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ENERGETICS OF ADVANCED INTEGRATED WASTEWATER POND SYSTEMS

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ABSTRACT

An energy balance is presented for a second generation Advanced Integrated Wastewater Pond System (AIWPS) prototype at the University of California, Berkeley, Environmental Engineering and Health Sciences Laboratory in Richmond, California. Modifications were made to the existing 1.8 ML facultative pond in order to further optimize methane fermentation and to demonstrate the recovery of methane using a submerged gas collector. Methane production rates were determined over a range of in-pond digester loadings and temperatures. The feasibility of submerged gas collection was proven, and the advantages of in-pond digestion in terms of BOD_5 and VSS removal as well as biogas scrubbing were quantified. Biogas methane concentrations increased by more than 50% as the biogas emerged through the overlying water column and most of the carbon dioxide fraction was utilized by microalgae. Electrical power requirements for mixing two 0.1 hectare algal High Rate Ponds (HRPs) were measured over a range of channel depths and velocities, and electrical power requirements for daily recirculation pumping were also measured. Oxygenation and total treatment energy requirements for the second generation AIWPS prototype at Richmond were compared with oxygenation and total treatment energy requirements for the first generation AIWPS at St. Helena, California and for two mechanical wastewater treatment plants of comparable capacity and effluent quality at Pinole and Brentwood, California. Using preliminary methane production and recovery rates achieved at Richmond, the cogeneration potential was estimated and projected for larger second generation AIWPSs of 2 MLD and 200 MLD capacities. By incorporating methane recovery and electrical power generation together with efficient HRP mixing using paddle wheels, full-scale second generation AIWPSs will be able to produce as much energy as they require for primary and secondary treatment. Additional energy would be required to produce a tertiary disinfected effluent suitable for unrestricted reuse in California, including recreational and indirect potable reuse. The additional power requirements for complete algal harvest using dissolved air flotation (DAF) and filtration were estimated for second generation AIWPSs based on data collected at Richmond and Stockton, California, and the additional power requirements for final UV disinfection were estimated.

KEYWORDS

Advanced Integrated Wastewater Pond Systems; Advanced Facultative Ponds; algal High Rate Ponds; electrical power generation; energetics; energy efficiency; in-pond digesters; methane fermentation; methane recovery; photosynthetic oxygenation.

INTRODUCTION

Disruptions in the international oil market during the 1970s signaled the inevitable depletion of fossil fuel energy resources and strengthened worldwide interest in energy conservation, increased efficiency, and the development of renewable energy resources. Greater attention to the environmental impacts and costs associated with energy supply have also stimulated the demand for greater end use efficiency and the development of renewable energy resources (Holdren, 1987). These factors have been influential in the development of innovative, energy efficient wastewater treatment systems. Advanced Integrated Wastewater Pond Systems have been developed by our group at the University of California, Berkeley over the past forty five years, and first generation municipal AIWPSs have operated successfully for 28 years and 16 years respectively at St. Helena and Hollister, California, USA. Cooperative research and technology transfer activities involving AIWPSs have been undertaken in many parts of the world in a wide range of climatic conditions and in diverse social and technological settings. Currently, AIWPSs are being designed and installed in Bolivia, Brazil, India, Mexico, South Africa, and the United States.

First generation AIWPSs, such as those at St. Helena and Hollister, consist of at least four ponds in series, each uniquely designed to optimize one or more unit processes (Oswald, 1990). The series includes an *Advanced Facultative Pond* (AFP) with internal fermentation pit(s) for optimal methane fermentation; followed by an algal *High Rate Pond* (HRP) for optimal photosynthetic oxygen production and nutrient assimilation; followed by an *Algae Settling Pond* (ASP) for algae sedimentation and removal; followed by a *Maturation Pond* (MP) for effluent storage and further water quality improvement prior to reuse. While first generation AIWPSs have provided superior secondary effluent suitable for safe agricultural irrigation, they have not included the recovery and utilization of methane or the harvest and utilization of algal biomass. The HRPs at St. Helena and Hollister have been mixed by mechanical devices that are less efficient than are paddle wheels. Paddle wheels provide the additional advantage of promoting the growth of algal species which tend to flocculate and settle.

Second generation AIWPSs such as the Richmond prototype and other full-scale systems under design or renovation include the recovery and utilization of methane produced in AFPs, paddle wheel mixing of HRPs, and the harvest and utilization of algal biomass. Depending on local needs and regulatory requirements, second generation AIWPSs may also include dissolved air flotation (DAF) and filtration in order to produce an essentially clear effluent (< 2 NTU — nephelometric turbidity units) and to allow for final UV disinfection such that unrestricted reuse standards as established by the State of California Department of Health Services (NWRI, 1993; CA DHS, 1995) can be met.

Oxygenation versus aeration power requirements. Aeration, the mechanical introduction of atmospheric oxygen into primary effluent, is usually the most energy intensive process in mechanical wastewater treatment systems. Typically in activated sludge and extended aeration systems, between 0.4 and 1.1 kWh is required to transfer 1 kg of O_2 into primary effluent (Owen, 1982). In AIWPSs, oxygen is introduced by the photosynthetic disassociation of water molecules by microalgae growing in HRPs and in the euphotic zone of AFPs. During photosynthesis algae grown in HRPs receiving primary effluent produce approximately 1.6 times their cell mass by weight in free molecular oxygen (Oswald and Gotaas, 1957, 1958). In contrast to duckweed and water hyacinths, algae produce oxygen within the water column where it is readily available to aerobic bacteria that oxidize complex organic material into its constituent plant nutrients. Daytime dissolved oxygen (DO) concentrations in HRPs range between 10 and 30 mg/L. Despite these and many other advantages, HRPs and the microalgal photosynthetic oxygenation they provide do require a small amount of electrical power for mixing to maintain algal cell suspension. The energy required for HRP mixing is influenced by a number of factors such as velocity, channel geometry, and surface roughness. After decades of experience with various methods of HRP mixing, including propeller pumps, lift pumps, and Archimedes Screw pumps, we have established that gentle mixing at an optimal mean surface velocity of 15 cm/s can be most efficiently achieved by simple motor driven paddle wheels. The two Richmond paddle wheels have been in use since 1978. Generally the electrical power requirements for photosynthetic oxygenation in paddle wheel mixed HRPs is 0.075 to 0.15 kWh/kg O_2 produced. In addition to oxygen production and high rate oxidation, paddle wheel mixed HRPs foster the autoflocculation and bioflocculation of algae and the subsequent rapid sedimentation and removal in ASPs. Higher sedimentation efficiencies lower the energy requirements for further algal removal should it be required. Surplus oxygen produced during daylight hours in HRPs is typically recirculated to the upwind surface of the AFP at approximately 25% of the influent flow in order to reduce the energy requirements for supplemental surface aeration. The overall energy savings of photosynthetic oxygenation in paddle wheel mixed HRPs are significant when compared with the energy requirements of mechanical aeration in activated sludge and extended aeration systems. Furthermore, significantly higher levels of plant nutrients are removed in HRPs than are removed in aeration basins or oxidation ditches.

METHODS

To optimize methane fermentation and the recovery of methane-rich biogas, the 0.1 hectare circular AFP shown in Fig. 1 was retrofitted by the installation of two in-pond digesters and submerged gas collectors. A cross section of the AFP and details of the first digester and submerged gas collector installed in 1991 are shown in Fig. 2. Both digesters have an overall depth of approximately 2.6 m and a rim wall that extends above the pond bottom approximately 1 m to prevent the intrusion of dissolved oxygen into the fermentation zone by wind-induced vertical mixing. The environmental requirements and optimization of in-pond methane fermentation have been discussed elsewhere (Oswald *et al.*, 1963; Oswald *et al.*, 1994; Green, *et al.*, 1995). The Richmond in-pond digesters have a volumetric capacity of 31 m^3 and 61 m^3, respectively. The submerged gas collectors suspended above each digester were fabricated using a 0.5 mm polyester scrim-reinforced laminated PVC liner material. The twelve panels of the inverted cone shaped collector shown in Fig. 2 were seamed using nylon thread and strips of 50 mm wide nylon webbing for reinforcement. The bottom of each seam strap was attached with 10 mm Dacron rope to eye bolts set in the top of the digester wall, and the top of each seam strap was buckled around the styrofoam flotation collar. Gas emerging from the digester was focused through the central opening between the flotation collar and the support column and was collected at the surface in a rigid circular PVC cap also riding on the support column. The gas collector positioned above the second digester, a rectangular wedge-shaped pit installed in 1993, was attached to the surrounding wooden berm wall by 10 mm Dacron rope passing through grommets in the outside hem of the canopy and eye bolts in the berm wall. The canopy was elevated toward the central aperture by two ridge beams extending from each end wall to the aperture and there attached to the bridge.

Biogas entering each surface cap was metered continuously, and its composition was analyzed weekly by gas chromatography, along with biogas samples collected from smaller stationary collectors located inside each digester. Standard water quality parameters such as total and soluble BOD_5, TSS, VSS, total Kjeldahl nitrogen, organic nitrogen, ammonia nitrogen, total phosphorus, soluble reactive phosphorus, total and fecal coliforms, temperature, pH, DO, total organic and inorganic carbon, and alkalinity were measured in the influent and effluent of each element of the AIWPS on a twice weekly basis over a two year period. The electrical power requirements for HRP paddle wheel mixing and recirculation pumping of 25% of HRP effluent to the surface of the AFP were measured using two Fluke model 27 digital multimeters, and the head loss in each HRP was measured over a range of depths and mixing velocities in order to verify the hydraulic equations used to estimate HRP paddle wheel mixing power requirements.

The energy balance was estimated by comparing the sum of these two energy requirements with the rate of methane recovery and its cogeneration potential assuming a 30% efficient gas engine generator. The preliminary energy balance of the Richmond prototype was then compared with the treatment energy requirements for the first generation AIWPS at St. Helena and with the treatment energy requirements for two mechanical wastewater treatment plants at Pinole and Brentwood, California using five years of electrical utility data and other measurements. Finally, the energy balances for 2 MLD and 200 MLD second generation AIWPS were estimated based on the energy production potential and the treatment energy requirements observed at Richmond. Additional energy requirements for final algae removal and UV disinfection were estimated using DAF and filtration data from Richmond and Stockton and using UV disinfection energy requirements provided by two UV equipment manufacturers.

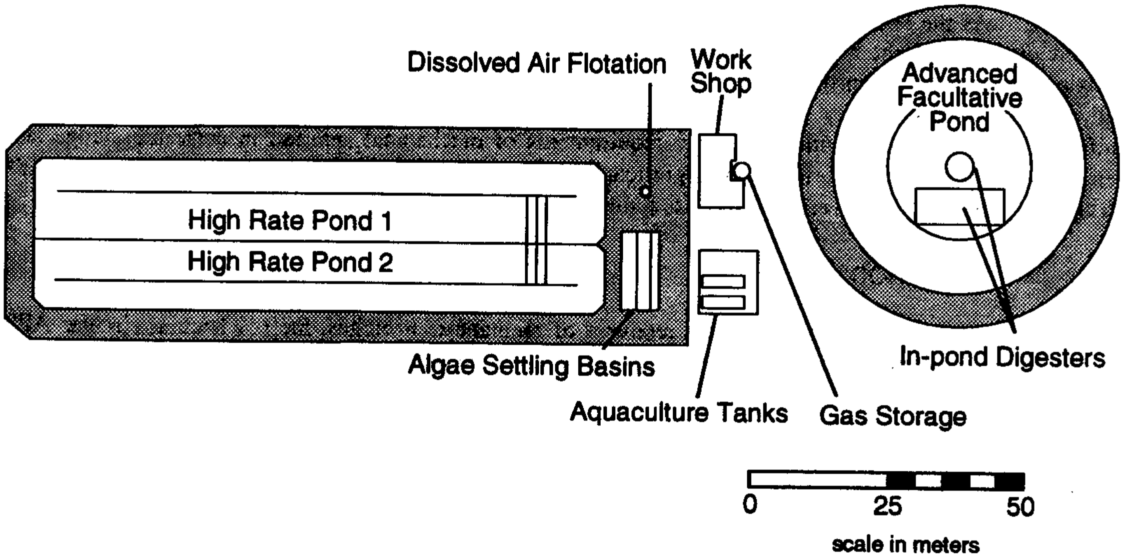


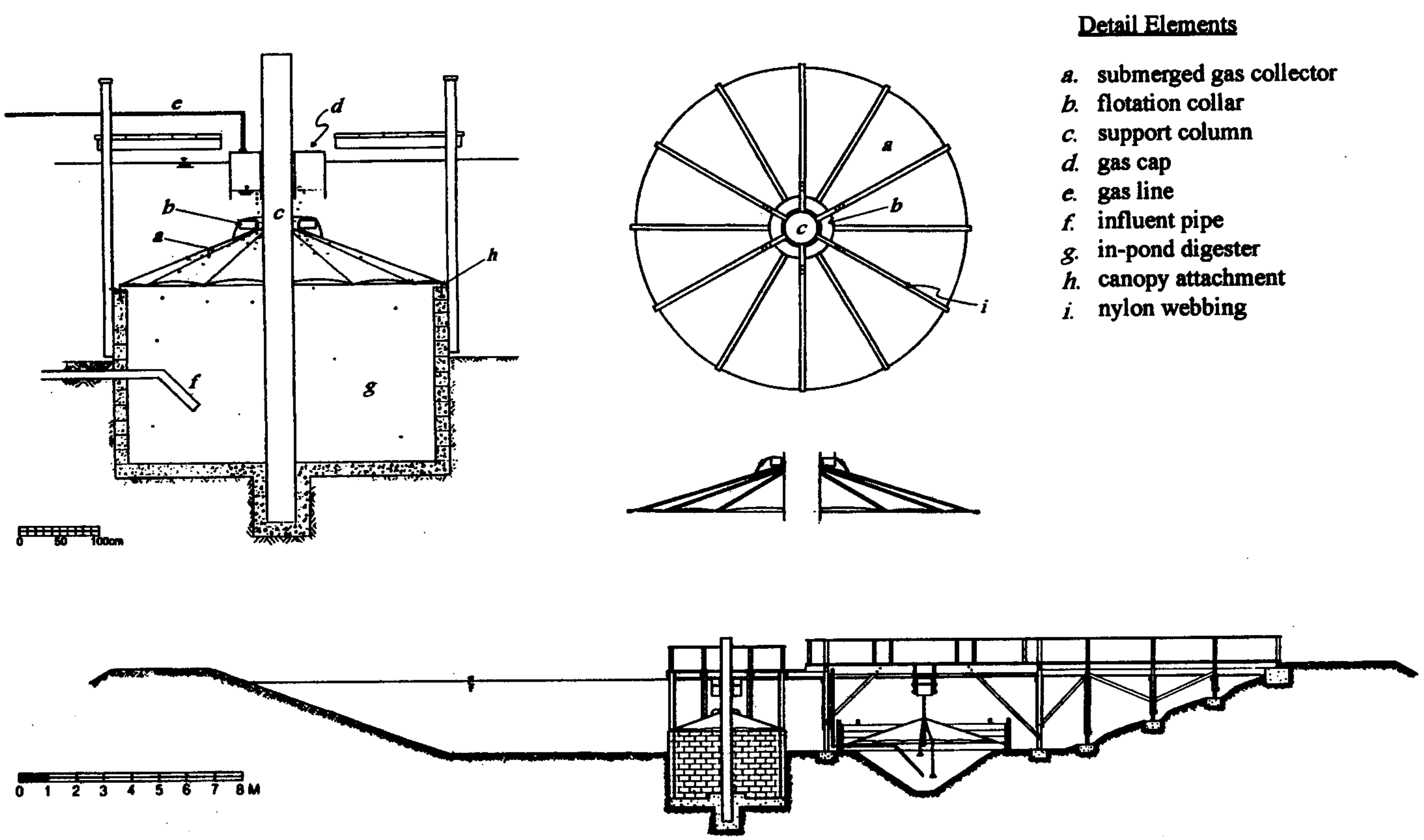
Figure 1. Plan of the second generation AIWPS prototype at the University of California, Berkeley in Richmond, California, USA.

Power requirements for paddle wheel mixed HRPs. Electrical energy is required to drive paddle wheels which provide continuous flow and gentle mixing in HRP channels such that algae and algal flocs remain in suspension near the surface and within the depth of sunlight penetration, while larger bacterial flocs utilizing photosynthetic oxygen to oxidize influent BOD move more slowly along the HRP bottom. Paddle wheel mixing further prevents thermal stratification. The optimal mean surface velocity needed to accomplish these objectives in a typical wastewater HRP is approximately 15 cm/s (Oswald, 1988). The paddle wheel used in HRP 2 at Richmond is shown in Fig. 3.

Classical hydraulic equations such as kinetic head loss, Manning's equation for open channel flow, and a hydraulic power equation have been used to calculate the power required to mix the elongated raceways of HRPs (Oswald, 1988). In the two paddle wheel mixed HRPs at Richmond, head loss, mean surface velocity, and armature power were measured over a range of depths and mixing velocities, and these measurement were used to verify the equations and to compare with the HRP mixing power requirements measured in other studies.

Head loss measurement. The difference in water head across the paddle wheels was measured 3 m upstream and 3 m downstream of each paddle wheel. The average water level across the channel was determined using six evenly spaced needle gages and a transit. One millimeter water elevation differences were discernable. Elevation values across the channel were averaged to give a mean water elevation on each side of the paddle wheel. The measured head difference represents the work being done by each paddle wheel to overcome frictional and kinetic head losses in each HRP raceway consisting of two 180° bends and two straightaways.

HRP mean surface velocity measurement. Mean surface velocity was determined by measuring the travel time of 2.5 cm x 5 cm plastic bottles over a distance of 6 m. The bottles were weighted so that the entire bottle was underwater minimizing the effect of wind. Velocity was measured at one meter intervals across the channel width 37 m downstream from the paddle wheels. The resulting velocity curve was integrated to determine the mean surface velocity. Mean surface velocity has been used in place of the actual mean velocity. Weissman *et al.* (1989) found that mean velocity was about 80% of the near-surface velocity in a plastic-lined HRP.



Detail Elements

- *a.* submerged gas collector
- *b.* flotation collar
- *c.* support column
- *d.* gas cap
- *e.* gas line
- *f.* influent pipe
- *g.* in-pond digester
- *h.* canopy attachment
- *i.* nylon webbing

Fig. 2. Cross section of the Advanced Facultative Pond showing both digesters, submerged gas collectors, sampling platform and bridge with details of the first digester, and submerged gas collector.

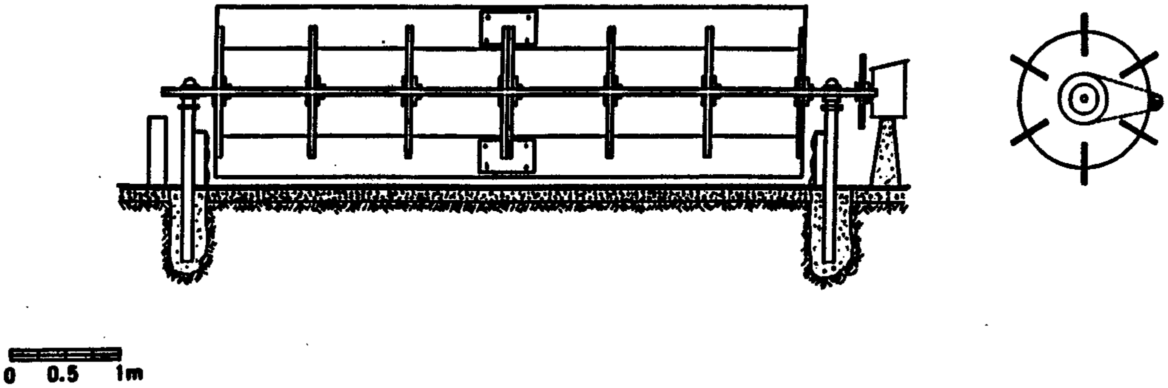


Figure 3. Cross section of paddle wheel and motor drive assembly in HRP 2 at Richmond as installed in 1978 and renovated in 1992.

Power measurement. Armature power consumption was determined using two Fluke model 27 digital multimeters connected to the motor circuit after the DC speed controller/rectifiers. Simultaneous DC voltage and ampere readings were recorded. The motor loads oscillated because of the uneven load created by the six-bladed paddle wheel. High and low voltage and amperage readings were recorded for each flow and depth condition and averaged. Power consumption by the speed controller was approximately three times higher than the motor power consumption. Both are 17 years old, oversized, and inefficient. A new paddle wheel drive system for the same HRP would require 1/3 of the currently rated power, would be directly coupled to the paddle wheel axle, and would use a more efficient speed controller.

Power must be applied to overcome kinetic head loss in the bends as well as the frictional head loss in the channels and bends. The kinetic head loss that occurs as water flows around a 180° curve may be expressed as:

$$h_k = Kv^2/2g \tag{1}$$

where, h_k = kinetic head loss in m;
v = the mean surface velocity in m/s;
g = the acceleration of gravity, 9.81 m/s^2; and,
K = kinetic loss coefficient for 180o bends (theoretically equal to 2).

Manning's equation can be used to calculate frictional losses which occur along the length of the raceways:

$$h_L = v^2n^2L/R^{4/3} \tag{2}$$

where, v = channel velocity in m/s;
n = roughness factor (Manning's n);
R = channel hydraulic radius (the cross sectional area/wetted perimeter);
h_L = head loss in m;
L = channel length in m.

The total head loss in a two-bend HRP is the sum of the straightaway and kinetic head losses.

$$\text{Total } h_L = v^2n^2L/R^{4/3} + 2Kv^2/2g \tag{3}$$

The power in Watts required to overcome the total head loss is given by the equation:

$$9.80 \times Qwh/e = W \quad (4)$$

where,
Q = channel flow in m^3/s;
w = unit mass of water, 998 kg/m^3 at 20 °C;
h = applied head (head loss) across paddle wheel in m;
e = paddle wheel drive system efficiency;
9.80 = conversion factor in W-s/kg-m.

By substituting equation (3) into equation (4), the following expression for mixing power requirements is found:

$$9.80 \times Qw(v^2n^2L/R^{4/3} + 2Kv^2/2g)/e = W \quad (5)$$

Using power data collected over a range of HRP depths and velocities and a linear programming method, the best fit for Manning's n and the kinetic head loss coefficient (K) were determined. Then using the best fit values for n and K, the paddle wheel drive efficiency (e) was determined.

RESULTS

Loading of the 31 m^3 digester began in September 1991. At the optimal loading rate of 0.032 kg $VSS/m^3/d$ (0.043 kg $BOD_5/m^3/d$), the average rate of biogas production was 0.22 m^3/d. Mean sludge temperature was 20 °C. This best average biogas production rate is equal to 0.22 m^3/kg VSS introduced or 0.15 m^3/kg BOD_5 introduced. Higher loadings of 0.12 to 0.2 kg $VSS/m^3/d$ resulted in lower biogas yields. The reduction in biogas yield was due to the lower sedimentation efficiency of influent solids introduced at higher overflow rates. The methane concentration in the recovered biogas increased from 51% to 86% as the biogas passed through the overlying water column (Fig. 4).

Water quality data shown in Table 1 indicates the excellent treatment performance and superior effluent quality achieved by the second generation AIWPS prototype at Richmond. Using these water quality data, Richmond treatment energy may be expressed as kWh/ML treated and as kWh/kg BOD_5 removed as shown in Table 2.

Measured head loss at various pond depths and surface velocities were used to determine the best fit for Manning's n (0.008) and the kinetic head loss coefficient K (2.4) for each 180° bend. As expected, the majority of the head loss occurred in the bends rather than in the asphalt-lined straightaways. The best fit K value compares well to K values calculated from data presented by Weissman and Tillett (1992). The armature power required for paddle wheel mixing at Richmond was 208 W for a surface water velocity of 15.4 cm/s at a depth of 27 cm. This value corresponds to 4.7 kWh/d for a 15 cm/s water velocity which is nearly 50% more than was measured by Benemann *et al.* (1978). Presumably the discrepancy is due to newer paddle wheel drive equipment and to the different method used in determining mean surface velocity. Benemann *et al.* showed that within the range of depths of 21 to 39 cm, the power requirement for mixing at surface velocities of 15 cm/s or less was virtually independent of depth. Therefore, it was assumed that the 4.7 kWh/d measured for HRP mixing at a depth of 27 cm and velocity of 15 cm/s would approximate closely the energy requirement for HRP mixing at the actual average depth of 35 cm during the two year experimental period.

As Fig. 5 illustrates, at a constant depth the power consumption for mixing increases with the cube of the velocity. The typical mixing velocity in an oxidation ditch is 60 cm/s and would presumably require 64 times as much energy as a HRP mixed at 15 cm/s.

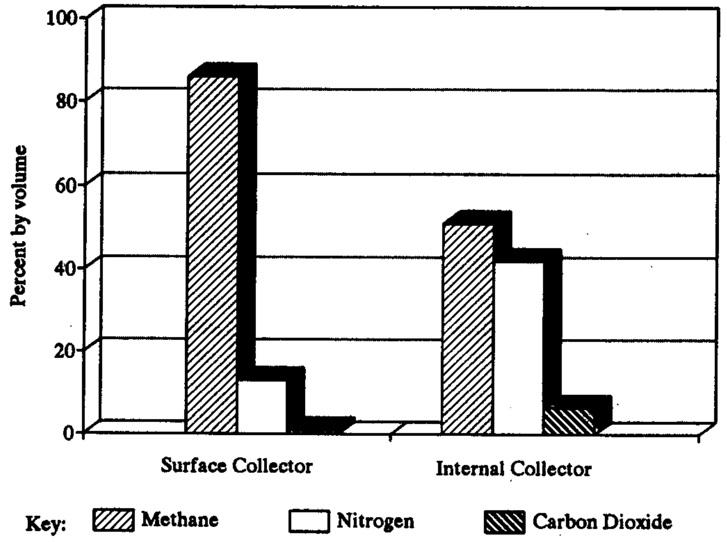


Figure 4. Mean composition of biogas collected in main surface collector 3.9 m above the digester floor and in the internal collector 0.9 m above the digester floor of the Richmond AIWPS May–September 1992.

Table 1. Mean pollutant concentration and cumulative percent removal (CPR) in each element and overall percent removal achieved in the second generation AIWPS prototype at Richmond from May 1992 through April 1994

Parameter (mg/L)	Influent Sewage	Advanced Facultative Pond Effluent (CPR)	High Rate Pond Effluent (CPR)	Average Settling Basin Effluent (CPR)	DAF + Sand Filter Effluent[1]	Overall Percent Removal
Total BOD_5	236	104 (56%)	66 (72%)	42 (82%)	2	99
Soluble BOD_5	100	33 (67%)	6 (94%)	7 (93%)	ND	
Total Suspended Solids	202	152 (25%)[2]	241 (+59%)[2]	111 (54%)[2]	2	99
Volatile Suspended Solids	182	148 (19%)[2]	225 (+52%)[2]	107 (52%)[2]	ND	
Organic Nitrogen	7.8	2.6 (67%)	20.3 (-160%)	13.1 (-67%)	1	78
Ammonia Nitrogen	37.1	26.5 (29%)	5.3 (86%)	4.0 (89%)	0.42	99
Nitrate Nitrogen	4.5	1.6 (64%)	3.0 (33%)	3.2 (29%)	ND	
Total Phosphorus	6.8	5.5 (19%)	5.5 (19%)	3.7 (46%)	0.52	92
Soluble Reactive Phosphorus	4.1	3.4 (17%)	1.8 (56%)	2.1 (49%)	0.17	96
Total Coliform[3] (MPN per 100 mL)	2.6 $\times 10^7$	3.8 $\times 10^6$ (85.4%)	5.2 $\times 10^4$ (99.8%)	4.6 $\times 10^3$ (99.98%)	3	6.9 log units
Fecal Coliform[3] (MPN per 100 mL)	1.4 $\times 10^7$	7.9 $\times 10^5$ (94.4%)	1.9 $\times 10^4$ (99.9%)	1.4 $\times 10^3$ (99.99%)	2	6.6 log units

ND = not determined.

[1] Preliminary DAF+Filter data collected April 1994.

[2] Percent removal (or increase) from previous value, not cumulative percent removal.

[3] Geometric mean of coliform data collected November 1993-April 1994 when the HRPs operated in series; values reflect HRP-2 effluent.

Table 2. Comparison of mechanical equipment, oxygenation energy requirements, and total treatment energy requirements at four California wastewater treatment plants

Treatment Process and Location (average flow in MLD)	Mechanical Equipment Required in Oxygenation	Oxygenation Energy[1]	Total Treatment Energy[2]
		kWh/ML	kWh/ML
		kWh/kg BOD_5 destroyed	kWh/kg BOD_5 destroyed
Second Generation AIWPS prototype	PW/RP[3]	213	109
at Richmond (0.10)		1.11	0.57
First Generation AIWPS	SA/LP/RP[4]	296	296
at St Helena (1.8)		1.25	1.25
Activated Sludge	MB[5]	241	570
at Pinole (7.4)		0.338	0.80
Oxidation Ditch-Extended Aeration	KB/SA[6]	315	414
at Brentwood (3.1)		2.35	3.09

[1] All values were derived from five years of electrical utility data (1989-1994) except at Richmond (1992-1994), and percentages of total treatment energy were calculated by measured or rated power, measured or estimated load, and duty cycle.

[2] Total treatment energy excludes influent pumping, flow metering, and effluent pumping.

[3] Two paddle wheels (PW) used to mix two HRPs where microalgae provided oxygen photosynthetically and one recirculation pump (RP) used to transfer oxygen-rich HRP effluent to the AFP surface consumed 62% and 38% of total oxygenation energy respectively.

[4] Two surface aerators (SA) in the AFP, two lift pumps (LP) used to mix the algal HRP, and one recirculation pump (RP) used to transfer oxygen-rich HRP effluent to the AFP surface consumed 57%, 39%, and 4% of total oxygenation energy respectively.

[5] Motor Blowers (MB) consumed 100% of aeration energy.

[6] Two Kessener Brushes (KB) in a single oxidation ditch and multiple surface aerators (SA) in an aerobic digester consumed 81% and 19% of total oxygenation energy respectively.

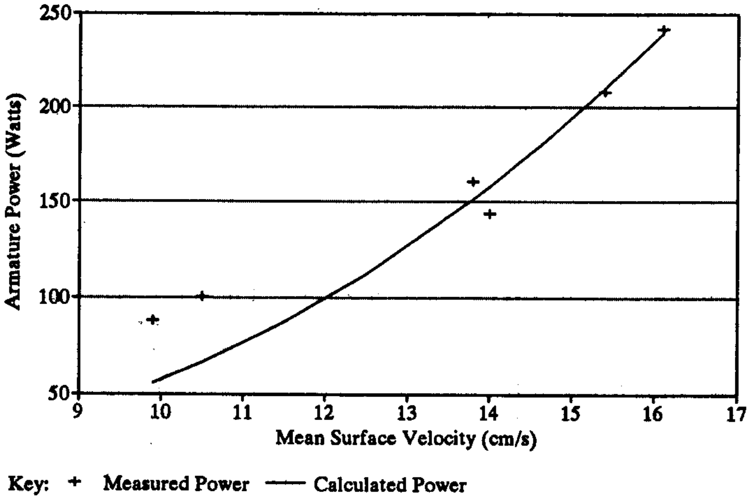


Figure 5. Armature power consumed by a HP (0.75 kW) HRP paddle wheel motor at Richmond. The curve represents equation. (5) with n = 0.008, K = 2.4, and e = 8.9%. Water depth was constant at 27cm, and velocity was varied. The lack of fit at low power was a result of low motor efficiency under partial loads.

Partial load inefficiencies below a current of 2 amps significantly affected the power consumption. Over the range of measured velocities, the amperage at each motor fell below 1 when only one paddle wheel blade was fully submerged. Thus, according to the partial load curves provided by the motor manufacturer, the drive motor efficiency varied between 20% and 78% six times during each paddle wheel rotation. The paddle wheel drive efficiency was also reduced by the large clearance between the blade tips and the HRP bottom and between the blade ends and the HRP side walls which varied between 6 and 12 cm and allowed a considerable back flow. Newer eight-bladed paddle wheels set in invaginated paddle wheel stations equalize the electrical load, minimize back flow, and increase the paddle wheel drive efficiency.

Using equationn (5) and the best fit values for n and K, the efficiency of the paddle wheel drive was estimated to be 8.9% at 15 cm/s mean surface velocity as reflected by the curve in Fig. 5. The low paddle wheel drive efficiency is the product of the efficiency of each component estimated as follows: the electric motor (62% from partial load curve), gear motor (83%), chain drive (90%), and paddle wheel (19%). The loss of 81% of the input power by the paddle wheel is probably due in large part to the large clearance and back flow under and at each end of the paddle wheel blades. Despite the low efficiency, the overall power consumption of the Richmond paddle wheels is low in comparison with conventional aeration equipment. Efficiencies considerably higher than 17% should be obtainable in systems with eight-blade paddle wheels and paddle wheel invaginations.

Energy balance of the second generation AIWPS prototype

Operation of the second generation AIWPS prototype at Richmond provided information needed to estimate the energy consumption and production in full-scale second generation AIWPSs. The Richmond prototype, however, is not as energy efficient as a new full-scale system would be. The two HRPs at Richmond permit controlled experiments, but also require two paddle wheel drive assemblies, motors, and controllers whereas full-scale AIWPSs would most likely not have two HRPs. Furthermore, the large 2.4-m difference in water level between the AFP and the HRPs and the inefficiency of fractional horsepower sump pumps also contributed to excessive energy use for recirculation. Despite these and other inefficiencies inherent in small-scale demonstration systems, it is instructive to calculate the actual energy balance for the Richmond prototype.

Potential electrical power generation. Of the in-pond digester organic loading rates tested so far, 0.032 kg VSS/m^3/d produced the greatest methane yield of 0.22 m^3 CH$_4$/kg VSS introduced. During the period in which this organic loading rate was used, the Richmond AIWPS treated an average flow of 0.071 MLD with a VSS concentration of 182 mg/L. But only the first in-pond digester was in use, and as a result only a fraction of the influent sewage passed through the digester; the remainder of the influent was discharged near the bottom of the AFP. Had sufficient digester capacity (approximately 140 m^3) been available to receive the entire influent flow, the methane production rate would have been 2.5 m^3/d. Assuming a 30% efficient internal combustion gas engine generator, this methane production rate could supply approximately 7.4 kWh/d of electricity.

$$2.5\ \text{m}^3\ \text{CH}_4/\text{d} \times 33{,}888\ \text{Btu/m}^3\ \text{CH}_4 \times \text{kWh}/3{,}414\ \text{Btu} \times 0.3 = 7.4\ \text{kWh/d}$$

Net energy consumption. Energy was expended at Richmond during 1992 for paddle wheel mixing at 15 cm/s and recirculation of 33 m^3/d of HRP water to the surface of the AFP. The HRP power consumption was 195 W (armature power) per paddle wheel motor (Fig. 5) or 9.4 kWh/d for both paddle wheels. It should be noted that paddle wheel mixing is more efficient for large ponds with long straightaways and fewer bends as compared with the 95-m long HRP channels at Richmond. Increased depth also improves mixing efficiency. Watt meter readings showed that recirculation with two sump pumps consumed 5.8 kWh/d. The net electrical energy consumption at Richmond was calculated by adding the total energy required for HRP mixing and for recirculation pumping and subtracting the potential electrical energy that could be generated from methane recovered from an in-pond digester of adequate capacity to receive the entire influent flow:

$$(9.4\ \text{kWh/d} + 5.8\ \text{kWh/d}) - 7.5\ \text{kWh/d} = 7.7\ \text{kWh/d net consumption.}$$

Expressed as net energy consumption per volume of treated flow, the Richmond prototype required 109 kWh/ML. The difference in pollutant concentration between the influent and the Settling Basin effluent was multiplied by the treated flow to determine mass removals, and net treatment energy requirements for

Richmond were expressed in terms of pollutant mass removed: 0.57 kWh/kg BOD_5, 3.6 kWh/kg N, and 32 kWh/kg P removed.

The net electrical energy requirements of the Richmond AIWPS expressed in terms of BOD_5 removal (0.57 kWh/kg BOD_5 removed) is lower than conventional mechanical treatment processes which require between 0.9 and 3.3 kWh/kg BOD_5 removed (Owen, 1982). Using methane production data from Richmond, equation (5), and more realistic estimations of recirculation power requirements, the energy balances for primary and secondary treatment in 2 MLD and 200 MLD second generation AIWPS were projected. More electrical energy could be generated than is required to operate second generation AIWPSs for primary and secondary treatment. Additional energy requirements for dissolved air flotation, filtration, and UV disinfection are shown in Table 3.

Table 3. Projected net energy production (+) for a 2 MLD and a 200 MLD second generation aiwps providing primary, secondary, and partial tertiary treatment and the additional energy requirements (-) for advanced treatment

Capacity	Primary and Secondary Treatment[1]	Dissolved Air Flotation & Filtration[2]	UV Disinfection[3]
MLD		kWh/ML kWh/kg BOD_5 removed	
2	+100 +0.52	-230 -1.1	-20 to -100
200	+110 +0.59	-230 -1.1	-20 to -100

[1] Net energy projections were based on data collected at the second generation AIWPS prototype at Richmond 1992-1994 and on the assumption of 50% VSS destruction in the in-pond digesters, 17° C average annual sludge temperature, 25% recirculation from HRP to AFP at 1 m of head with a 40% efficient pump, and supplemental surface aeration for 3 months each year.

[2] Additional DAF and filtration energy requirements were based on the DAF and filtration plant treating oxidation pond effluent at Stockton, California in 1994.

[3] Energy requirements provided by Elsag Bailey Canada, Inc. (1994) and Trojan Technologies, Inc. (1994). The range reflects various influent pathogen concentrations and effluent standards.

SUMMARY

During the two year operation of the second generation AIWPS prototype at Richmond, the energy requirements for HRP mixing and recirculation pumping were measured. Assuming 30% efficient electrical generation from recovered methane, the net energy requirement was determined to be 109 kWh/ML treated. In full-scale second generation AIWPSs producing secondary effluent, electricity generated at 30% efficiency from recovered methane would satisfy all of the energy requirements for HRP paddle wheel mixing, recirculation pumping, and supplemental surface aeration. Meeting unrestricted reuse effluent standards in California would require additional treatment energy. Even so, the treatment energy requirements of second generation AIWPSs are several times less than those of first generation AIWPSs and mechanical treatment processes. Second generation AIWPSs have the potential to reduce significantly energy consumption and associated environmental impacts in the wastewater treatment sector.

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