Pergamon

Wat. Sci. Tech. Vol. 30, No. 12, pp. 287–295, 1994.
Copyright © 1995 IAWQ
Printed in Great Britain. All rights reserved.
0273–1223/94 $7·00 + 0·00

0273-1223(95)00134-4

PERFORMANCE OF METHANE FERMENTATION PITS IN ADVANCED INTEGRATED WASTEWATER POND SYSTEMS

William J. Oswald, F. Bailey Green and Tryg J. Lundquist

University of California, Berkeley, Environmental Engineering and Health Sciences Laboratory, Richmond Field Station, 1301 S. 46th Street, Bldg. 112, Richmond, CA 94804, USA

ABSTRACT

Advanced Integrated Wastewater Pond Systems (AIWPSs) involve a series consisting of Advanced Facultative Ponds with internally located fermentation pits; secondary ponds with either photosynthetic oxygenation or mechanical aeration; tertiary ponds for sedimentation of either algae or aeration solids; and, quaternary ponds for controlled discharge, irrigation storage, aquaculture, or other beneficial uses of reclaimed wastewater.

This paper deals mainly with design and performance of Advanced Facultative Ponds containing internally located fermentation pits. Experiences with a 1,894 m^3 day^{-1} (0.5 MGD) AIWPS and a 7,576 m^3 day^{-1} (2.0 MGD) AIWPS indicate that primary facultative ponds with internal fermentation pits require less land than do conventional anaerobic ponds and that sludge removal is postponed for many years. New, more detailed, and controlled scientific studies on a 133 m^3 day^{-1} (0.035 MGD) demonstration AIWPS at the University of California, Berkeley, Environmental Engineering and Health Sciences Laboratory in Richmond, California provide evidence that these simple pits remove suspended solids and biochemical oxygen demand more effectively than do comparably loaded conventional anaerobic ponds and produce much less odor. In addition they improve removal of parasites, bacteria, viruses, heavy metals, and halogenated hydrocarbons. The reliability and cost effectiveness of AIWPS is compared with more conventional ponds and with mechanical wastewater treatment systems.

KEYWORDS

Algae; anaerobic digestion; fermentation pits; facultative ponds; heterotrophic nitrification; heterotrophic denitrification; high rate ponds; methane fermentation.

INTRODUCTION

It has long been known that one of the most efficient ways to dispose of waste organic matter is to convert it to methane and carbon dioxide. Scientific study of the production of methane from river muds and cattle intestines has been known for at least 12 decades and was clearly elucidated by Barker and coworkers in the early 1940s (Stephenson, 1949). Also according to Stephenson, Barker's success in the first isolation of a methane-producing bacterium resulted from the insightful use of Na_2S as a scavenger of free molecular oxygen. This clearly illustrated the strict anaerobic requirements of the methane producers and permitted the isolation of many additional species. From an efficiency standpoint there are specific requirements which, if followed, will permit the practical application of methane fermentation in either separate sludge digesters or in the fermentation pits of Advanced Integrated Wastewater Pond Systems (AIWPS). Many of these requirements are outlined in Table 1.

TABLE 1. Environmental Requirements for Maximized Methane Production in Fermentation Pits

Item	Requirement or Source	Method of Attaining
Reactor Construction	Isolated Volume within Pond	Earth, wood or block walls
Organic Source	Agricultural, industrial and domestic wastes	Solid or liquid conveyance into isolated volume
Formation of organic, acids, alcohols esters hydrogen, and CO_2	Autolysis and/or attack of organic matter by facultative heterotrophic microorganisms	Retaining non-living organic matter in an anoxic state for several days at ambient temperature
Methane and CO_2 Release	Large population of Methanogenic bacteria (MB)	Intensive seeding with active MB. MB retention on media or semi inert solids.
Time	Several months for start up	Sludge residence time greater than 200 days.
Complete absence of molecular, dissolved oxygen (DO), oxides	Isolated volume; O_2 scavenging bacteria	Exclusion of air or oxygen bearing water. Loading > 0.16 kg VS/m^3/day
Temperature 4° C - 40° C	Heat energy to increase rates	Retain sewage warmth, exclusion of cold water, solar energy, exothermic action
Temperature Stability	Isolation from main pond volume; earth insulation. Avoid sudden chances in temperature	Underground and/or underwater isolation. Submerged cover. Exclusion of cold or oxygenated water
Neutral pH 6.8 - 7.2	Buffer capacity (alkalinity) Rapid conversion of organic acids to methane	Immediate conversion of organic acids to methane and reduction of CO_2
Negative redox potential 0.35 to 0.5 volt, negative	Anoxic microbes electrochemical	Exclusion of O_2 or easily reduced substances such as NO_3^-
Minimization of NO_2^-, NO_3^-, or $SO_4^=$	Exclude highly oxidized effluents	Anoxic denitrification. Negative redox potential
Toxicity minimization	Heavy metals, chlorinated HC and other organic toxicants	Form insoluble metal sulfides Degrade to CO_2 water, halogen
Gas collection	Prevent oxidation of CH_4 in pond	Plastic cone or "roof". Gas utilization

The historical evolution of separate sludge digesters in waste treatment resulted from a growing realization that when sewage sludge is subjected to strictly anaerobic conditions, a combustible biogas is produced, and the previously gelatinous sludge becomes drainable. In practice the production of a fully drainable sludge has become the dominant criterion for the design of separate sludge digesters. The production of gas is, therefore, a useful adjunct primarily as a measure of digester performance and coincidentally as a source of energy in larger systems. It is, however, a simple matter to show that because of the high unit cost of volume in separate sludge digesters, it is unlikely that economical energy will ever be obtained from them.

During 10 decades of development, separate sludge digesters have been made more and more complex; most are now heated, recirculated, and mixed vertically by gas to improve efficiency and speed the process. Each of these developments has added to digester cost and has increased the need for precise operational controls to avoid the many problems that can result from sudden overloading and hyperacidity. The cost of some elaborately formed and controlled digesters, such as egg-shaped units, is now approaching \$1,000 per m^3 of capacity. This cost should be contrasted with well built earthwork reactors which are unlikely to cost more than \$10 per m^3 of capacity. This huge disparity in cost led to the question: what if instead of short residence time digesters, we use earthwork digesters and increase the sludge residence time to hundreds of days thereby permitting sludge to digest to completion. This initiated our studies of sludge digestion in waste stabilization ponds. Our early studies of oxidation ponds showed that significant amounts of methane are produced during warm periods, and that there is an inverse relationship between the areal amount of methane produced and the distance from the pond inlet (Oswald, *et al.*, 1963). It was also clear from our studies that wind mixing which caused oxygenation of bottom sludges interrupted methane production sometimes to the extent that the ponds become acidic and odorous. Our first efforts in improved design were to make ponds deeper, thus increasing the probability of having a stable anaerobic bottom layer due to stratification. Deepening ponds did improve their performance, but the sludge layer tended to be cooler than desirable since the natural warmth of the sewage was dissipated quickly in the hypolimnion-like environment. These findings led us to the idea of concentrating the settleable material into a smaller area that could be protected from intruding oxygen by submerged berms and could conserve the natural warmth of the entering sewage. We continue to study this concept of in-pond fermentation, and in addition to improved digestion, several other important and unexpected advantages have become obvious. In the following we shall refer to this confined volume as a fermentation pit.

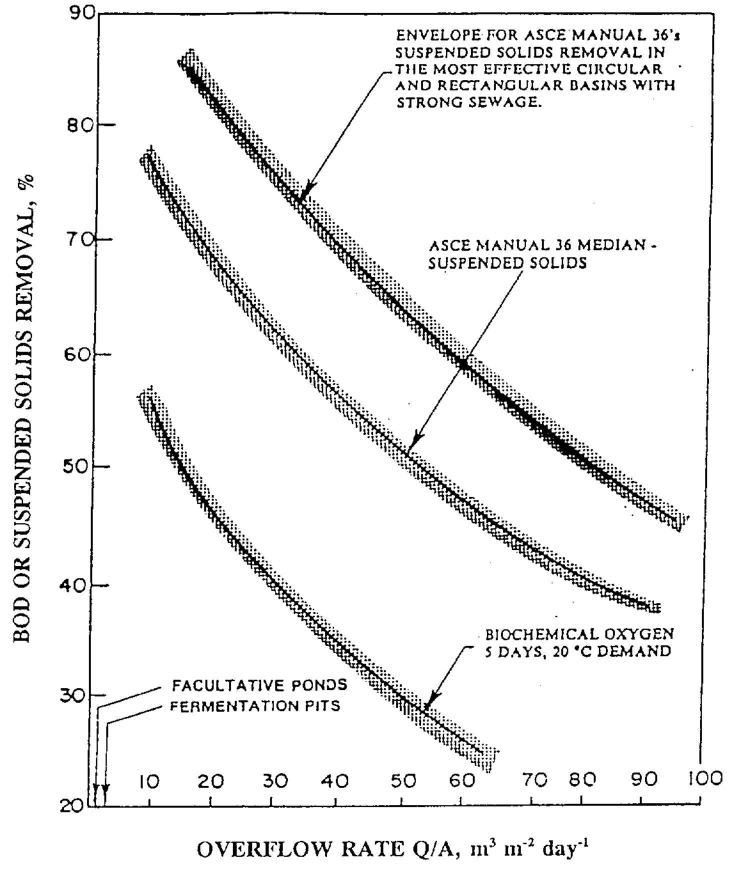

Fig. 1. ASCE gulidelines for sedimentation tanks. Overflow rate Q/A.

FERMENTATION PIT VOLUME

Although the purpose of the in-pond fermentation pit (FP) is to digest sewage solids to completion, it turns out that solids removal criteria provide important guidelines for pit design. Decisions regarding pit volume should be dominated by the intent to maximize the deposition of settleable solids in the fermentation pit. Settling tank design and performance relations are valuable in this respect. As may be seen in Figure 1 drawn from American Society of Civil Engineers, *ASCE Manual 36*, tanks with a 2-hour residence time and overflow velocity of about 50 m^3 m^2 day^{-1} will remove 25% of the influent Biochemical Oxygen Demand (BOD) and about 55% of the influent Suspended Solids (SS); whereas, with a 1-day residence time and overflow velocity of 2 m^3 m^2 day^{-1}, the removal is 60% of the BOD and 80% of the SS. We accordingly have assumed a minimum 1-day hydraulic residence time (HRT) in a fermentation pit. One may then see from Figure 1 that a pit with a 1-day HRT would remove almost all SS. A 1-day HRT fermentation pit would also provide sufficient volume for the retention of 200 mg l^{-1} of SS at 1% solids for 50 days and at 10% solids for 500 days. Sludge volume, of course, diminishes as methane fermentation proceeds toward completion. Assuming that SS are 10% ash, and that only ash remains, one may expect a 99% reduction in volume. It is apparent then that solids residence time in a fermentation pit with a 1-day HRT becomes a matter of years, and the extent of fermentation is much less sensitive to temperature, as is the case for heated separate sludge digesters of conventional design having solids retention time (SRT) of 10 to 40 days. A third factor is that some of the inorganic fraction in the solids is rendered soluble by the fermentation, and some colloidal particles escape from the pit with the liquid upflow further increasing the residence time for those solids remaining in the pit. This phenomenon has been proven by the first in-pond fermentation pits in St. Helena, California which have functioned for over 27 years without the need to remove residual sludges. Some of these relationships have been described previously for St. Helena and Hollister, California (Oswald, 1991).

CURRENT STUDIES

In this paper we wish to describe the design and performance relationships for our intermediate-scale demonstration Advanced Integrated Wastewater Pond System at the University of California, Berkeley Environmental Engineering and Health Sciences Laboratory in Richmond, California. A plan view of the Richmond AIWPS system is shown in Figure 2. The facultative pond has a surface area of about 0.1 hectare and a bottom area of 0.045 hectare. The volume at a 2.3 metres water depth is approximately 1,514 m^3, providing a HRT of about 8 days for a sewage flow of 190 m^3 day^{-1} and a HRT of 16 days for a flow of 95 m^3 day^{-1}. Two in-pond digesters have an average depth of about 2.1 metres and a combined volume of about 140 m^3, providing an HRT of 0.7 days at a flow of 190 m^3 day^{-1} and 1.5 days at a flow of 95 m^3 day^{-1}. The smaller of these two digesters was built and operated first and has a volume of only about 28 m^3. The second digester volume is about 112 m^3. The side walls of all ponds are lined with plastic to prevent weed growth and mosquito breeding. The wastewater comes from a middle income neighborhood near the Richmond Field Station and is strictly domestic in origin.

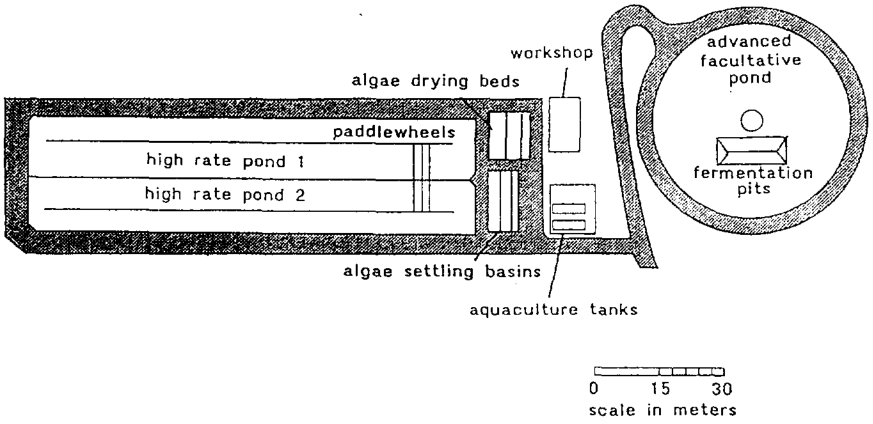

Fig. 2. Plan view of the intermediate-scale (133 m^3 day^{-1}) Advanced Integrated Wastewater Pond System at the Univeristy of California, Berkeley, Environmental Engineering and Health Sciences Laboratory in Richmond, California USA.

In operating the demonstration AIWPS at Richmond, influent sewage is coarsely screened at the pumping station inlet and then pumped directly into the fermentation pits. The daily volume is controlled by pumping time during the day. As it is currently constructed, we have two FPs with a combined volume sufficient to permit an HRT of 1-day. However, all of the data reported here describes the operation of the facultative pond with the original FP. Because of its small volume, the original FP received only 1/4 of the flow and the remaining 3/4 of the 133 m^3 influent was bypassed into the facultative pond bottom. Consequently, sedimentation and digestion of the influent solids were clearly incomplete. Currently, effluent from the first and second FPs overflows into the outer facultative pond having an HRT of approximately 10 days. We have not yet initiated our experimental variation of HRTs in the combined FPs and in the outer facultative pond. The HRT in the outer facultative pond, approximately 12 days, was complicated by exfiltration during the first several months of operation. Experience with this pond has shown that the exfiltration rate diminishes with time and eventually becomes negligible.

Following its sojourn in the outer facultative pond, effluent is drawn from a depth of 1.2 metres below the surface and is introduced into the paddle-wheel-mixed High Rate Ponds (HRPs). HRP influent is introduced downstream of the paddle wheel.

The HRPs are comprised of endless raceways and are each 0.1 hectare in area. Flow velocity in the raceways is maintained at 15 cm per second, a velocity sufficiently high to prevent thermal stratification and to maintain algal suspension and sufficiently low to avoid lifting the flocculent bacterial phase into the high pH surface waters. The bacterial phase must be maintained near a neutral pH to speed oxidation and CO_2 release for the algae. Because the HRP is designed to provide photosynthetic oxygenation in excess of BOD, the HRP is always aerobic throughout its depth. The normal operating depth for the HRPs is 30 cm, and the HRT can be varied by changing flow into the facultative pond or by bypassing some of the facultative pond effluent. Nominal HRT in the HRPs is 3 to 4 days. Longer residence times cause excess algal growth and ageing and resultant release of nutrients from the algae.

Effluent from the HRPs is drawn from the surface at a point about 6.1 metres upstream of the paddle wheels. By drawing from the surface, one obtains water that has reached a high pH and has been irradiated by the sun. Each of these phenomenon enhance disinfection of pathogenic organisms. HRP effluent is directed into one of three settling units. Because of their small size, these units are constructed of concrete rather than earthwork. HRTs in these units can be varied from 2 hours to over 1 day, the latter by bypassing some of the flow. Overflow from the settling units is drawn through a series of parallel holes at the distal ends of the units. To harvest the settled algae, the supernatant liquid is decanted and the thickened algae is removed by pumping for subsequent experimental use. This thickened algae has a solids content of approximately 3%. Effluent from the settling units would normally discharge into maturation ponds or irrigation holding ponds or wetlands, but due to space limitations only a fraction of the effluent is introduced into experimental aquaculture tanks for fish propagation and growth studies. After testing, excess treated water is returned to the City of Richmond sewer.

Analytical procedures for the determination of BOD, suspended solids, nitrogen, phosphorus, biogas composition, and indicator bacteria are conducted in accordance with *Standard Methods* (1992). Sample points include influent sewage and effluents from the facultative pond, high rate ponds, and settling basins. Biogas is collected near the bottom of the FP and on the surface of the Advanced Facultative Pond after it has emerged through the water column and is ready for use. Gas analyses are done by calibrated gas chromatography.

RESULTS

Major characteristics of the influent domestic sewage are reported in Table 2. Experimental data for various stages of the system are shown in Table 3. As noted above, only the median flow rate of 133 m^3 day^{-1} has been applied, and only about 1/4 of this was passed through an FP. Data on the full 1-day HRT combined fermentation pits are now being collected and will be reported in a later paper. Also due to the various adjustments always required in a new demonstration plant, the results reported here must be regarded as preliminary. Further results with statistical evaluation will be reported in a later paper. Figure 3 shows typical composition of gases emerging from the sludge and from the water column.

DISCUSSION

The demonstration AIWPS has the research advantage of being large enough to avoid the scale-up problems inherent in bench scale systems and small enough to be manipulated. Such manipulation is of course difficult or impossible in a full-scale municipal plant. Earlier studies at St. Helena and Hollister which are reported elsewhere (Oswald, 1991) are essentially born out in the current work even though the demonstration AIWPS was not completed until very recently.

As may be seen from the data in Table 2, the mean BOD of 233 mg l^{-1} and mean SS of 193 mg l^{-1} for the Richmond sewage used for these experiments was somewhat stronger than average U.S. sewage perhaps because of the continuation of water conservation practised during California's recent seven-year drought. These higher values could also have resulted from the fact that influent sewage was collected in the daytime. The sewage total nitrogen is also high averaging 50 mg l^{-1}. Total phosphate of 15 mg l^{-1} is correspondingly high. Based on limited data, total coliform MPN is about normal, but fecal MPN appears to be somewhat higher than normal. Sewage total BOD varied by as much as 15% from the mean; SS by more than 20% of the mean; organic nitrogen by as much as 100% of the mean; and, ammonium by as much as 12% of the mean. A 4 mg l^{-1} nitrate level is not unusual for domestic sewage with a total nitrogen of 50 mg l^{-1}.

TABLE 2. Influent Sewage Quality at the Richmond AIWPS June to September 1992

Parameter	Concentration (mg/l)	Standard Deviation
Total BOD_5	233	32
Soluble BOD_5	91	23
Total Suspended Solids	193	42
Organic Nitrogen	9.5	9.1
Ammonia	39.5	6.1
Nitrate*	4	--
Total Phosphorus	7.9	0.48
Orthophosphate	5.1	0.48
Total Coliform* (MPN per 100 ml)	1.4×10^8	--
Fecal Coliform* (MPN per 100 ml)	9.0×10^7	--

* Preliminary data

As may be seen from the data presented in Table 3, a major part of the wastewater treatment is accomplished in the facultative pond. Because of the long HRT in the facultative pond, 56% of the total BOD and 66% of the soluble BOD is removed. Algal growth and resuspended solids in the facultative pond give the appearance of poor SS removal. This is attributed to the bypassing of the major portion of the sewage to the outer facultative pond. Algal growth in the High Rate Pond contributes a large amount of SS which are normally over 50% removed in the settling units despite the poor removals indicated in Table 3. If the water is to be used for irrigation such SS levels would be of no adverse significance. On the other hand if the water is to be used where human contact is involved, disinfection by UV, ozone, or chlorine is indicated. Doses of chlorine below 6 and 8 mg l^{-1} are unlikely to kill algae (Hom, 1970) but are sufficient to kill residual indicator bacteria, particularly when as many as 5 logs of disinfection are already attained in the AIWPS sequence (see Table 3). Recent personal observation of UV disinfection of pond effluents indicates that indicator bacteria are much more vulnerable to UV than are pond algae. Viable algae are observed at the outlet of the UV system, while MPN levels are low or zero. This phenomenon will be further explored in the future.

TABLE 3. Treatment Performance in the Richmond AIWPS June to September 1992

Parameter (mg/l)	Influent sewage	Facultative Pond Effluent	High Rate Pond Effluent	Settling Basin Effluent	DAF and Sand Filter Effluent*	Overall Percent Removal
Total BOD_5	233	102	62	43	0.86	99%
Soluble BOD_5	91	31	6	6	N/A	93%
Total Suspended Solids	193	139	326	163	11	94%
Organic Nitrogen	9.5	2.7	27.2	16.8	0.90	91%
Ammonia	39.5	31.5	3.0	2.6	0.22	99%
Nitrate*	4	2	3	3	N/A	25%
Total Phosphorus	7.9	7.3	7.4	4.5	0.37	95%
Orthophosphate	5.1	5.0	2.1	2.5	0.12	98%
Total Coliform* (MPN per 100 ml)	1.4×10^8	2.4×10^6	2.3×10^4	9.0×10^2	2	$99.\bar{9}$%
Fecal Coliform* (MPN per 100 ml)	9.0×10^7	7.0×10^5	5.0×10^3	1.7×10^2	<2	$99.\bar{9}$%

* Preliminary data

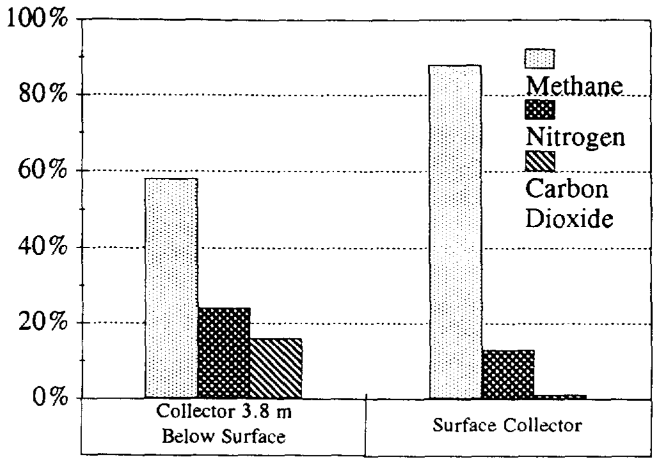

Fig. 3. Change in biogas composition due to scrubbing in the Advanced Facultative Pond of the Richmond AIWPS.

The significant nitrogen removals attained in the facultative pond of the demonstration AIWPS result from a process known as heterotrophic nitrification and denitrification first described by Verstraete and Alexander (1973). The presence of heterotrophic denitrification is indicated by the differential gas composition shown in Figure 3. As shown bottom gases are less than 60% methane and over 20% nitrogen. Whereas gas from the surface collector is almost 90% methane and less than 10% nitrogen. Clearly free molecular nitrogen is produced from nitrogen-rich organic substances in the bottom sludges and is dissolved in the overlying water column as the gas emerges. Also carbon dioxide which is almost 15% in the bottom gas is less than 2% of the gas that emerges indicating that it is also dissolved in the overlying water column. Thus a purified methane is produced. Levels of hydrogen sulfide were less than 1%. Apparently most of the sulfides are precipitated with metals in the intensely anoxic environment of the fermentation pit. Obviously the removal of heavy metals commonly found in sewage is another important advantage of the AIWPS technology that we expect to precisely quantify in future reports. Toxic organic compounds are also known to be biodegraded in such anoxic environments (Davis *et al.*, 1983) and efforts are being made to quantify this benefit as well.

Experiments with a full 1-day HRT fermentation pit are now underway, and in the future all influent sewage will pass through this extremely anoxic environment. We expect that more than 60% of the influent carbon will be converted to methane and carbon dioxide and that heavy metals will be immobilized and many organic toxicants will be destroyed. By decreasing the amounts of both carbon and nitrogen in the facultative pond effluent, algal growth in the HRP will be more limited and more prone to settle when removed from the mixing field. It is expected, however, that final polishing of the final effluent by dissolved air flotation and filtration followed by UV or ozone disinfection will be required for reuse involving human contact. Disinfection should be simplified by the significant reduction in *E. coli* and fecal coli demonstrated by these preliminary experiments.

Suspended solids in final effluents of AIWPS are of concern, particularly when chemical disinfection is required and when SS limits are strict. Detailed studies of algal removal by dissolved air flotation (DAF) (Nurdogan, 1988) indicate that although DAF is an additional expense, it combined with an AIWPS is far less costly than conventional tertiary treatment of equal capacity.

SUMMARY AND CONCLUSIONS

A experimental study was conducted with an Advanced Integrated Wastewater Pond System consisting of an Advanced Facultative Pond with internal fermentation pits, High Rate Ponds mixed with paddlewheels, followed by settling units and a dissolved air flotation unit for algal removal. Strictly domestic sewage of moderate strength was treated in this series. Total BOD removals exceeded 90%. Sewage suspended solids were replaced by algal suspended solids which, although settled for 2 hours, were less than 50% removed. The facultative pond itself was a major source of suspended solids, bacterial and algal, probably due to the majority of the wastewater being directed into the outer facultative pond rather than into the fermentation pit. As noted above, the original fermentation pit could only accept about 1/4 of the sewage flow during the period reported here. The balance of the flow diverted to the outer facultative pond stimulated behavior typical of a facultative pond without a fermentation pit. A 1-day HRT fermentation pit is now in place for use in future experiments. The MPN predictions of Marais (1974) and others are clearly born out by the preliminary *E.coli* and fecal coliform data. In spite of the lack of a long HRT digester up front, fecal coliform levels in the final effluent (1.7×10^2) were well below World Health Organization (WHO) recommended standards (1×10^3). Total coliform removals were also less than WHO standards. Results of gas analyses of samples taken from the fermentation pit and from the pond surface clearly indicate the presence of heterotrophic nitrification and denitrification and the nitrogen and carbon dioxide scrubbing provided by the overlying pond volume.

ACKNOWLEDGEMENTS

We are indebted to the California Energy Commission and the California Institute of Energy Efficiency for their continued support of this research.

REFERENCES

American Public Health Association. (1992). *Standard Methods for Examination of Water and Wastewater*, 18th Ed., APHA, New York.

American Society of Civil Engineers. (1957). *ASCE Manual 36*, ASCE, New York.

Davis, E. M., Moore, J. D., Frieze, T. R. and Scherm, M. (1983). Efficiency of waste stabilization ponds in removing toxic organics. In: *Toxic Materials: Methods for Control*, N. E. Armstrong and A. Kudo (eds.). Center for Research in Water Resources, University of Texas at Austin, pp. 95-107.

Horn, L. W. (1970). *Kinetics of chloride disinfection in algal-bacterial systems*. Ph.D. Thesis, University of California, Berkeley, pp 252.

Marais, G. v. R. (1974). Faecal bacterial kinetics in stabilization ponds. *J. of the American Soc. of Civ. Engin.*, **100**, 119-139.

Nurdogan, Y. (1988). *Microalgal separation from high rate ponds*. Ph.D. Thesis, University of California, Berkeley.

Oswald, W. J., Golueke, C. G., Cooper, R. C., Gee, H. R. and Bronson, J. C. (1963). Algal production and methane fermentation in waste ponds. *J. Int. Air and Water Poll.*, **7**, 6.

Oswald, W. J. (1991). Introduction to advanced integrated wastewater ponding systems. *Wat. Sci. Tech.*, **24**(5), 1-7.

Stephenson, M. (1949). *Bacterial Metabolism*. Longmans, Green and Company, London, pp. 53-55.

Verstraete, W. and Alexander, M. (1973). Heterotrophic denitrification. *Appl. Microbiol.*, **7**, 39-42.