The Anaerobic Baffled Reactor

A study of the wastewater treatment process using the anaerobic baffled reactor

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I. Introduction

Increasingly stringent standards for wastewater discharge drove the demand for more efficient wastewater treatment systems. Over the last decade, anaerobic digestion has proven to be a better alternative than aerobic processes, especially in the treatment of high-strength wastewaters (1). Compared to aerobic processes, anaerobic treatment processes consume less energy and produce less sludge, which lead to lower operational costs (1, 16).

In addition to these advantages, the increased use of anaerobic systems has been associated with the development of high-rate anaerobic reactors (3, 17). These high-rate reactors amend the principal drawback of anaerobic treatment, which is the long hydraulic retention time (HRT). High-rate reactors separate the HRT from the solid retention time (SRT) thereby allowing the slow growing anaerobic bacteria to remain within the reactor independently of the wastewater flow. The reactor's high SRT keeps the HRT to a minimum which allows a higher volumetric load, significantly enhanced removal efficiencies (1, 2, 3, 15, and 17).

II. Background and Theory

One type of high-rate reactor is the anaerobic baffled reactor (ABR). Developed by McCarty and co-workers at Stanford University, the ABR was described as a series of upflow anaerobic sludge blanket reactors (UASBS) because it is divided into several compartments (3, 5, 16). (Refer to Figure 1 and 2 for a schematic of an UASBS and an ABR). A typical ABR consists of a series of vertical baffles that direct the wastewater under and over the baffles as it passes from the inlet to the outlet. The over and underflow of the liquid reduces bacteria washout, which enable the ABR to retain active biological mass without the use of any fixed media. The bacteria within the reactor tend to rise and settle with gas production in each compartment, but they move down the reactor horizontally at a relatively slow rate, giving rise to a SRT of 100 days at a HRT of 20 hours. The slow horizontal movement allows wastewater to come into intimate contact with the active biomass as it passes through the ABR with short HRTs (6-20 hours) (3, 4, 18).

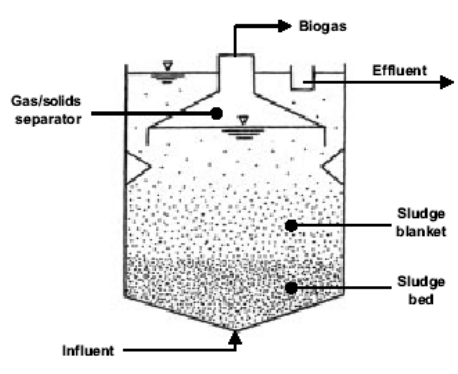

Figure 1: Schematic of UASBS (7)

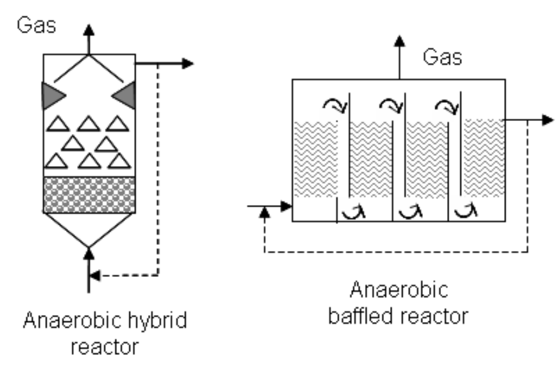

Figure 2: Schematic of ABR (4)

Anaerobic digestion that takes place in an ABR consists of different groups of organisms. The first group of organisms is the hydrolytic fermentative (acidogenic) bacteria that hydrolyze the complex polymer substrate to organic acids, alcohols, sugars, hydrogen, and carbon dioxide. The second group is hydrogen producing and acetogenic organisms that convert fermentation products of the previous step (hydrolysis and acidogenesis) into acetate and carbon dioxide. The third group is the methanogens that convert simple compounds such as acetic acid, methanol, and carbon dioxide and hydrogen into methane. The four main steps that usually determine the organisms' reaction in an anaerobic process are: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (11). Figure 3 is a schematic showing the conversion reaction in the anerobic digestion. Refer to Section V: Operation for more information regarding biogas.

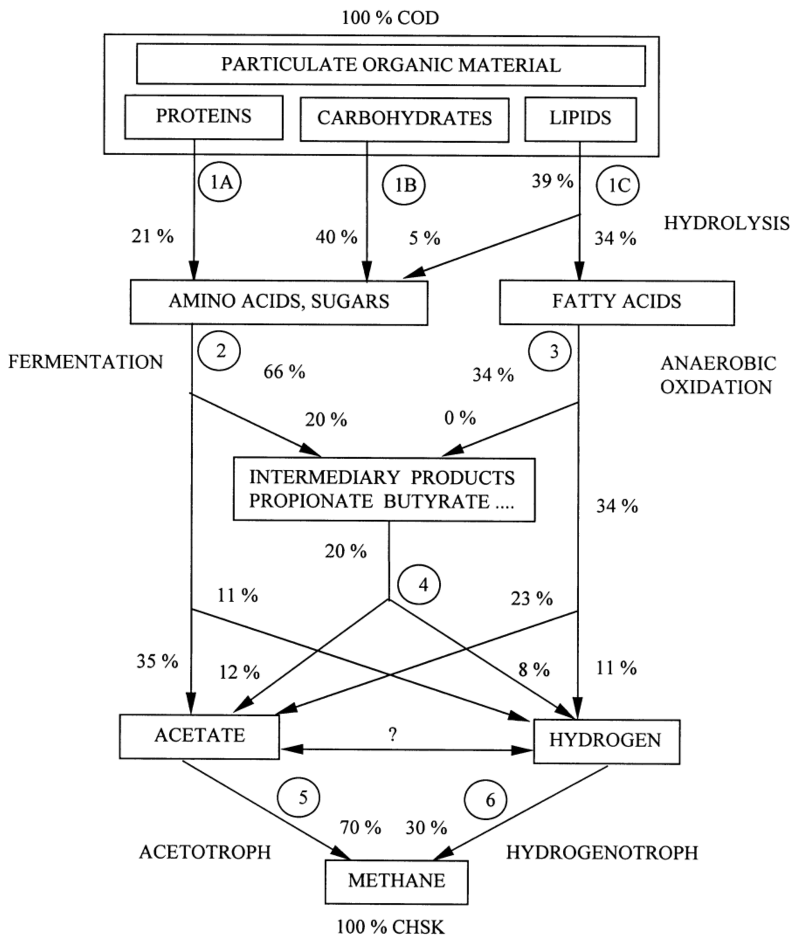

Figure 3: Schematic showing conversion reaction in anaerobic digestion of complex substrates (11)

Although not commonly developed on a large scale, the ABR has several advantages over other well established systems. These advantages are summarized in Table 1. Due to the many advantages of the ABR, the reactor had been researched and applied in different low strength wastewaters of chemical oxygen demand (COD) < 1000 mg/L (14, 16).

Table 1: Advantages associated with the ABR (3)

Construction	Biomass	Operation
• Simple design • No moving parts • No mechanical mixing • Inexpensive to construct • High void volume • Reduced clogging • Reduced sludge bed expansion • Low capital and operating costs	• No requirement for biomass with unusual settling properties • Low sludge generation • High solids retention times (SRT) • Retention of biomass without fixed media or a solid-settling chamber • No special gas or sludge separation required	• Low hydraulic retention times (HRT) • Intermitten operation possible • Extremely stable to hydraulic shock loads • Protection from toxic materials in influent • Long operation times without sludge wasting • High stability to organic shocks

Probably the most significant advantage of the ABR is its ability to separate acidogenesis and methanogenesis longitudinally down the reactor, which allow different bacterial groups to develop under the most favorable conditions. This specific advantage also allows the reactor to behave as a two-phase system without the associated high cost and control problems. Two-phase operation permits acidogenesis to dominate in the first compartment and methanogenesis to dominate in the subsequent section. This can increase acidogenic and methanogenic activity by a factor of four because the separation of the two phases causes an increase in protection against toxic materials and higher resistance to changes in environmental parameters (i.e. pH, temperature, and organic loading rates) (3, 15, 18).

Since the development of the ABR in the early 1980s, several modifications have been made to improve the reactor performance. The main driving force behind these modifications has been to enhance the solids retention capacity. However, other design modifications were developed in order to treat difficult wastewater (e.g. with high solids content) and to reduce capital costs (3). Table 2 summarizes the main alternations to the ABR design.

Table 2: Development of ABR (3)

Modification	Purpose	Ref.
addition of vertical baffles to a plug-flow reactor	enhances solids retention to allow better substrate accessibility to methanogens	Fannin *et al.*, 1981
(i) downflow chambers narrowed	(i) encourages cell retention in upflow chambers	Bachmann *et al.*, 1983
(ii) slanted edges on baffles (40–45°)	(ii) routes flow towards centre of compartment encouraging mixing	
(i) settling chamber (ii) packing positioned at top of each chamber	(i) enhances solids retention (ii) prevents washout of solids	Tilche and Yang, 1987
(iii) separated gas chambers	(iii) ease and control of gas measurement, provides enhanced reactor stability	
enlargement of first chamber	better treatability of high solids wastewater	Boopathy and Sievers, 1991

Laboratory, pilot, and full-scale experiments has shown that the ABR is capable of treating a variety of wastewaters of varying strength (0.45 < 1,000 g/L) over a wide range of loading rates (0.4 < 28 g/m^{3}d), and with high solids concentrations with satisfactory result. For example, Boopathy et al. evaluated the performance of ABR treating the strong effluent of a Scotch Whisky factory with COD of 51 g/L at organic loading rates (ORLs) of 2.2 to 3.5 kg COD/ m^{3}d. They achieved treatment efficiencies of up to 90%. Polprasert et al. used an ABR to pre-treat slaughterhouse wastewater with COD ranging from 480 to 730 mg/L at organic loading rates (ORLs) ranging from 0.9 to 4.73 kg COD/m^{3}d. The results achieved treatment efficiencies of up to 75% on a total COD basis, and up to 84% on a filtered COD basis (3, 15). Refer to Appendix A to review the performance of the ABR treating a variety of wastewaters, in particular low and high strength, low temperature, high influent solids, and sulphate containing waste.

III. Pre and Post Treatment

Although the anaerobic process is efficient in the removal of organic material and suspended solids from low strength wastewater, the process has no effect on nitrogen and phosphorus concentrations. In addition, pathogenic organisms within the wastewater are only partially removed. Post-treatment is therefore needed in removing residual COD and total suspended solids (TSS) as well as reducing concentrations of nutrients and pathogens. After an anaerobic pretreatment, most often an aerobic post treatment is needed to meet effluent standards (2, 18).

There are a variety of wastewater purification methods that may be applied to fulfill the post treatment requirements. One functional example of a system using an ABR is the DEWATS system for use in decentralized waste water treatment options in peri-urban environments (7). The DEWATS system uses a sedimentation tank for primary treatment, an ABR for secondary treatment, and an anaerobic filter and planted gravel bed filter for tertiary treatment. See Figure 4 below.

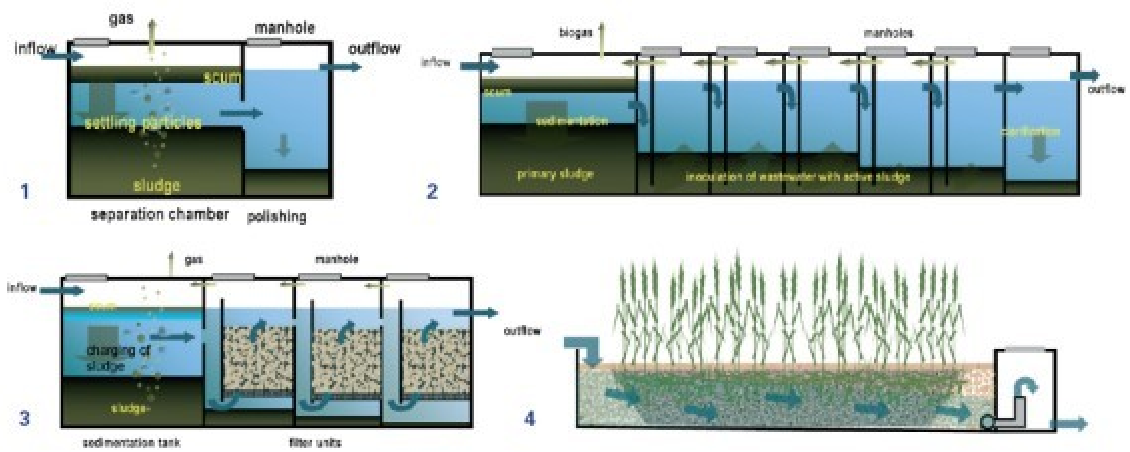

Figure 4: DEWATS pre and post treatment scheme for use with an ABR (7)

The DEWATS treatment configuration achieves a high quality effluent quality as shown in Figures 5 and 6 below.

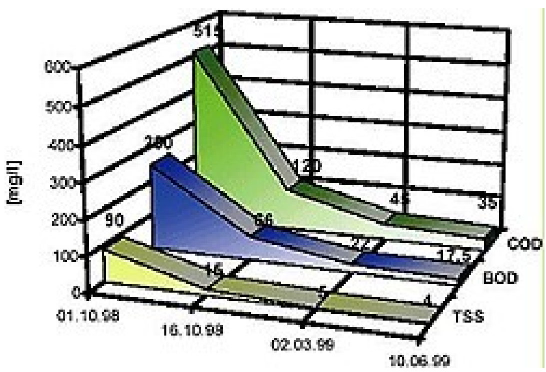

Figure 5: Effluent Quality during first month of DEWATS operation (7)

DEWATS Treatment Efficiency

No	Para-meter	Unit	Anlytical-Results Inlet	Outlet	Reduction [%]
1	Temp.	°C	27	27	–
2	pH	–	7,6	7,3	4 %
3	BOD 5	mg/l	290	53,6	83 %
4	COD	mg/l	590	84	86 %
5	Phosphate	mg/l	18,33	3,67	80 %
6	TSS	mg/l	172	84	51 %
7	Ammonia	mg/l	0,19	0,07	63 %

Source: Graha Asih Hospital Bali, Anaerobic Filter + Horizontal Sandfilter + Purification Pond

Figure 6: DEWATS Treatment Efficiency (7)

IV. Energy Requirements

The only energy requirement of an ABR comes from the addition of thermal energy to maintain a proper temperature range (8). Flow within the reactor is directed by baffles under the force of the pressure head at the influent. No mechanical mixing is required since flow is brought into intimate contact with the biomass as it is forced through the sludge bed. Therefore, there are no power requirements during normal operation (11). Furthermore, anaerobic systems produce methane which can be collected and used to generate energy. In the case that thermal energy addition is required, it is often generated from the biogas byproduct (8).

V. Operation

Little or no maintenance is required for an ABR. Desludging only involves grit removal which has shown to be an infrequent task (19).

There are two optimal temperature ranges for methane production in anaerobic systems. The mesophilic range is from 15-40°C and the thermophilic range for temperatures above 40°C. When in the psychrophilic range (temperatures below 15°C), methane can still be produced, but in very small quantities. For reasonable rates of methane production, temperatures should be maintained above 20°C. When operating in the mesophilic range, rates of methane production approximately double for each 10°C increase in temperature (8).

When discussing anaerobic systems, pH is the most important process control parameter. The optimum pH range for all methanogenic bacteria is between 6 and 8 (Zehnder *et al.*, 1982). At elevated pH values, free ammonia can be present and inhibit anaerobic metabolism. In addition, the accumulation of excess volatile acids occurs when pH is not held fairly constant. Anaerobic processes can operate over a wide range of volatile acids concentrations (from less than 100mg/L to over 5000 mg/L) if there is proper pH control. An ABR should contain some form of buffer to control pH in the system (8).

The normal composition of biogas produced from anaerobic processes ranges from 60-70% methane and 30-40% carbon dioxide. There are also trace amounts of hydrogen, hydrogen sulfide, ammonia, water vapor, and other gases. The energy content in the biogas comes from the methane, which has an energy content of 37 MJ/m^3. The other gasses present in the biogas lower energy content to about 22-26 MJ/m^3 (9).

VI. Byproduct Disposal

The only byproduct that needs to be removed from an ABR is the sludge. In some cases sludge may be recycled, but this generally reduces removal efficiency because the system acts more like a completely mixed system (3). Theoretically, recycle should have a negative effect on the hydrodynamics of a reactor because increased mixing disrupts the bacteria. There are some cases, however, when effluent recycle may be beneficial (see Table 3: Advantages and disadvantages of effluent recycle). In general, the use of recycle is dependent on the type of waste being treated.

Table 3: Advantages and disadvantages of effluent recycle (3)

Advantages	Disadvantages
1 Front pH increased	1 Overall efficiency reduced
2 Reduction of influent toxicity and substrate inhibition	2 Increased solids loss
3 Higher loading rates possible	3 Increased hydraulic dead space
4 Better substrate/biomass contact	4 Disruption of bacterial communities and bioflocs
	5 Encourages one-phase digestion

Anaerobic treatment generates considerably smaller quantities of sludge than aerobic treatment. The sludge produced may be used as fertilizer with proper treatment, thereby, eliminating the need for byproduct disposal altogether (8).

Arguably the most popular method of sludge disposal is composting. Composting is good for soil due to the high concentrations of phosphorous, nitrogen, and carbon in the sludge (20). A moisture level of approximately 50% is required in the sludge when composting. This can be achieved by either air drying the sludge or by the addition of materials such as newspaper or sawdust. Using newspaper or saw dust can also improve the carbon to nitrogen ratio from 1:2 in average wastewater to closer to 5:6, the optimal range. The optimum temperature for composting is 55˚C (131˚F). Individuals who generate sludge can make money by selling it as compost.

Some sludge cannot be composted due to some of the materials in it. This type of sludge must first be thickened prior to disposal. The thickening process can increase the percent of solids from 2% to 5%. This change may not seem large but it removes approximately 30 liters of water for every kilogram of solids. Thickening is carried out in a sedimentation tank or pond. The next step is dewatering where the solids content is increase to 20%. The sludge can be dried in drying bed or the water can be removed mechanically by using a press or centrifuge. The two later processes are generally preferred even though they are more costly do to the fact that the weather has no effect on them (20).

VII. Economics

The ABR has many economic advantages over other methods of wastewater treatment. As the ABR operates anaerobically, biogas is produced which may be used for energy production. The waste removal process generates income through the production of methane (3). Anaerobic treatment also generates considerably smaller quantities of sludge, saving on sludge removal costs. The quality of sludge produced has high fertilizer value, allowing further income generation and avoiding the high costs associated with sludge disposal (8).

According to a case study performed in Columbia by Orozco (19), construction costs for an ABR were 20% less than those for UASB reactors, and five times less than a conventional activated sludge plant for a small town. The basic mechanical design of the ABR is very simple and easy to build, making it a viable option for wastewater treatment in low income areas (11, 20). The ABR is also a very stable system yielding few long term maintenance and repair costs. Furthermore, the ABR does not require a skilled operator and does not need to be monitored full time.

VIII. Design Protocol

When designing a treatment facility using an ABR, the following design considerations must be made.

Flow rate (Q):

The flow for sewage treatment plants are based on the design population and commercial and industrial activity (9). Historical data should be used to find existing flow information. A typical rule for estimating domestic wastewater flows is 380 L/cap/day. The flow estimates for a location should show peak, minimum and average flow rates.

Hydraulic Retention Time (HRT) and Solid Retention Time (SRT or Θ_x):

In typical suspended solids reactors without recycle, the SRT has to be equal to the HRT (9). The minimum HRT in these reactors is about ten days at 35°C. One major advantage of an ABR is that the bacteria grow on fixed surfaces within the reactor, allowing very high SRTs. This also allows the HRT and SRT to be separated, which significantly reduce reactor volume. HRT can be calculated as shown below.

$$HRT = V/Q$$

Q	Volumetric flow rate
V	Volume of Reactor

A typical HRT value for an ABR is about 10hours (3, 4, 18, and 19).

The solids retention time can be described by the mass of sludge in the reactor divided by the mass removal rate of sludge from the reactor (9).

$$\Theta_x = VX_v/Q_wX_w$$

Qw	Volumetric flow rate of waste solids from system
Xw	VSS concentration in Qw
V	Volume of reactor
Xv	Average concentration of VSS in reactor

Volume of Reactor (V):

The volume of the reactor can be determined based on the flow rate and a set HRT or the HRT can be determined based on a set reactor volume, depending on the application (9).

$$V = Q * HRT$$

Q	Volumetric flow rate
HRT	Hydraulic Retention Time

This volume calculation describes the minimum volume needed in order for the tank to handle the incoming flow of wastewater. A factor of safety should be applied when designing a wastewater treatment plant to avoid flooding of the system. This safety factor will take into account population growth and any increased usage of water resources.

Methane Production (Q_m):

The methane produced in an anaerobic process is proportional to the amount of substrate removed (9). The rate of methane production is given by the following equation.

$$Q_m = QM(S_o-S_e) = QEMS_o$$

S_o	Total influent COD (suspended + soluble)
S_e	Total effluent COD (suspended + soluble)
M	Volume of CH_4 produced per unit of COD removed
Q	Influent Flow Rate
E	Efficiency factor

Substrate Removal S_e:

The effect of temperature on substrate removal can be determined by the following equation (9):

$$r_{st1} = r_{st2}\theta^{(T2-T1)}$$

r_{st1}	Substrate removal rate at temperature 1
r_{st2}	Substrate removal rate at temperature 2
θ	Constant (equals 1.105 for 10°C<T<30°C)
T_1	Temperature 1
T_2	Temperature 2

Figure 7 below shows how influent substrate concentration, S_o and temperature play critical roles in methane production. If the temperature differential is high or the influent concentration is low, the methane production will not be energetically favorable. The incoming wastewater must have a fairly low temperature differential and a relatively high organic content in order to consider using anaerobic treatment (9). Further research on the ABR has proven that decreasing the temperature from 35°C to 25°C had little effect on methane production, although temperatures should be maintained above 25°C. This adds stability to the system as it allows fluctuations in the temperature without negatively effecting reactor performance (3).

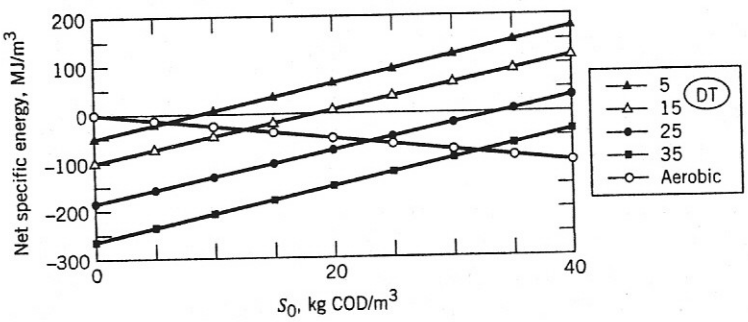

Figure 7: Energy comparison between aerobic and anaerobic processes (9)

Although anaerobic systems require a high organics content to produce favorable amounts of methane gas (9), lower organic loading rates offer better COD removal efficiency. See Figure 8 below.

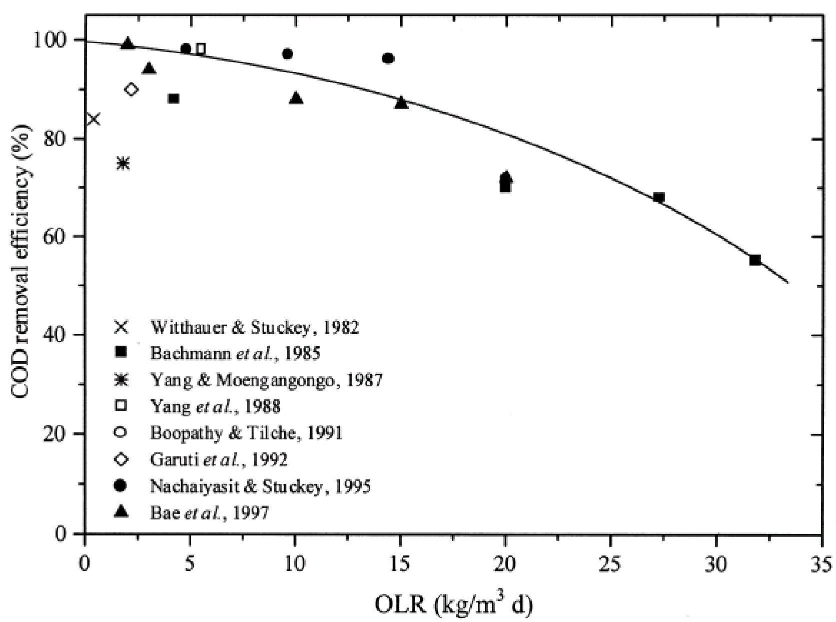

Figure 8: Performance efficiency against various loading rates (3)

Energy Potential (E):

The net energy potential can be determined for a waste, however, the heating energy required to maintain optimal temperature ranges for methane production must first be determined (9).

$$Q_H = 4.18 * Q * \Delta T * (1.1/B)$$

B Boiler efficiency
Q Flowrate
ΔT Temperature difference between influent and reactor contents

The net energy yield can now be determined using the following equation (9).

$$E=37Q_m - (Q_H+Q_{MP})$$

Q_{MP} Energy required for mixing and pumping (in ABR Q_{MP} =0)
Q_M Methane Produced

Pathogen Removal:

Since the sludge removed from an ABR has high fertilizer value, the reduction in pathogens is an important consideration as pathogens in the sludge pose a health risk. Fecal coliforms (FC) are the best indicator of pathogens. In the United States, sludge used for land application must contain less than 2,000,000 FC/g total solids. The temperature of the reactor also affects the rate of pathogen removal. Reactors operating in the thermophilic range achieve greater FC reductions (9). Table 4 shows the reduction of fecal coliforms in anaerobic digestion.

Table 4: FC Reduction in Anaerobic Digestion Processes (9)

	Rated capacity m^3/s (ft^3/s)	Primary digester HRT[c] d	VS load $kg/m^3/d$ ($lb/ft^3/d$)	Raw solids FC log FC/g TS	Digested biosolids FC log FC/g TS	Log_{10} reduction
Range	0.11–18.40 (3.9–650)	6–57	0.59–4.1 (0.037–0.26)	5.43–10.55	3.10–8.11	0.36–4.[illegible]

[a]Adapted from Stukenberg et al. (1994).
[b]Survey of 54 plants, all operated within temperatures of 34–37°C.
[c]Approximately half of the plants were two-stage systems equipped with primary and secondary digesters. Second stage digesters were usually unheated and unmixed. Two of the plants were two-phase systems with separate acid and methane digesters.

Construction material:

There are many materials that can be used in the construction of an ABR. Metal, concrete, and plastic are primarily used depending on the setting. Concrete is a cost effective and readily available construction material and is therefore a good option for remote and low income locations. Plastics and metals such as alloys, stainless steels, and coated metals are more expensive but save on space and land requirements. In addition, these can be constructed off site and shipped to the location (3).

IX. Design Example

Because of the ABR's many economic advantages, low operational and energy requirements, and mechanical simplicity, it is well suited for use in small scale, low income areas. One such area is the informal settlement of Monwabisi Park, located in the township of Khayelitsha in Cape Town, South Africa.

The abandonment of official planning during the erection of squatter camps like Monwabisi Park resulted in inadequate provision of even the most basic services. Many residents have constructed rudimentary pit latrines in order to achieve some form of local, private, and semi-structured toilet facility. However, these facilities are generally unsanitary and often contribute to the contamination of the region's ground water supply. There is a desperate need for immediate sanitation services as thousands of citizens continue to follow unsafe sanitation practices, largely due to the lack of available alternatives. The law requires a family-to-toilet ratio of 5:1, and yet even if all toilets are assumed functional, 69 families must still share a single toilet. In Khayelitsha alone, 80 children die per year from diarrhea-related illnesses. A proper form of waste control must be implemented in Monwabisi Park in order to deter the spread of disease (12, 8).

One idea toward improving waste management is to construct a small scale ABR for use by the community center and neighboring housing in Monwabisi Park. The ABR would be responsible for handling grey water from on site cleaning and laundry, and wastewater from onsite toilets for a target population of around 400 users. Evaluation of this pilot ABR would determine if it is an appropriate technology for decentralized wastewater treatment in informal settlements.

Average daily water usage has been estimated at 70L per person per day (8) with the following breakdown in Table 5.

Table 5: Water Usage Breakdown for Monwabisi Park (8)

Water Use	Volume (L)	On/Off Site	Description
Drinking and Cooking	10	Off	Will not enter our system
Bathing	20	Off	Will not enter our system
Laundry	34	On	~120L used per wash performed twice per week
Hand Washing	6	On	~1.5L per wash performed 4 times per day

The average human produces .2 liters of feces and 1.1 liters of urine per day (8). Using these numbers and the calculations in Table 5 we can determine our total estimated flow rate as shown in Table 6.

Table 6: Volumetric Flow Rates Entering System (8)

Volumetric flow rates, Q_o	Grey water	Black water	Total (L/d)	Total (L/hr)
Per person	40	1.3	41.3	1.72
Total into system	16000	520	16520	**688.3**

If we assume a hydraulic detention time of ten hours we can calculate the volume of the tank as shown below. Ten hours is an accurate HRT approximation according several studies (3, 4, 18, and 19).

$$V = Q_o * HRT$$

$$V=688.3 [L/hr] * 10 [hr]$$

$$V= 6883 [L]$$

$$\mathbf{V= 6.883 [m^3]}$$

This volume calculation describes the minimum volume needed in order for the tank to handle the incoming flow of wastewater. For the purposes of this system we will assume a safety factor of 45%. This will take into account the growth in population and any increased usage of water resources. The volume of the tank will therefore be:

$$6.833 m^3 + 3.1 m^3 = 9.98 m^3$$

$$\mathbf{V = 10 m^3}$$

Given Cape Town's relatively warm climate, as shown in Figure 9 below, it presents an ideal climate for ABR operation. The temperature differential between the wastewater and the reactor will be very small during the summer months and only slightly larger during the winter season. This is a big energy saving advantage as little to no heating will be necessary depending on the desired efficiency of the system.

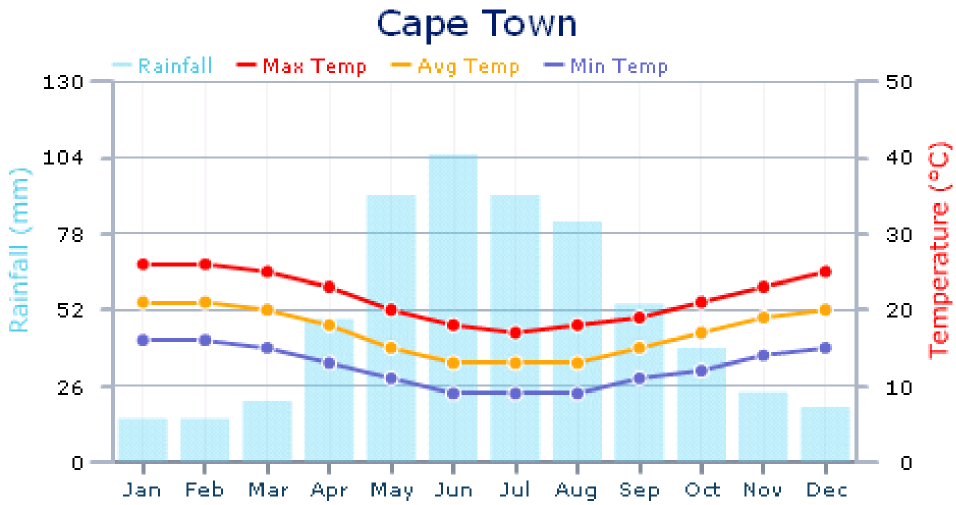

Figure 9: Temperature Plot for Cape Town, South Africa (5)

The following design parameters should be determined prior to designing the ABR:

Table 7: Design Parameters to be considered before construction of an ABR

Design Parameter	Description	Monwabisi Park Values
S_o	Initial substrate concentration of wastewater	Test wastewater samples
T	Wastewater Temperature data	Test wastewater samples
M	Volume of CH_4 produced per unit of COD removed	Test wastewater samples
Q	Initial flow rate into system	688.3 L/hr
V	Volume of Tank	10 m^3
HRT	Hydraulic Retention Time	10 hr (3, 4, 18, and 19)
Q_H	Heat Energy for optimal methane production	Q_H=4.18*Q*ΔT*(1.1/B)
E	Energy potential	E =37Q_m - Q_H

Table 8 shows the average values and standards for wastewater in a typical middle-income area of South Africa. For this design example, the ABR will be used in a low income area and the values will be different but this table gives us close estimates of what the wastewater will look like and what standards it needs to meet before discharge.

Table 8: Average values and standards for typical middle-income domestic wastewater in South Africa

	Unit	Inlet	Outlet	Discharge standard	Irrigation standard
COD	mgCOD/ℓ	716 ± 54.4 (n=32)	192 ± 21.1 (n=33)	75	400*
pH		6.9	6.5	5.5-9.5	6-9
Ammonia	mg N/ℓ	24.9 ± 4.2 (n=7)	33.2 ± 2.8 (n=6)	3	No limit
Phosphorus	mg P/ℓ	4.9 ± 4.1 (n=4)	5.5 ± 0.5 (n=5)	10	No limit
TSS	mg TSS/ℓ	480 ± 109 (n=14)	225 ± 55.2 (n=14)	25	No limit
VSS	mg VSS/ℓ	306 ± 60.8 (n=14)	127 ± 45.9 (n=14)	No limit	No limit
Total coliforms	cfu/100 mℓ	1.3 x10^8	5 x 10^7	1 000	100 000
* for a 500 kℓ/d discharge					

For our system we will assume no sludge recycle. The reactor and baffles will be constructed out of concrete for its local availability and cost efficiency. The system should have an emergency bypass system to protect against flooding during high water usage. This bypass can either take wastewater to a holding tank or run it to soak ways; perforated pipes that distribute water into ground. There will also be pre and post treatments as discussed in Section III: Pre and Post Treatment.

Appendix A: Performance Data on ABR Systems (3)

Substrate	Volume (l)	Chambers	Biomass (g VSS/l)	Inlet COD (mg COD/l)	Loading rate (kg/m^3/d)	COD removal (%)	HRT (h)	Temperature (°C)	Ref.
Undiluted sea kelp	9.8	5		6000–36,000	0.4–2.4		360	35	Chynoweth *et al.*, 1980
Diluted sea kelp	10	4			1.6			35	Fannin *et al.*, 1981, 1982
	10	4		67,200–89,600	5.6–6.4		288–336	35	
	10	4		80,000	1.6		1200	35	
Carbohydrate–protein	6.3	5		7100–7600	2–20	79–82		35	Bachmann *et al.*, 1983
Synthetic greywater	8	6		480	0.1–0.4	63–84	48–84	25–33	Witthauer and Stuckey, 1982
Carbohydrate–protein	6.3	5		8000	2.5–36	55–93	4.8–71	35	Bachmann *et al.*, 1985
Diluted swine wastewater	20	–		< 5000	1.8	75	60	30	Yang and Moengangongo, 1987
Molasses wastewater	150	3	5.3	5000–10,000	5.5	98		37	Yang *et al.*, 1988
Sucrose	75	11		344–500	0.7–2	85–93	6–12	13–16	Orozco, 1988
Whisky distillery wastewater	6.3	5		51,600	2.2–3.5	90	360	30	Boopathy *et al.*, 1988
Carbohydrate–protein	10	8		4000	1.2–4.8[b]	99	20	35	Grobicki and Stuckey, 1989
Carbohydrate–protein	7.8–10.4	4–8	30	4000	1.2–4.8	95	20–80	35	Grobicki and Stuckey, 1991
Molasses wastewater	150	3	4.01	115,771–990,000	4.3–28	49–88	138–850	37	Boopathy and Tilche, 1991
Molasses wastewater	150	3	4.01	115,771–990,000	20	70	~138	37	Boopathy and Tilche, 1992
Swine manure	15	2–3		58,500	4	62–69	360	35	Boopathy and Sievers, 1991
Municipal wastewater	350	3		264–906	2.17	90	4.8–15	18–28	Garuti *et al.*, 1992
Slaughterhouse wastewater	5.16	4		450–550	0.9–4.73	75–90	2.5–26	25–30	Polprasert *et al.*, 1992
Carbohydrate–protein	10	4–8	0–8.5	4000			1–80	35	Grobicki and Stuckey, 1992
Molasses wastewater	150	3		115,771–990,000	10	40–75	24–144	37	Xing and Tilche, 1992
Molasses wastewater	150	3	4.11 and 7.21	115,771–990,000	20	> 70	~140	37	Xing *et al.*, 1991
Carbohydrate–protein	10	8	18	4000	1.2–4.8	98, 93	20, 80	35	Nachaiyasit and Stuckey, 1995
Pharmaceutical wastewater	10	5		20,000	20	36–68	24	35	Fox and Venkatasubbiah, 1996
Phenolic		5	20–25	2200–3192	1.67–2.5	83–94	~24	21	Holt *et al.*, 1997
Glucose	6	5		1000–10,000	2–20	72–99	12	35	Bae *et al.*, 1997
Carbohydrate–protein	10	8	18	1000–4000	1.2–4.8	98	20–80	35	Barber and Stuckey, 1998
Domestic sewage/industrial waste	394,000	8		315[c]	0.85	70	10.3	15	Orozco, 1997
Carbohydrate–protein	10	8	18	4000	1.2–4.8	75–83, 93–97, 96	20, 20, 20	15, 25, 35	Nachaiyasit and Stuckey, 1997a
Carbohydrate–protein	10	8	18	4000	4.8–9.6	90–98	20	35	Nachaiyasit and Stuckey, 1997b
Carbohydrate–protein	10	8	18	4000	4.8–18	52–98	1–20	35	Nachaiyasit and Stuckey, 1997c

[a]Contains calculated results, either from graphs or from supplied data. [b]Also with shock loading of 96 kg/m^3 d. [c]BOD_5 value.

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