills of Spokane, Washington, constructed the first commercial size anaerobic filter system in the United States. CH2M HILL designed the system for high strength wastes generated from Centennial Mills' wheat starch processing operation. The treatment system achieved a COD reduction of 75 to 80 percent while Centennial Mills saved approximately $60,000 per year employing anaerobic rather than aerobic treatment.

The effort to reduce the high cost associated with aerobic biological treatment systems has continued. Recently, the Celanese Chemical Company has developed an anaerobic wastewater treatment process for high-strength industrial wastewater. The treatment process is known as the Celrobic Wastewater Treatment System and is currently in operation at three Celanese plants in Texas. In this process, as shown in Figure 3, the overflow is continuously recycled by a pump to the bottom of the tank where it is joined by the high strength wastewater feed to be treated. Greater reduction of COD can be achieved by sending the anaerobic effluent to a small aerobic finishing treatment facility such as an activated sludge plant. Sludge formed during aerobic treatment can be returned to the anaerobic filter where the sludge volume is greatly reduced by anaerobic digestion.

In a study CH2M HILL performed for the Potato Processors of Idaho Association, Pailthorp et al.(6) used two pilot scale anaerobic filters and an anaerobic contact system to demonstrate anaerobic treatability of potato processing wastewater. From the results, which are summarized in Table 3, they concluded that BOD reductions of 75 percent can be expected from an 8-foot deep anaerobic filter

TABLE 2
Summary of Results for Different Wastewaters Treated in ANAMET Pilot Plants[3]

	Dairy	Vegetable Cannery	Beet Sugar	Wheat Starch	Pulp & Paper	Citric Acid	Rum Distillery
Influent COD, $g.l^{-1}$	3.0	3.6	8.0	9.0	15	47	89
Influent BOD_5, $g.l^{-1}$	1.4	1.4	3.8	4.2	5.3	17	26
Influent BOD_5:N:P Ratio	35:1.9:1	-	180:8:1	-	400:5:1[a]	300:9:1	170:9:1
Anaerobic tank load, kg $COD\text{-}m^{-3}.d^{-1}$	2.0	1.0	3.0	2.5	5.0	2.5	4.5
Anaerobic tank F/M ration, kg COD-kg $MLSS^{-1}.d^{-1}$	0.6	0.2	0.4	0.25	0.25	0.07	0.15
Anaerobic effluent COD, $g.l^{-1}$	1.0	0.70	3.8	1.6	7.7	10	28
Anaerobic effluent BOD_5, $g.l^{-1}$	0.60	0.10	2.2	0.20	0.72	1.2	3.0
Aerobic effluent COD, $g.l^{-1}$	0.10	0.34	0.40	0.80	6.0	7.5	18
Aerobic effluent BOD_5, $g.l^{-1}$	0.03	0.01	0.12	0.12	0.20	0.35	0.30
Total efficiency, % COD	97	92	95	91	60	84	80
Total efficiency, % BOD_5	98	99	97	97	96	98	99
Gas production, $l.kg\ COD_{add}^{-1}$ (s.t.p.)	225	280	240	390	260	430	325
CH_4, %	85	60	80	70	70	50	50

[a]N and P added.

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FIGURE 3

CELANESE PATENT

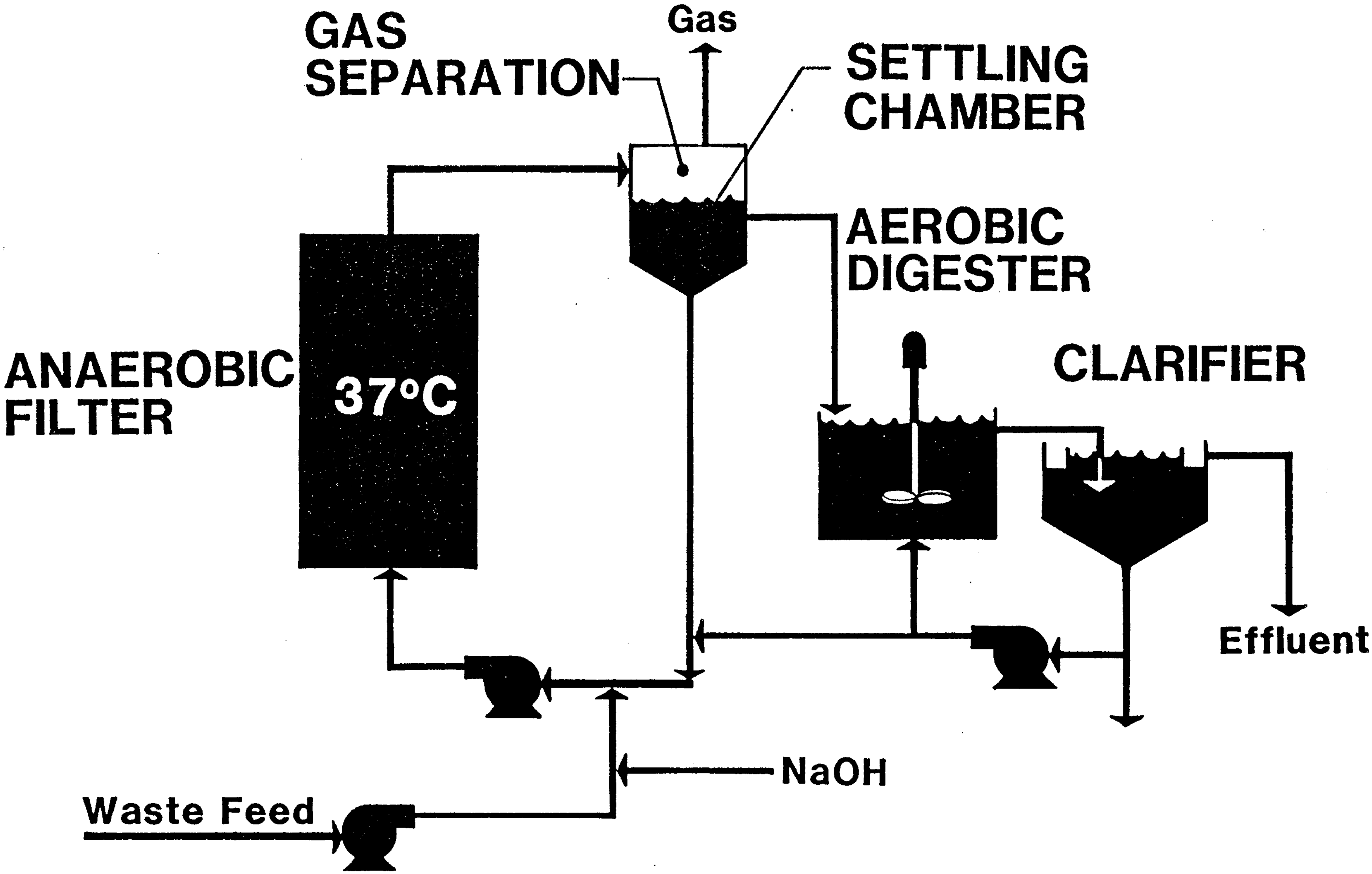


TABLE 3[6]

POTATO PROCESSORS OF IDAHO ASSOCIATION

SUMMARY OF ANAEROBIC SECONDARY TREATMENT DESIGN CRITERIA AS OBTAINED FROM CONTINUED PILOT PLANT STUDIES

TREATMENT PROCESS	TESTING PERIOD	AVERAGE ORGANIC LOADING (LB./1,000 CU.FT./DAY)	HYDRAULIC DETENTION TIME	AVERAGE ORGANIC REMOVAL	REMARKS
ANAEROBIC FILTER WITH 4' MEDIA DEPTH	3-4-69 TO 3-27-69	34 BOD 60 COD	31 HR.	45% COD 22% BOD	1. ALKALINITY ADDITION REQUIRED DURING INITIAL START-UP. 2. AVERAGE INFLUENT TEMPERATURE = 25° C. 3. AVERAGE EFFLUENT TEMPERATURE = 21° C. 4. COD AND BOD REMOVALS INCREASED WITH TIME BECAUSE OF INCREASED BACTERIAL ACCLIMATION TO WASTE AND BIOLOGICAL SOLIDS BUILD-UP.
	4-1-69 TO 4-29-69	83 BOD 145 COD	13 HR.	54% COD 47% BOD	
	5-1-69 TO 5-29-69	49 BOD 85 COD	21 HR.	63% COD 63% BOD	
ANAEROBIC FILTER WITH 8' MEDIA DEPTH	3-4-69 TO 3-27-69	23 BOD 40 COD	44 HR.	41% COD 35% BOD	1. ALKALINITY ADDITION REQUIRED DURING INITIAL START-UP. 2. AVERAGE INFLUENT TEMPERATURE = 25° C. 3. AVERAGE EFFLUENT TEMPERATURE = 21° C. 4. COD AND BOD REMOVALS INCREASED WITH TIME BECAUSE OF INCREASED BACTERIAL ACCLIMATION TO WASTE AND BIOLOGICAL SOLIDS BUILD-UP.
	4-1-69 TO 4-15-69	77 BOD 135 COD	15 HR.	56% COD 45% BOD	
	5-1-69 TO 5-29-69	51 BOD 90 COD	20 HR.	70% COD 66% BOD	
ANAEROBIC CONTACT SYSTEM	4-3-69 TO 4-29-69	105 BOD 185 COD	22 HR.	44% COD 39% BOD	1. ALKALINITY ADDITION REQUIRED DURING INITIAL START-UP. 2. AVERAGE INFLUENT TEMPERATURE = 25° C. 3. AVERAGE EFFLUENT TEMPERATURE = 22° C. 4. COD AND BOD REMOVALS INCREASED WITH TIME BECAUSE OF INCREASED BACTERIAL ACCLIMATION TO WASTE AND BIOLOGICAL SOLIDS BUILD-UP. 5. ORGANIC REMOVAL EFFICIENCIES HINDERED BY MECHANICAL PROBLEMS ENCOUNTERED WITH SYSTEM.
	5-1-69 TO 5-29-69	120 BOD 210 COD	32 HR.	58% COD 43% BOD	
ANAEROBIC FILTER WITH 8' MEDIA DEPTH	10-15-69 TO 10-23-69	19 BOD 33 COD	59 HR.	74% BOD 74% COD	1. ALKALINITY ADDITIONS REQUIRED DURING INITIAL START-UP. 2. AVERAGE INFLUENT TEMPERATURE = 26° C. 3. AVERAGE EFFLUENT TEMPERATURE = 19° C. 4. COD AND BOD REMOVALS INCREASED WITH TIME BECAUSE OF INCREASED BACTERIAL ACCLIMATION TO WASTE AND BIOLOGICAL SOLIDS BUILD-UP.
	10-23-69 TO 11-6-69	30 BOD 53 COD	36 HR.	61% BOD 76% COD	
	11-6-69 TO 11-25-69	58 BOD 102 COD	19 HR.	85% BOD 79% COD	
ANAEROBIC CONTACT SYSTEM	10-15-69 TO 11-6-69	48 BOD 84 COD	52 HR.	52% BOD 55% COD	1. ALKALINITY ADDITION REQUIRED DURING INITIAL START-UP. 2. AVERAGE INFLUENT TEMPERATURE = 26° C. 3. AVERAGE EFFLUENT TEMPERATURE = 20° C. 4. ORGANIC REMOVALS WERE HINDERED BY INABILITY TO KEEP SOLIDS IN SYSTEM.
	11-6-69 TO 1-22-70	108 BOD 190 COD	26 HR.	32% BOD 41% COD	

treating primary clarifier overflow, with loadings of 60 pounds of BOD per 1000 cubic feet per day. In addition, they concluded that potato process wastewater is amenable to anaerobic biological treatment.

Anaerobic Fluidized Bed

In this process, a fluidized medium, such as sand, is used to provide an extremely large surface area for biomass attachment. This prevents microorganism washout even with high hydraulic flow. Figure 4 shows a schematic of the process. Wastewater is mixed with recycled effluent and introduced at the bottom of the reactor at a hydraulic velocity sufficient to fluidize the sand. Soluble wastes are best treated with this type of process, since any influent suspended solids will not be degraded in the short retention time provided.

Because of high hydraulic loadings and volumetric gas production rates, excellent mixing characteristics are achieved and the fluidized bed can be considered completely mixed. Turbulence in the reactor prevents biofilm thickening and accumulation of gas on the sand particles, which might limit substrate mass transfer.

COD removal rates of 65 to 75 percent have been reported in anaerobic fluidized bed reactors. The "Anitron" treatability unit, marketed by Dorr-Oliver, is based upon this type of reactor.

Anaerobic Attached-Film Expanded-Bed Process (AAFEB)

In a study conducted by Morris and Jewell(5) on the anaerobic attached-film expanded-bed (AAFEB) process, a reactor configuration shown schematically in Figure 5 was used.

The AAFEB process has been shown to treat a variety of wastewater streams successfully, including primary settled domestic wastewater at 20°C with hydraulic retention periods shorter than 30 minutes and producing an effluent containing less than 40 mg/L total COD and 5 mg/L suspended solids. The process appears to have remarkable resiliency when subjected to large, instantaneous changes in temperature, flow rate, and substrate concentration. Based upon laboratory-scale studies, the AAFEB appears to hold great potential for the treatment of a large range of wastestreams containing organic particulates.

FIGURE 4

ANAEROBIC FLUIDIZED BED

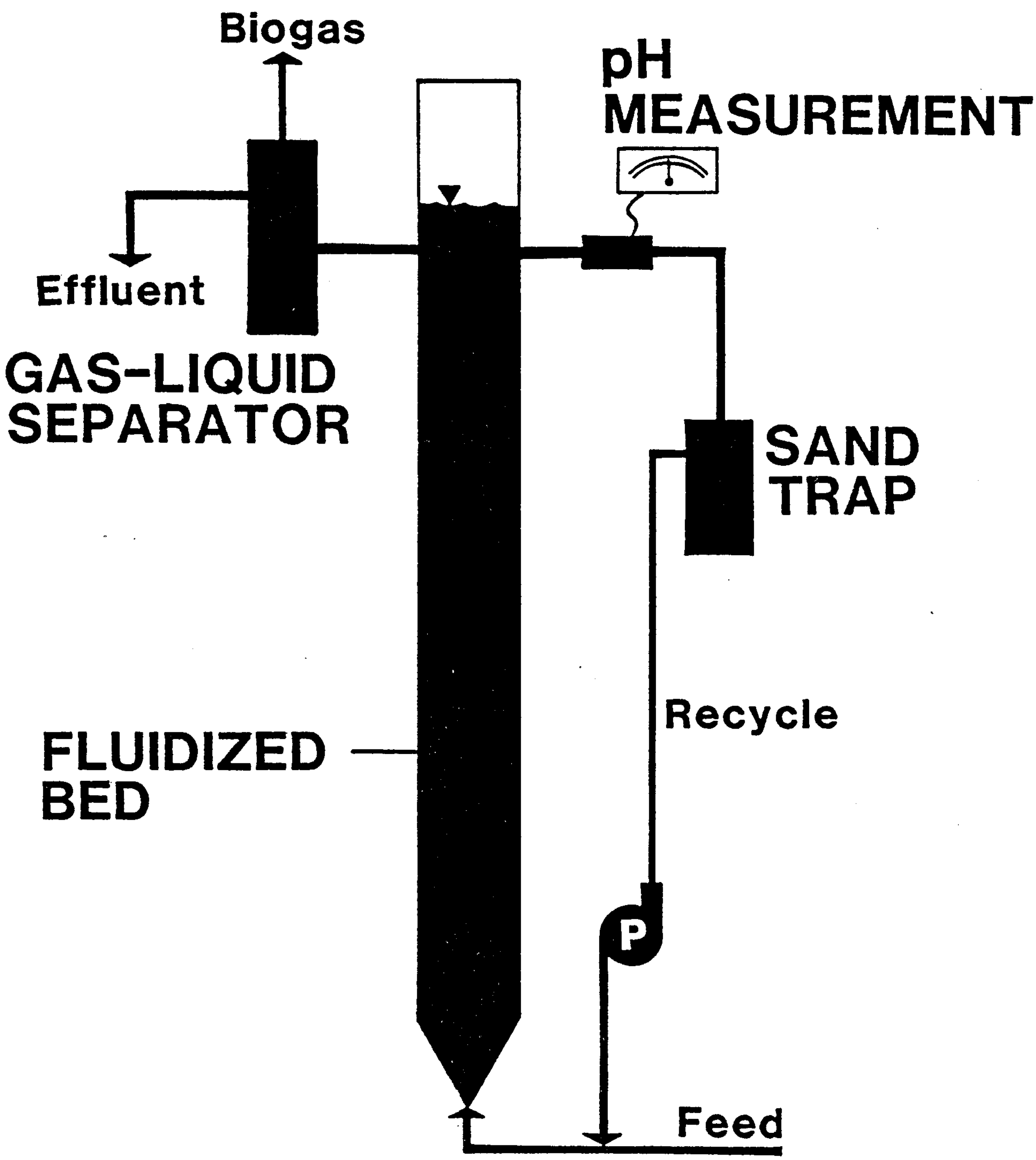
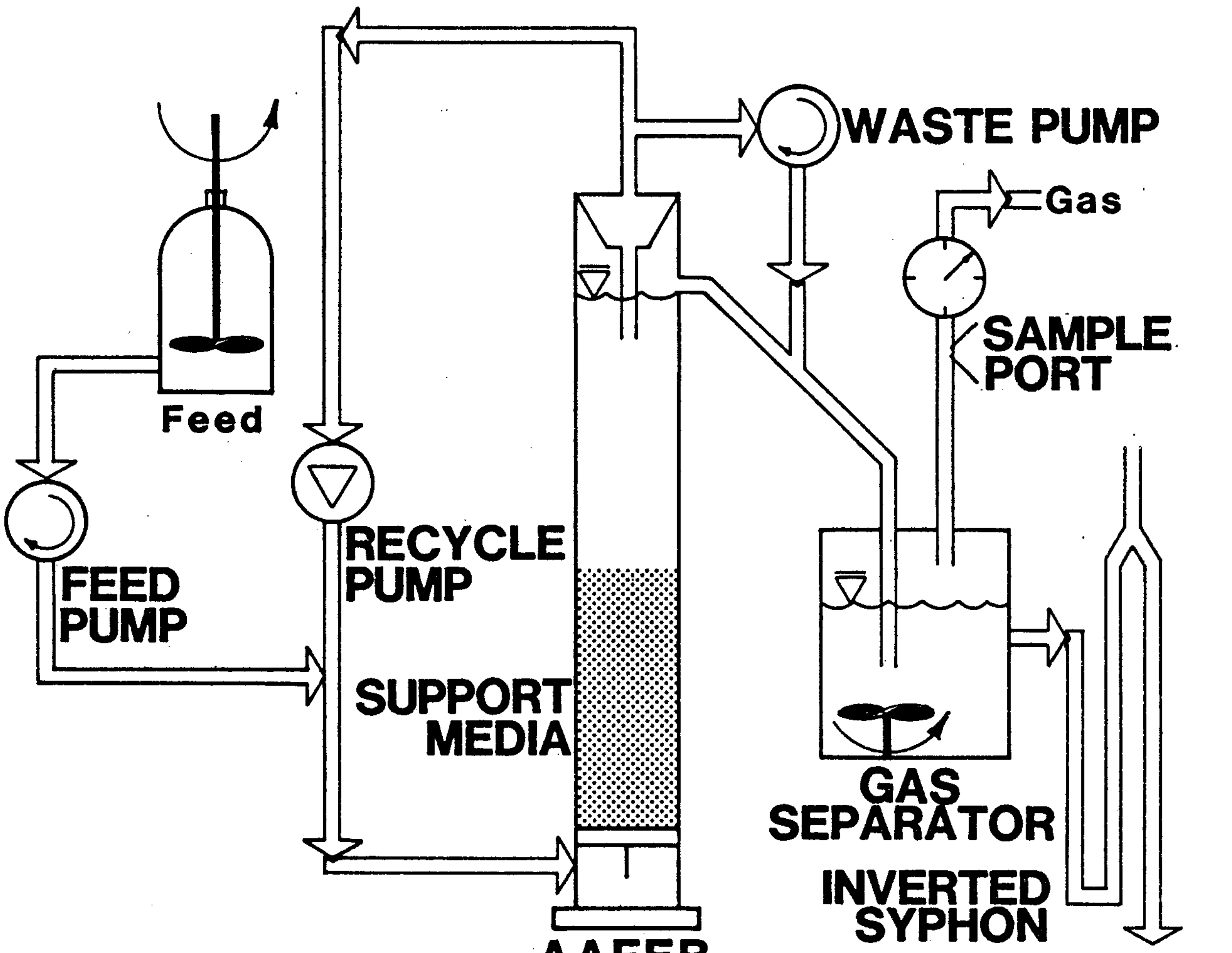


FIGURE 5

AAFEB SYSTEM



Upflow Anaerobic Sludge Blanket Reactor (UASB)

The UASB is a suspended growth anaerobic system which depends on a concentrated sludge blanket formation to achieve adequate BSRT. The reactor is initially seeded with anaerobic sludge and wastewater is introduced at the bottom. A period of time, possibly lasting several months, is required to develop an adequate sludge blanket concentration. This occurs through retention of the biological solids produced, in the reactor, with the heavier, granular solids settling to form a more highly concentrated sludge blanket at the bottom. Mixing occurs through feed velocity and gas bubbles rising through the sludge blanket. A schematic diagram of the UASB process is shown in Figure 6.

A commercial application of this type of reactor is the Biothane® process. This process was developed in Europe, and has been applied only in the last few years in the United States. U.S. applications include wastewaters from a brewery, potato processor, starch manufacturer, and yeast manufacturer. Pilot studies have been conducted on other wastewaters, including cheese whey. Table 4 lists performance data for some Biothane® system applications.

TABLE 4
Biothane® System Performance Data

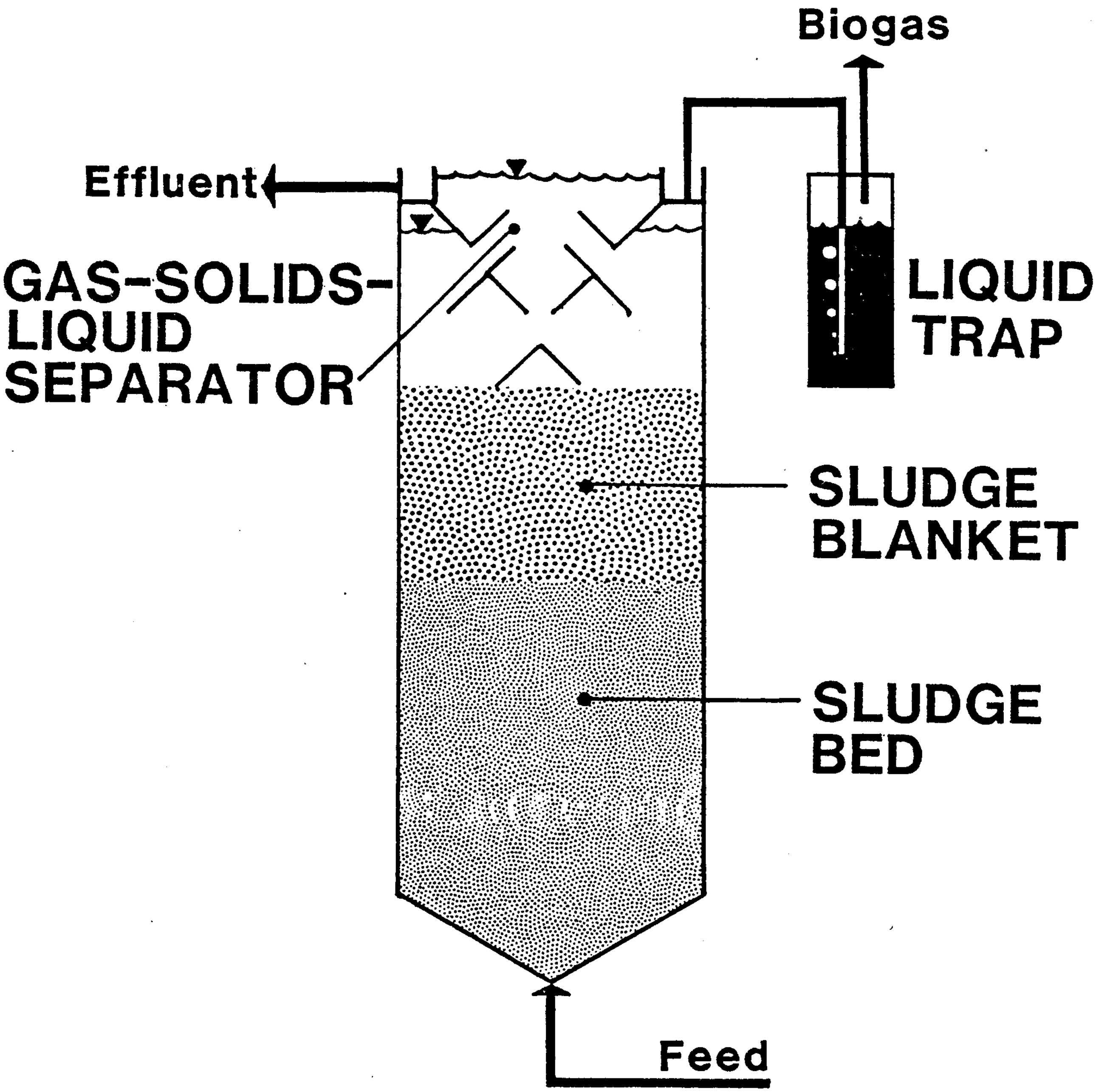
Wastewater	Feed Concentration (mg/L COD)	Gas Production Ft^3/lb COD Removed	COD Removal (%)
Brewery	2,500	5.8 @ 75% CH_4	80
Cheese Whey (Pilot Plant)	10,000	8.0 @ 80% CH_4	96
Potato	4,300	5.9 @ 70% CH_4	80
Starch	22,00	4.2 @ 77% CH_4	85
Yeast (Pilot Plant)	-	5.1	67
Beet Molasses	40,000	- 80% CH_4	90

Anaerobic Treatment Economics

This paper has emphasized that, for high strength wastes (COD≤1000 mg/L), the reduced power requirements and sludge production associated with anaerobic treatment result in lower operating costs compared to aerobic treatment. In addition, recently developed processes with high SRTs have

FIGURE 6

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR



allowed the HRTs to be reduced so that anaerobic reactors are approximately the same size as aerobic reactors. These new developments have resulted in anaerobic system capital cost roughly equal to those for aerobic systems. Additional operating advantages can be derived from using methane gas produced by the anaerobic treatment for process energy. With these advantages, anaerobic treatment should be considered a viable option for pretreating high strength industrial waste streams prior to discharge to municipally-owned treatment systems.

The economic benefits of anaerobic pretreatment can be demonstrated through a recent analysis CH2M HILL conducted for a food processing client required to pretreat prior to discharging wastewater into a municipally-owned waste treatment system. Both anaerobic and aerobic pretreatment systems were evaluated. An anaerobic sludge blanket process was selected for installation. Although the capital cost of the anaerobic process was greater ($2.5 million versus $1.9 million) than the aerobic process, operating cost differences were considerably lower on an annual basis for the anaerobic process ($125,000 vs. $375,000).

CONCLUSIONS

Anaerobic biological treatment has been mainly used for primary and excess sludges at municipal wastewater treatment plants. However, anaerobic treatment is receiving considerable more attention as a pretreatment alternative to aerobic pretreatment of high strength industrial effluents where COD concentrations are greater than or equal to 1000 mg/L. The prime advantages are: (a) low energy requirements; (b) production of energy in the form of methane; (c) reduced nutrient requirements; and (d) reduced sludge production.

In recent years, a great deal of research and development into anaerobic waste treatment processes has taken place, resulting in the development and successful application of a number of high rate anaerobic treatment process configurations. These process advantages and technological strides make anaerobic treatment an attractive alternative for the pretreatment of high strength industrial wastewaters. Use of this technique should be evaluated on a site-specific basis.

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