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A WASTEWATER TREATMENT MODEL FOR WASTE HEAT UTILIZATION ASSESSMENT*

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ABSTRACT

Thermal effluents from power plants can be used to accelerate the treatment of wastewater. Under controlled temperature conditions, retention time in anaerobic digesters and oxidation ponds is minimized. This article presents models for simulating the performance of anaerobic digesters, algae ponds, and the U-tube aeration system. Materials balances are provided for the fermentation of water hyacinths into ethanol and the production of clams and crayfish. Heat balances are performed for an anaerobic digester and for a water hyacinth pond with a protective plastic cover. Flow requirements are examined from both oxygen replenishment and metabolite reduction perspectives. Livestock manure and municipal wastewater can yield methane through anaerobic digestion, and ethanol through the fermentation of water hyacinths grown in wastewater. The nutrient-laden effluents can be used to produce algae, which serves as food for freshwater clams and crayfish. By simulating the biological treatment of wastewater as part of an integrated waste heat utilization complex, we are able to evaluate the benefits of thermal enrichment in terms of the valuable byproducts and waste treatment services provided.

Considerable amounts of low grade heat are rejected annually to the environment [1]. The temperature of this low grade heat is too low for most industrial processes, but it is ideal for living organisms. Fish, livestock, and plants grow faster at

* This is the seventh in a series of articles on the utilization of waste heat from power plants. The first article presented our methodology for site-specific assessment of technology options. Subsequent articles described models for simulating the aquaculture, evaporative pad greenhouse, livestock, surface heated greenhouse, and crop drying components of an integrated waste heat utilization complex. The final article in the series will present a summary of our findings.

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optimum temperatures, and require less nutrients. Biological waste treatment is accelerated, so a greater volume of wastes can be handled. Air flow requirements for crop drying can be reduced if the temperature of the air is elevated.

Further efficiency improvements can be obtained by linking together several operations into a single integrated complex. This mimics the natural cycling of nutrients among plants and animals, thereby minimizing both waste disposal and feed costs. Consider the arrangement shown in Figure 1.

The waste-laden effluent of the aquaculture facilities passes through a series of waste treatment ponds. The fish waste provides nutrients for water hyacinth and algae production. The water hyacinths are harvested mechanically and fermented into ethanol, while the algae are filtered biologically by clams in the clam and crayfish pond. The renovated water is aerated and returned to the aquaculture facility. Livestock shelters for broiler chickens and swine litters provide ample manure for the anaerobic digesters. Municipal sewage and refuse can be added as necessary to achieve the proper moisture content and chemical composition. The anaerobic digestion process yields methane gas, which can be burned to provide backup heating whenever waste heat supplies are inadequate. The liquid byproduct supernatant is treated in the algae pond, while the solid sludge portion becomes fertilizer for the greenhouses. This complex produces fish, shellfish, livestock, vegetables, flowers, ethanol, and methane for wholesale markets, and also provides waste treatment and crop drying services.

By varying the proportion of the complex which is devoted to each particular technology, we can adapt this arrangement to a specific site. We must consider power plant operating data, local market prices, anticipated weather conditions, biological production functions, and interconnections among the facilities in order to select the best configuration. This can be accomplished using simulation and optimization techniques [2-4].

In this article, we describe several models for simulating biological wastewater treatment facilities. Complete models are presented for anaerobic digesters and algae ponds. Materials balances are provided for the fermentation of water hyacinths into ethanol and the production of clams and crayfish. Heat balances are performed for an anaerobic digester and for a water hyacinth pond with a protective plastic cover. Flow requirements are examined from both oxygen replenishment and metabolite reduction perspectives. A U-tube aeration system is modeled to show how water can be oxygenated economically before being returned to the aquaculture facilities.

ANAEROBIC DIGESTERS

Municipal waste treatment facilities have long practiced anaerobic digestion of sludge, but the energy content of the gaseous byproducts has been overlooked in the past. Digester gas consists of two-thirds methane and one-third carbon dioxide, with a heating value of over 22,000 KJ/m^3 (600 Btu/ft^3). One Chicago

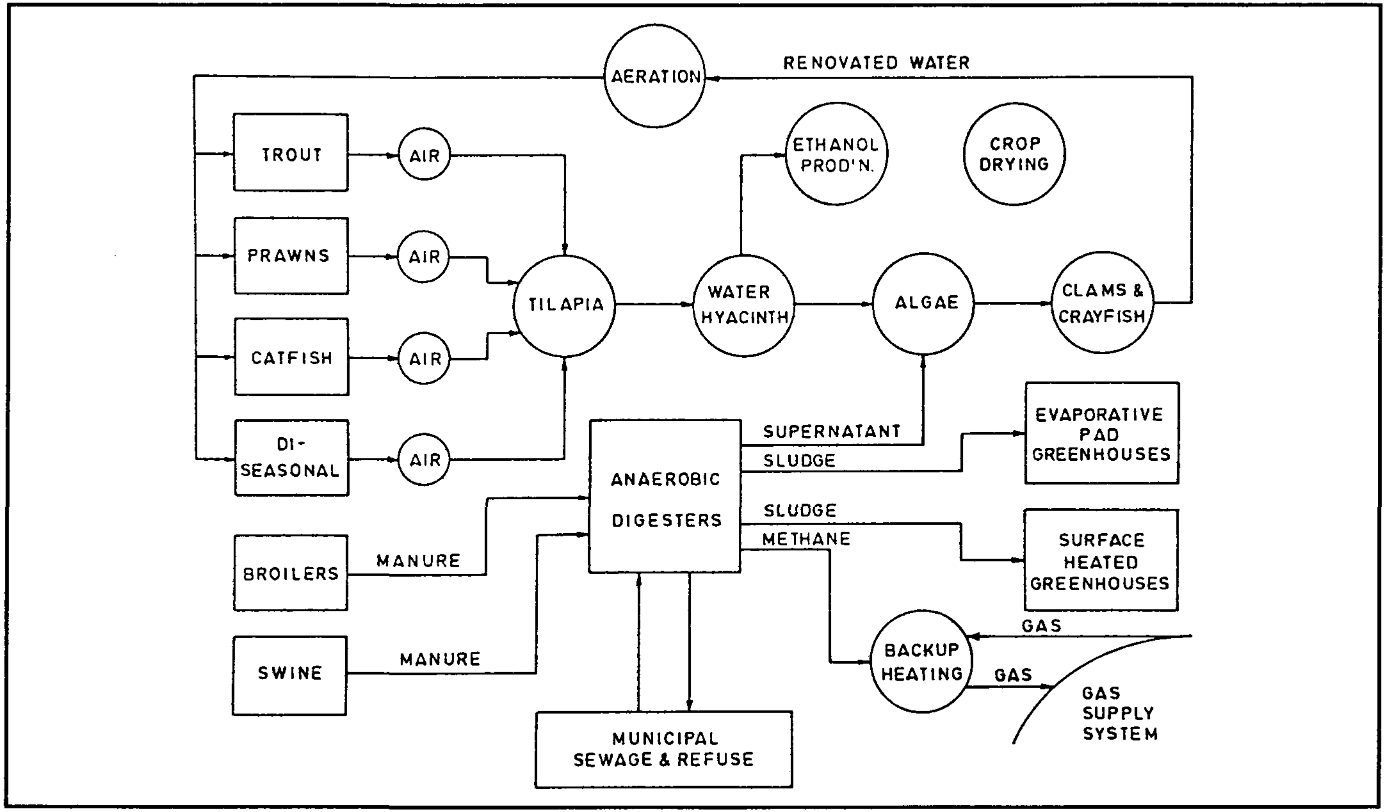

Figure 1. Integrated waste heat utilization facility.

facility currently produces 57,000 m^3/day (2,000,000 ft^3/day) of gas, of which about 66 percent is utilized and 33 percent is flared [5].

Anaerobic digestion has also been proposed as a means for disposing of solid wastes; it reduces volume without incineration and produces valuable gas. Production rates of approximately 0.035 m^3 gas/kg (0.56 m^3 gas/lb) of classified municipal solid waste have been reported [6]. It has been estimated that American livestock produce 42.6×10^9 kg/yr (47×10^6 tons/yr) of waste on a dry weight basis, which could product 72.6×10^{12} kcal/yr (285×10^{12} Btu/yr) of gas [7].

Algae and methane production complement each other well. By bubbling digester gas through active, alkaline algae cultures, carbon dioxide is removed, thus improving the quality of the gas while simultaneously boosting algae production by increasing the availability of CO_2 for photosynthesis [8].

Materials Balance

This model is based on the work of Merrill and Fry [9], who combined grassroots lore and field tests into a practical method for designing methane digesters. Leckie, Masters, Whitehouse, and Young elaborated upon this method [10]. We have adapted their technique, with some revisions.

For each substance i added to the digester the following information is needed:

W_i = weight of the portion, lb
M_i = moisture content of the portion, decimal
S_i = volatile solids (as a fraction of total solids), decimal
R_i = carbon:nitrogen ratio (of total solids), decimal
N_i = nitrogen content (as a fraction of total solids), decimal
$i = 1, 2, \ldots, n$ = subscript which indexes substances to be added to the digester

Table 1 provides this information for each of the substances which we will be handling. While we will only be dealing with three forms of waste (i = 1,2,3) and a carbon extender (subscripted by "c"), we will run the index from i to n in each of the formulae in order to keep the model general.

Table 1. Properties of Digester Inputs [2]

Material	M_i	S_i	R_i	N_i
Chicken manure	.76	.775	15	.063
Swine manure	.87	.85	18	.038
Raw sewage	.92	.67	11	.06
Municipal refuse	.073	.636	45	.0074

We want a mixture with a carbon:nitrogen ratio of 30:1 for optimal gas production. The manures and sewage are high in nitrogen; we will need to add a portion of carbon extender (municipal refuse) in order to satisfy:

$$R_{mix} = \frac{\text{total carbon}}{\text{total nitrogen}} = 30 \qquad (1)$$

where:

$$R_{mix} = \frac{\sum_{i=1}^{n}(1 - M_i)\, W_i N_i R_i + (1 - M_c)\, W_c N_c R_c}{\sum_{i=1}^{n}(1 - M_i)\, W_i N_i + (1 - M_c)\, W_c N_c} \qquad (2)$$

= carbon:nitrogen ratio of the mixture, decimal

We substitute $R_{mix} = 30$ into equation (2), solve for W_c, and simplify to obtain:

$$W_c = \frac{\sum_{i=1}^{n}(1 - M_i)\, W_i N_i\, (30 - R_i)}{(1 - M_c)\, N_c (R_c - 30)} \qquad (3)$$

Equation (3) gives the weight of carbon extender (municipal refuse) which must be added to bring the carbon:nitrogen ratio of the entire mixture (R_{mix}) up to 30.

For every other calculation, the carbon extender (formerly subscripted "c") is just an additional component (i = 4). We now have n + 1 components, with the extender included, so all of the summations from now on will run from i = 1 to n + 1.

The weight and moisture of these n + 1 components, when mixed, is obtained by:

$$W_{mix} = \sum_{i=1}^{n+1} W_i \qquad (4)$$

$$M_{mix} = \frac{\sum_{i=1}^{n+1} W_i M_i}{W_{mix}} \qquad (5)$$

where:

W_{mix} = weight of the mixture, lb
M_{mix} = moisture content of the mixture, lb water/lb total

We wish to add enough water to obtain a moisture content of 0.92. We add a quantity of water weighing W_{wat}:

$$\text{Desired moisture content} = 0.92 = \frac{W_{mix}M_{mix} + W_{wat}}{W_{mix} + W_{wat}} \tag{6}$$

where:

W_{mix} = weight of water added to mixture (1b)

We solve for W_{wat} then convert to volume of water V_{wat} by dividing by the density of water, which is approximately 62.3 lb/ft^3 at room temperature. This gives us equation (7). Thus, we must add (if positive) or remove (if negative) the following volume of water to the mix in order to form a slurry having a moisture content of 0.92:

$$V_{wat} = 0.1846\, W_{mix}(1 - 1.087M_{mix}) \tag{7}$$

where:

V_{wat} = volume of water to be added (removed), ft^3

The Chemical Oxygen Demand (COD) in ppm can be approximated as 0.75 times the volatile solids concentration:

$$\frac{\text{COD}}{.75} = \left[\frac{(\text{weight of volatile solids (lb)})\ \left(\text{conversion factor}\left(\frac{\text{ppm}}{\text{lb}/\text{ft}^3}\right)\right)}{(\text{weight of slurry (lb)}) + (\text{density of slurry }(\text{lb}/\text{ft}^3))}\right] \tag{8}$$

where:

COD = chemical oxygen demand (ppm)

The weight of the volatile solids in the slurry is

$$W_{vs} = \sum_{i=1}^{n+1} (1 - M_i)\, W_iS_i \tag{9}$$

where:

W_{vs} = weight of the volatile solids in the slurry, lb

The weight of the slurry is the weight of the original mix plus the weight of the water that has been added to it. We solve equation (6) for W_{wat}, add this to W_{mix}, and simplify to obtain:

$$W_{slurry} = \frac{W_{mix}\,(1 - M_{mix})}{0.08} \tag{10}$$

where:

W_{slurry} = weight of the slurry, lb

The density of the slurry can be approximated as $65\,\frac{\text{lb}}{\text{ft}^3}$ and the conversion factor as $16{,}000\frac{\text{ppm}}{\text{lb}/\text{ft}^3}$. We get:

$$\text{COD} = \frac{0.75\,(16000)\sum_{i=1}^{n+1}(1 - M_i)W_iS_i}{\left(\frac{1}{65}\right)\left(\frac{W_{mix}\,(1 - M_{mix})}{0.08}\right)} \tag{11}$$

We combine the numerical values to get our final equation for Chemical Oxygen Demand (COD) in ppm:

$$\text{COD} = \frac{62400\sum_{i=1}^{n+1}(1 - M_i)W_iS_i}{W_{mix}(1 - M_{mix})} \tag{12}$$

There is a minimum solids retention time (SRT_{min}), measured in days, which is dependent upon temperature and bacterial metabolism. Below this critical value, bacterial digestion cannot keep pace with the solids loading rate [10]:

$$SRT_{min} = \left[\left(ak\left(1 - \sqrt{\frac{K_c}{K_c + \text{COD}}}\right) - b\right)\right]^{-1} \tag{13}$$

where:

a = bacterial conversion constant (approximately 0.04), decimal
b = bacterial mortality constant (approximately 0.015), decimal
$k = 3.366\,e^{0.19(T_d - 59)}$ (14)
= digestion rate factor, day^{-1}
$K_c = \exp\left[7.712 + 0.059\,(95 - T_d)\right]$ (15)
= minimum COD requirement for growth (ppm)
T_d = digester temperature, °F

In practice, SRT_{min} must be multiplied by a safety factor to allow enough time for complete digestion. There is no simple formula for finding the correct safety factor. For a well-controlled digester operating at the optimum temperature of 95°F (35°C), the safety factor is about 3. This value is supported by numerous studies [11].

The number of 3531 ft^3 (100m^3) digesters needed is:

$$\mathrm{ND} = \frac{\left(\text{weight of slurry}\left(\frac{\text{lb}}{\text{day}}\right)\right)\left(\text{density of slurry}\left(\frac{\text{ft}^3}{\text{lb}}\right)\right)\left(\text{safety factor}\right)\left(\mathrm{SRT_{min}}\right)}{(\text{volume of an individual digester})} \qquad (16)$$

Now we can substitute values for the weight of the slurry (equation (10)), the density of the slurry (65 lb/ft^3), and the volume of an individual digester (3531 ft^3) into equation (16) to arrive at:

$$\mathrm{ND} = \frac{W_{mix}(1 - M_{mix})\ \mathrm{SF}\ (\mathrm{SRT_{min}})}{18361.2} \qquad (17)$$

where:

SF = safety factor (about 3), dimensionless
ND = the number of digesters needed
$\mathrm{SRT_{min}}$ = minimum solids retention time, days

After digestion, the dry weight of the sludge solids remaining will be:

$$W_{solids} = W_{mix}\ (1 - M_{mix})\left(1 - \frac{\mathrm{COD}}{124800}\right) \qquad (18)$$

The dry weight of the bacteria produced will be:

$$W_{bact} = \frac{0.04\ (\mathrm{COD})\ W_{mix}\ W(1 - M_{mix})}{83200\ (0.015\ \mathrm{SF}(\mathrm{SRT_{min}}) + 1)} \qquad (19)$$

The weight of the solid matter in the sludge emerging from the digester will be the sum of the dry weight of the bacteria and the dry weight of the solids remaining. Since the digester sludge will have a moisture content of .90 (that is, 10% solids by weight), the weight of the sludge will be ten times that sum:

$$W_{sludge} = 10\ (W_{solids} + W_{bact}) \qquad (20)$$

where:

W_{sludge} = total weight of sludge, lb
W_{solids} = dry weight of sludge solids, lb
W_{bact} = dry weight of bacteria, lb

Combining equations (18), (19), and (20), we get:

$$W_{sludge} = 10\ W_{mix}\ (1 - M_{mix})\left[1 - \frac{\mathrm{COD}}{124800}\left(1 - \frac{0.06}{1 + 0.015\ \mathrm{SF}(\mathrm{SRT_{min}})}\right)\right] \qquad (21)$$

The volume of methane produced can be estimated by:

$$V_{meth} = \frac{5.62\,(COD)\,W_{mix}\,(1 - M_{mix})}{83200}\left[0.6 - \frac{0.0568}{1 + 0.015\,SF(SRT_{min})}\right] \qquad (22)$$

where:

V_{meth} = volume of methane gas produced, measured at 32°F and 14.7 psi, ft^3

Finally, the weight of the supernatant (the liquid remaining after digestion) will be the weight of the material entering the digester minus the weight of the sludge and of the biogas. Note that for each cubic foot of methane produced, there are 0.5 ft^3 of CO_2 and 0.083 ft^3 of water vapor. These volumes can be converted into weights by multiplying by the densities of the gases. The total weight of the biogas is roughly proportional to the volume of methane produced. By subtracting the weight of the sludge and the weight of the biogas from the weight of the slurry, equation (10), we obtain:

$$W_{supnat} = 12.5\,W_{mix}\,(1 - M_{mix}) - (W_{sludge} + 0.022\,V_{meth}) \qquad (23)$$

where:

W_{supnat} = weight of the supernatant, lb

To summarize, given any number of digester inputs, we are able to design and predict the performance of an anaerobic digestion system. We need to have data on the properties of the digester inputs, such as in Table 1. We are able to figure out how much carbon extender (municipal refuse) and water should be added to the mixture (equations (3) and (7)). We can calculate how many of the 3531 ft^3 digester modules will be needed, equation (17). Finally, we are able to calculate the total output of sludge, methane gas, and supernatant, equations (21), (22), and (23).

Heat Balance

Figure 2 shows a simple heat balance for an anaerobic digester. This diagram, and equations (24) through (28), are based on an analysis by Lavagno, Ravetto, and Ruggeri [12]:

$$H_t = H_r + H_a + H_b + H_f \qquad (24)$$

where:

H_r = heat lost through roof, Btu/hr
H_a = heat lost through wall above ground, Btu/hr
H_b = heat lost through wall below ground, Btu/hr
H_f = heat lost through floor, Btu/hr
H_t = total heat lost, Btu/hr

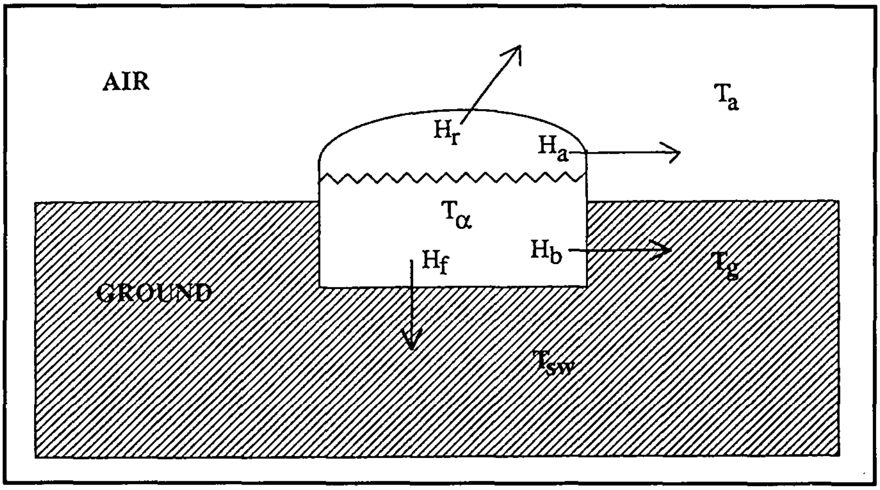

Figure 2. Anaerobic digester heat balance.

These are all of the same form:

$$H_r = U_r A_r (T_d - T_a) \tag{25}$$

$$H_a = U_a A_a (T_d - T_a) \tag{26}$$

$$H_b = U_b A_b (T_d - T_g) \tag{27}$$

$$H_f = U_f A_f (T_d - T_{gw}) \tag{28}$$

where:

T_a = air temperature, °F
T_d = digester temperature, °F
T_g = ground temperature (to depth of 3 ft), °F
T_{gw} = ground-water temperature (below depth of 3 ft), °F

Table 2 gives values for the heat transfer coefficients (U_r, U_a, U_b, U_f) and surface areas (A_r, A_a, A_b, A_f) of a single 100 m^3 (3531 ft^3) digester module. These values are based on experiments conducted at the Pennsylvania State University on a 100 m^3 (3531 ft^3) prototype digester [13].

Recall that these digesters are being heated using thermal effluents from power plants. If we assume that the warm water exits the digesters at temperature T_d, we can calculate the flow requirements as follows:

$$\dot{m}_d = \frac{ND \times H_t}{c(T_h - T_d)} \tag{29}$$

Table 2. Digester Heat Transfer Information [13]

Section	Area (ft^2)	Heat Transfer Coefficient $\left(\frac{Btu}{hr\text{-}ft\text{-}°F}\right)$
Roof	$A_r = 505.72$	$U_r = .05283$
Wall (above ground)	$A_a = 376.60$	$U_a = .06868$
Wall (below ground)	$A_b = 624.08$	$U_b = .06868$
Floor	$A_f = 312.04$	$U_f = .09510$

where:

$\dot{m}_d$ = mass flow rate of thermal effluent used to heat the digesters, lb/hr

H_t = heat lost by a single digester module, Btu/hr

c = specific heat of water = 1.00, Btu/lb-°F

T_h = temperature of thermal effluent entering digester heat exchangers, °F

T_d = digester temperature, °F

WATER HYACINTHS

Aquatic macrophytes such as duckweed and water hyacinth have been studied as biological waste treatment agents. Removal rates of nitrogen, phosphorus, and BOD by water hyacinth indicate that a 1 ha (2.5 ac) plantation could treat the wastes of 500 people [14].

Water hyacinth productivity is phenomenal. Harvests of 20 to 40 metric tons per hectare-day (9 to 18 ton/ac-day) of wet water hyacinths, yielding 600 kg/ha-day (535 lb/ac-day) of dry matter, are possible using sewage fertilization [15]. Water hyacinth systems already in use include sewage treatment for Lucidale, Mississippi (population 2500) and cattle feeding trials by N.A.S.A.'s National Space Technology Laboratory [16].

Many of these highly productive plants are also quite nutritious. For example, 1 ha (2.5 ac) of the water willow *Justica americana* can supply the protein requirements of 300 people [17]. They have also been judged as being superior to conventional livestock forage in acidity and protein content, but the 85 to 95 percent water content necessitates extensive dehydration [18].

The water hyacinths in our integrated waste heat utilization complex serve as a means of waste treatment and as a source of cellulose. This cellulose is used as the raw material in ethanol production. Water emerging from the aquaculture facilities passes through the water hyacinth ponds on its way to the algae ponds. The hyacinths remove nutrients from the water and grow at a rapid rate. They are harvested mechanically and then chopped into a mash which is fed into the ethanol fermenters. Thermophilic bacteria produce ethanol, which is then concentrated by distillation.

Both waste treatment by water hyacinth and Direct Microbial Conversion (DMC) of cellulose to ethanol are fledgling technologies. Therefore, their materials balances will be based upon the yields and rates which have come out of the initial experiments.

Materials Balance

Under the nutrient loading conditions of the effluent from the tilapia pond, a maximum productivity of 25 m/m^2-day dry weight (463 g/m^2-day wet weight) should be expected [19]. Residence times of less than five days lead to maximum productivity of the hyacinth biomass [20]. A depth of 0.33 m (13 inches) has been shown to provide the best quality effluent [21].

Much of the treatment is carried out by the zooplankton inhabiting the roots of the water hyacinth, rather than by the plant itself [22]. Due to "leakage" of organic matter from the plants, the effluent BOD cannot fall below 5 ppm [21].

Over a wide range of BOD levels, 60 percent of the remaining BOD is removed per day of detention time. This can be expressed as a reaction rate equation:

$$L = L_0 (1 - e^{-0.025t}) \tag{30}$$

where:

L = final BOD concentration, ppm
L_0 = initial BOD concentration, ppm
t = time, hr

The water hyacinth BOD removal equation, equation (30), forms an important link between the aquaculture facilities and the treatment facilities. As we shall see, the algae, clam, and crayfish production are all dependent on the incoming BOD.

In an earlier article, a materials balance was performed for an evaporative pad heated greenhouse [23]. The growth of vegetables and flowers in the greenhouse was represented by the logistic equation:

$$\frac{dX}{dt} = rX\left(1 - \frac{X}{K}\right) \tag{31}$$

where:

X = quantity of plant biomass, lb
K = carrying capacity, lb
r = intrinsic rate of natural increase, hr^{-1}

The growth rate depends upon the availability of nutrients, sunlight, space, and optimum temperature. There will be sufficient nutrients in the aquaculture

Table 3. Water Hyacinth Growth Parameters [2]

K = carrying capacity = 4073 lb dry weight/acre
r_{max} = maximum growth rate = 0.003635 hr^{-1}
t_{harv} = time of harvest = 1752 hr (when $r = r_{max}$)
X_{harv} = weight at time of harvest = 3380 lb dry weight/acre
X_0 = weight at time of planting = 34 lb dry weight/acre

effluent, and optimum temperature will be maintained by the double polyethylene cover and thermal effluent in underwater pipe heat exchangers. Equation (31) predicts slower growth of the water hyacinths as the carrying capacity is approached, which is accounted for by crowding. The limiting factor will most likely be the availability of sunlight, which can be modeled by:

$$r = 0.3\, r_{max} \left[\ln \left(\frac{2.71\tau S}{600} \right) + 1 \right] \tag{32}$$

where:

r_{max} = maximum growth rate, hr^{-1}
τ = solar radiation transmittance, decimal
S' = total insolation, $Btu\text{-}ft^{-2}\text{-}d^{-1}$

Equation (32) is similar to the equation used to model the growth of vegetables and flowers [23], but modifications were made to account for the higher optimum light levels of water hyacinths.

The growth rate determines the time-to-harvest [23]:

$$t_{harv} = \frac{1}{r} \ln \left[\frac{X_{harv}\,(K - X_0)}{X_0\,(K - X_{harv})} \right] \tag{33}$$

where:

t_{harv} = time of harvest, hr
X_{harv} = weight at time of harvest, lb
X_0 = weight at time of planting, lb

The data needed to apply this growth model are contained in Table 3.

Heat Balance

Since the water hyacinths float above the surface of the water, in most areas it is necessary to provide a protective covering to ensure the rapid yields which are commonplace in the tropics. This arrangement is shown in Figure 3.

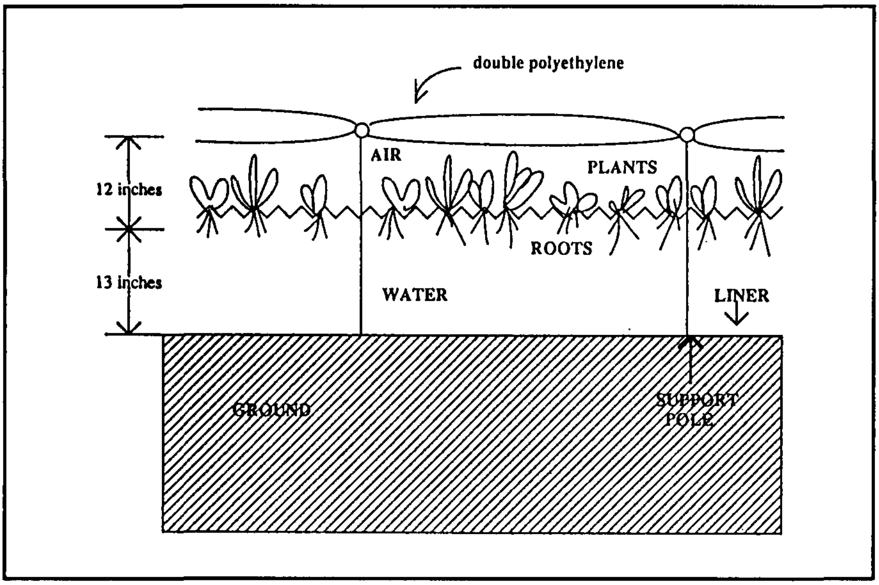

Figure 3. Protective cover for water hyacinths.

We can treat this system as a greenhouse with a water floor. Therefore, we can use the heat balance which was developed for the evaporative pad greenhouse [23], with some minor modifications.

The heat balance for the water hyacinth pond is:

$$H_w = H_c + H_d + H_v - H_s \tag{34}$$

where:

H_w = total heat lost by water hyacinth pond, Btu/hr
H_c = heat lost by conduction, Btu/hr
H_d = heat lost by thermal radiation, Btu/hr
H_v = heat lost by ventilation, Btu/hr
H_s = heat gained by solar radiation, Btu/hr

Heat is lost by conduction through the double polyethylene roof ($U = 0.56$), the double polyethylene above-ground wall ($U = 0.56$), the below-ground sides of the pond ($U = 0.1$), and the bottom of the pond ($U = 0.1$). Since the sides of the pond are approximately one foot high above ground and one foot deep below ground, we can use the perimeter of the pond as the area of the walls which are above ground and as the area of the sides which are below ground.

Therefore:

$$H_c = 0.56A\,(T_i - T_a) + 0.56(T_i - T_a) + 0.1P(T_i - T_g) + 0.1A(T_i - T_{sw}) \qquad (35)$$

where:

T_i = temperature of water hyacinth ponds, °F
T_{sw} = surface water temperature, °F
A = area of water hyacinth ponds, ft^2
P = perimeter of water hyacinth ponds, ft

For example, if each water hyacinth pond is square and covers an area of 36100 ft^2, then the perimeter of each pond is 760 ft.

The heat lost by radiation is:

$$H_d = 8.35 \times 10^{-10}A[\,0.9(T_i + 460)^4 - 0.82(T_a + 460)^4\,] \qquad (36)$$

where the factor 8.35×10^{-10} includes the Stefan-Boltzman constant (1.714×10^{-9} $Btu\text{-}hr^{-1}\text{-}ft^{-2}\text{-}°F^{-4}$) and the thermal transmittance of double polyethylene (0.4872).

The heat lost by ventilation is:

$$H_v = 0.0135A\,(T_i - T_a) + 58.9A(w_i - w_a) \qquad (37)$$

where:

w_i = specific humidity of air inside enclosure, lb H_2O/lb air
w_a = specific humidity of ambient air, lb H_2O/lb air

Equation (37) assumes 75 percent of the air changes each hour due to infiltration. The temperature term calculates sensible heat loss based on the specific heat of air; the specific humidity term calculates latent heat loss based on the heat of vaporization of water.

The solar heat gain is given by:

$$H_s = 0.6237AI \qquad (38)$$

where:

I = solar intensity on a horizontal surface.

The factor 0.6237 includes the solar radiation absorptivity of the plants (0.77) and the overall transmittance of the double polyethylene (0.81).

Using equations (34) through (38), we are able to calculate the net heat loss from the water hyacinth ponds to their surroundings. This heat must be replenished by circulating thermal effluent through pipes submerged at the bottom of the ponds.

A complete analysis of the submerged pipe heating system was presented in an earlier article on the aquaculture components of the integrated waste heat utilization complex [24]. However, we can calculate the approximate flow requirements as follows:

$$\dot{m}_h = \frac{H_w}{c(T_h - T_i)} \tag{39}$$

where:

$\dot{m}_h$ = mass flow rate of thermal effluent used to heat water hyacinth ponds, lb/hr
c = specific heat of water = 1.00, Btu/lb-°F
T_h = temperature of thermal effluent entering heat exchangers, °F

We have assumed that the thermal effluent exits the submerged pipes at the temperature of the water hyacinth ponds, T_i. Compared with the other aquaculture facilities, the water hyacinth ponds have a substantially lower heat loss, due to the protective double polyethylene cover.

ETHANOL PRODUCTION

Three conversion technologies are available for converting cellulose to ethanol–these are acid hydrolysis, enzymatic hydrolysis, and direct microbial conversion. Acid hydrolysis requires either high temperatures or high acidity; both conditions have economic disadvantages. Enzymatic hydrolysis is a complex procedure, and each stage requires a separate reaction apparatus. The advantage of direct microbial conversion is that all steps except distillation can be carried on simultaneously in a single reaction vessel [25].

Although direct microbial conversion (DMC) technology is relatively new, its future appears promising. It is particularly well suited to our needs for two additional reasons–the process temperature of 60°C (140°F) is only slightly above thermal effluent temperatures, and the high water content of the water hyacinth feedstock is not an obstacle. Water hyacinth contains 55 percent cellulosics and 6 percent lignin on a dry weight basis. The moisture content of water hyacinth is a very high 95 percent [26]. It will be necessary to lower the moisture content to 90 percent and to chop the hyacinth into small pieces. Special cutters and presses are available for this task.

Materials Balance

The formula for the DMC process is [27]:

$$\begin{aligned} &C_6H_{10}O_5 + 0.74\ H_2O + 0.257\ NH_4OH \rightarrow \\ &0.257\ C_5H_7NO_2 + 0.783\ C_2H_5OH \\ &+ 0.783\ CH_3COOH + 1.57\ H_2 + 1.57\ CO_2 \end{aligned} \tag{40}$$

Table 4. Ethanol Production Materials Balance [27]

Substance	*Pounds of Substance Per Pound of Cellulose*
Reactants	
cellulose	1.000
water	0.082
ammonium hydroxide	0.056
Products	
cell matter	0.179
ethanol	0.222
acetic acid	0.290
hydrogen	0.019
carbon dioxide	0.426
Nonreactants	
lignin	0.108
miscellaneous	0.805

Note: Nonreactant water is not included.

Table 4 gives the weights of the various substances in proportion to the weight of cellulose.

Based on the assumptions of twenty-four-hour batch operation and on the materials balance listed in Table 4, we can calculate that a single 100 m^3 (3531 ft^3) digester can produce a maximum of 2691 lb/day (408 gal/day) of ethanol.

Besides the ethanol, which can be blended with gasoline to form gasohol, the DMC process has several valuable byproducts. Carbon dioxide from ethanol production has been used in greenhouses to boost plant production by 10-20 percent [28]. The nonreactants include crude protein, fat, fiber, and ash. Properly treated, these byproducts may be sold as a livestock feed extender [29]. A ready market also exists for the acetic acid. The hydrogen can be used to fuel the distillation process, which is necessary to isolate the ethanol.

ALGAE PONDS

Nutrient-laden wastewater, which can cause severe eutrophication if discharged into a waterway without treatment, is an excellent growth medium for algae. Normally, settleable solids are removed by sedimentation to be treated by anaerobic digestion, and the clarified wastewater flows into a pond which is 20 to 40 cm (7.9 to 15.7 in) deep. Such a pond is shallow enough to allow sunlight to penetrate through the entire depth. High-rate algae ponds in tropical regions may be loaded to 350 kg/ha-day (308.7 lb/ac-day) and still have an effluent with a BOD of less than 20 mg/l after filtration. Conversion of nutrients to algae may take as little as three to four days. Productivity varies widely, but 30 g/m^3-day (0.00615 lb/ft^2-day) of dry matter is about average. This corresponds to 109 t/ha-yr (48 tons/ac-yr) of dry matter production, which would contain 49 t/ha-yr (21.61 tons/ac-yr) of protein. This is a 37-fold better protein yield than that of soybeans [30].

The effluent from the water hyacinth ponds and the supernatant from the anaerobic digesters both flow into the algae ponds. Pumps recirculate the water continuously, to promote higher biological efficiency and nutrient recovery by thorough mixing. By allowing better access to the light at the surface and the nutrients on the bottom of the pond, the overall yield is improved. Mixing also helps maintain dissolved oxygen at acceptable levels during the hours of darkness.

Materials Balance

We can fit the following curve to experimental data presented by Oswald and Gotaas [31]:

$$C_c = 325\left(1 - e^{\frac{-L_t}{140}}\right) \tag{41}$$

where:

C_c = algal cell concentration, ppm
L_t = biochemical oxygen demand concentration, ppm

A suspension of algal cells absorbs light according to the Beer-Lambert Law [32]:

$$\frac{I_d}{I_i} = e^{-C_c \alpha d} \tag{42}$$

where:

I_d = light intensity at depth d, footcandles
I_i = incident light intensity, footcandles
d = depth of the algae pond, cm
α = empirically determined constant (approximately 1.5×10^{-3}), dimensionless

The depth of the pond will be determined by the effective depth of light penetration. To achieve maximum utilization of the organic wastes, the pond should be no deeper than the light penetration. At the bottom of the pond, I_d is approximately zero. We set $I_d = 1$ at depth d for convenience, since then $\ln(I_d) = \ln(1) = 0$ at depth d. Taking the natural log of both sides of equation (42) and solving for d, we find:

$$d = \frac{\ln I_i}{\alpha C_c} \qquad (43)$$

The photosynthetic efficiency of energy conversion is the ratio between the stored energy content of the organic matter synthesized and the total solar energy incident upon the pond [31]:

$$F = \frac{\text{energy stored in organic matter}}{\text{energy available from light}} \qquad (44)$$

$$F = \frac{C_h C_c d A_a}{1000 S \theta A_a} \qquad (45)$$

where:

F = photosynthetic efficiency of energy conversion, decimal
C_h = heat of combustion of algae (approximately 6), cal/mg
S = Insolation on pond, cal/cm^2-day
A_a = area of algae pond, cm^2
θ = detention time, days

$$1000 = \text{conversion factor} = \left(\frac{1000 \text{ cm}^3}{1 \text{ liter}}\right) \times \left(\frac{1 \text{ ppm}}{1 \text{ mg/l}}\right)$$

Next, we note that F is a function of temperature. Therefore, we introduce a temperature coefficient T_c such that:

$$F = f T_c \qquad (46)$$

where:

f = maximum photosynthetic efficiency (approximately 0.05, from [33]), decimal
T_c = temperature coefficient, decimal

The temperature coefficient relates the photosynthetic efficiency to the water temperature [2]:

$$T_c = \frac{T_w^3 - 136 T_w^2 + 3328 T_w}{-88128} \qquad (47)$$

where:

T_w = water temperature in algae pond, °F

If we combine equations (45) and (46) and solve for θ, we arrive at:

$$\theta = \frac{h d C_c}{1000 f T_c S} \qquad (48)$$

Field tests indicate that this detention time will result in a BOD removal efficiency of 0.80 [32].

Finally, we can calculate the minimum area of algae ponds required to treat a given flow rate of influent:

$$A_{ma} = \frac{\theta \, Q_a}{0.03281 \, d} \tag{49}$$

where:

A_{ma} = minimum algae pond area, ft^2
Q_a = flow rate of influent, ft^3/day
0.03281 = conversion factor, ft/cm

CLAMS AND CRAYFISH

Harvesting and processing algae is a difficult, costly operation, and its economic viability depends on the existence of a market for raw algae [34]. Biological processing (allowing filter-feeders such as clams to consumer the algae, and then harvesting the filter-feeders) sidesteps this issue, and provides valuable waste treatment as well. The economic feasibility of clam production from algae has been demonstrated, and water emerging from such facilities is sufficiently clarified to meet EPA discharge regulations [1].

Nutrients lost in the form of clam waste may be partially recovered using crayfish ("freshwater lobsters"), which feed on this waste.

Materials Balance

Since the nutritive value of algae is extraordinarily high, and since the clams are highly efficient, a food conversion efficiency of 2:1 is common. Thus, for each pound of algae contained in the influent to the clam/crayfish pond, a half-pound of clam meat will be produced, along with a half-pound of clam waste. Since the clam waste is relatively inert, only a tenth of a pound of crayfish is produced for each pound of clam waste [35].

We know the cell concentration of the algae in the influent from equation (41). We can calculate the mass inflow of algae using:

$$P_A = 6.2447 \times 10^{-5} \, Q \, C_c \tag{50}$$

where;

P_A = mass inflow of algae, lb/day
C_c = algal cell concentration, ppm
Q = flow rate of influent from the algae pond, ft^3/day
6.2447×10^{-5} = conversion factor, lb/ppm-ft^3

Therefore, the production of clam meat is one-half of this, and the production of crayfish is one-twentieth of this:

$$P_{cl} = 3.122345 \times 10^{-5}\, Q\, C_c \tag{51}$$

$$P_{cr} = 3.122345 \times 10^{-6}\, Q\, C_c \tag{52}$$

where:

P_{cl} = production of clam meat, lb/day
P_{cr} = production of crayfish, lb/day

These formulae yield estimates which are consistent with the results of numerous experiments and field tests [35].

There is a space requirement, since clams and crayfish are benthic (bottom-dwelling) creatures. Approximately 158.94 ft^2 are needed for each lb/day of clam production [36].

Therefore:

$$A_{min} = 158.94\, P_{cl} \tag{53}$$

where:

A_{min} = minimum area of clam/crayfish pond, ft^2
158.94 = space requirement factor, ft^2-day/lb

Crayfish ponds are generally about three feet deep [1].

WATER RECIRCULATION

Water will be recirculated through the ponds for several reasons. First, the water is of high quality after passing through the waste treatment ponds. It is likely that this is the best source of clean water available. Second, the water has already become heated to optimum growth temperatures. Third, there is less waste, and no need for either discharge permits or a sizeable water diversion. The reader may wish to look at Figure 1 to be reminded of the interconnections between the various facilities.

The rate of flow of water through the system will depend primarily on the levels of ammonia nitrogen, dissolved oxygen, and biochemical oxygen demand (BOD). Metabolite production and oxygen consumption by the fish are directly related to the feeding rate [37]:

$$N_A = 0.0289\, F_R \tag{54}$$

$$BOD = 0.60\, F_R \tag{55}$$

$$O_c = 0.538\, F_R \tag{56}$$

where:

N_A = ammonia nitrogen production, $\frac{\text{kg NH}_4-\text{N}}{\text{100 kg fish-day}}$

BOD = biochemical oxygen demand, $\frac{\text{kg BOD}}{\text{100 kg fish-day}}$

O_c = oxygen consumption, $\frac{\text{kgO}_2}{\text{100 kg fish-day}}$

F_R = feeding rate, $\frac{\text{kg food}}{\text{100 kg fish-day}}$

The minimum flow rate needed to cleanse the metabolite from the pond or raceway follows from:

$$Q_{min} = 1 \times 10^8 \left(\frac{M\,G\,V}{B_0 - B_i}\right) \tag{57}$$

where:

M = metabolite production (BOD or ammonia nitrogen), $\frac{\text{kg metabolite}}{\text{100 kg fish-day}}$

Q_{min} = minimum flow rate, L/d

G = density of fish in the pond or raceway, kg fish/L

V = volume of the pond or raceway, L

B_i = metabolite concentration at the inlet, mg/L

B_o = metabolite concentration at the outlet, mg/L

The effluent from the clam/crayfish pond, which is the influent to the prawn, trout, or catfish raceways, serves as a benchmark. The lower limit on nutrient removal in a biological recirculating system is approximately 0.2 mg/l for ammonia nitrogen, and 4 mg/L for BOD [19]. The minimum acceptable dissolved oxygen level for aquaculture is 5 mg/L and the maximum recommended BOD level is 20 mg/L [38]. In the raceways, the ammonia nitrogen should be no more than 0.5 mg/L [37]. The effluent from the algae and clam/crayfish ponds will be approximately 25°C (77°F), since this is a heated aquaculture system. At this temperature, the saturation concentration of oxygen is 8.4 mg/L [37]. This data are summarized in Table 5.

We calculate three minimum flow rates using equation (57), using the values of B_o and B_i which are given in Table 5. In place of M, we use the ammonia nitrogen production, equation (54), the biochemical oxygen demand production, equation (55), or the oxygen consumption, equation (56). This gives us three minimum flow rate equations:

$$Q_{mn} = 9.633 \times 10^6 F_R G V \tag{58}$$

$$Q_{mb} = 3.75 \times 10^6 F_R G V \tag{59}$$

$$Q_{mo} = 15.82 \times 10^6 F_R G V \tag{60}$$

Table 5. Data for Determination of Flow Rates

Water Quality Factor	*B_i (mg/l) Inlet of Raceways*	*B_O (mg/l) Inlet of Raceways*
N_A (ammonia nitrogen)	0.2 (minimum attainable)	0.5 (maximum allowable)
BOD (biochemical oxygen demand)	4.0 (minimum attainable)	20.0 (maximum allowable)
O_c (dissolved oxygen)	8.4 (minimum attainable)	5.0 (minimum allowable)

where:

Q_{mn} = minimum flow rate to ensure acceptable ammonia nitrogen, L/d
Q_{mb} = minimum flow rate to ensure acceptable BOD, L/d
Q_{mo} = minimum flow rate to ensure acceptable dissolved oxygen, L/d

We choose the largest of the minimum flow rates, Q_{mo}, which ensures that all three concentrations will be acceptable.

U-Tube Aeration System

The U-tube aerator has by far the highest energy efficiency of the aeration systems used in aquaculture [39]. It also has low maintenance and space requirements, along with low construction costs [40]. Figure 4 shows how a U-tube operates.

The U-tube aerator consists of a deep hole, divided by a baffle, through which water is drawn in a U-shaped path. The head at the entrance to the tube provides a siphoning action which draws water to the bottom of the shaft and then back up to the surface. Air bubbles are injected at the entrance. The water velocity is designed to exceed the buoyant velocity of the bubbles. Thus, the bubbles are drawn beneath the baffles where they experience high pressures. This increases the saturation concentration of dissolved oxygen and consequently increases the driving force for oxygen transfer. Complete saturation is readily achieved [41].

A regression equation describing U-tube performance was obtained by Speece and Orosco [41]:

$$P_o = 20 + 0.76\, P_i + 295\, R + 0.47\, D - 2.5\, P_i R \qquad (61)$$

where:

P_o = percentage of oxygen saturation at the outlet
P_i = percentage of oxygen saturation at the inlet
R = air-to-water volume ratio
D = depth of the U-tube, ft

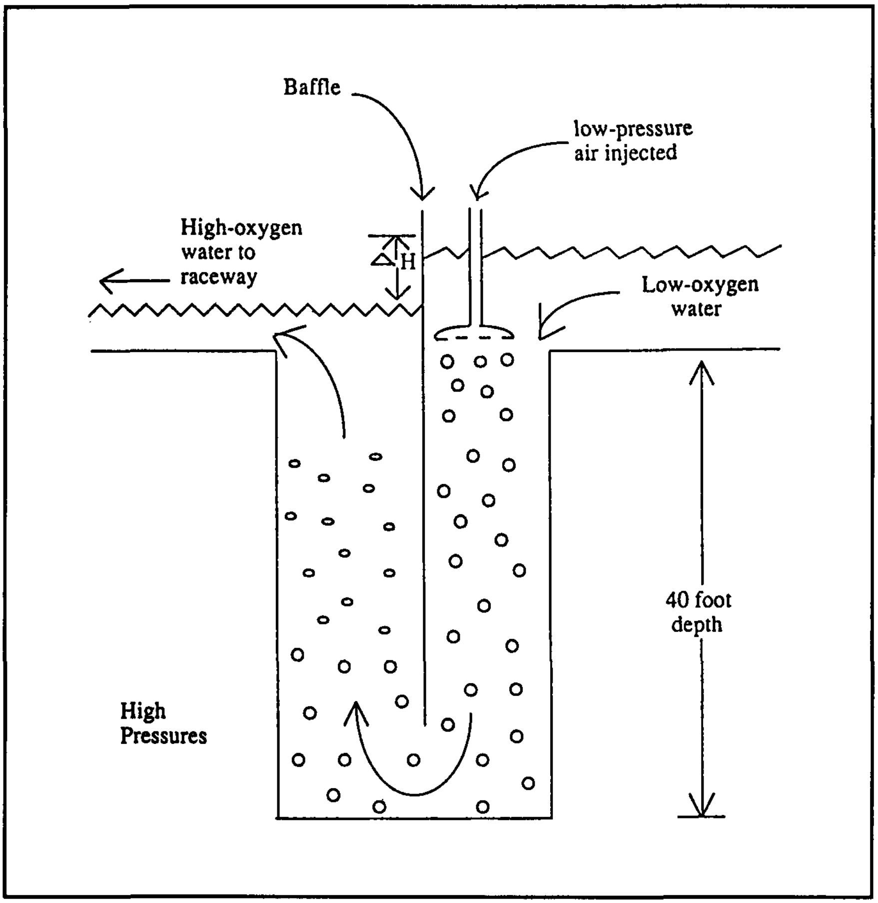

Figure 4. Diagram of a U-tube aerator.

We want the water to be completely saturated when it enters the raceways, since we want to maintain the oxygen level with the smallest water flow possible. It takes less power to force additional air into the water than it takes to pump additional water through the system. For these reasons, a U-tube depth of 40 feet is recommended. This is deep enough so that complete saturation can be achieved using relatively low air-to-water ratios, and yet not so deep that construction costs become prohibitive.

The buoyancy of the air bubbles opposes the passage of the water through the U-tube. Therefore, additional pumping head is required to overcome this retarding force. The pumping head required is a function of the air-to-water ratio.

According to tests by Speece, Adams, and Wooldridge [42], the head needed to force the air downward is approximately:

$$h = 17.4\,R^{1.32} \qquad (62)$$

where:

h = additional pumping head required, ft

For example, with a typical air-to-water ratio of 0.20, the additional pumping head required is 2.08 ft.

SUMMARY AND CONCLUSIONS

To aid in the design of integrated waste heat utilization complexes, several wastewater treatment models have been developed. A materials balance for the anaerobic digesters enables us to maximize methane production by optimizing the moisture content and carbon to nitrogen ratio of the incoming waste. The yield of water hyacinths can be predicted using a plant growth model. These water hyacinths can be converted into ethanol and other valuable products, as specified by a materials balance. The growth of algae is related to photosynthetic efficiency and nutrient availability. The cell concentration of algae, in turn, determines the yield of clams and crayfish.

Heat balances are presented for the anaerobic digesters and the covered water hyacinth ponds. A heat balance applicable to uncovered ponds, such as the algae and clam/crayfish ponds, was presented in an earlier article [24].

The flow requirements are determined by the needs of the aquaculture facilities, which must maintain high levels of dissolved oxygen. This can be accomplished by a U-Tube aeration system, which has been described.

NOMENCLATURE

A = area of water hyacinth ponds, ft^2
A_a = area of algae pond, cm^2
A_{ma} = minimum algae pond area, ft^2
A_{min} = minimum area of clam/crayfish pond, ft^2
B_i = metabolite concentration at the inlet, mg/liter
B_0 = metabolite concentration at the outlet, mg/liter
BOD = biochemical oxygen demand, (kg BOD/100 kg fish-day)
C_c = algal cell concentration, ppm
C_h = heat of combustion of algae (approximately 6), cal/mg
COD = chemical oxygen demand (ppm)
D = depth of the U-tube, ft
F = photosynthetic efficiency of energy conversion, decimal

F_R = feeding rate, (kg food, 100 kg fish-day)
G = density of fish in the pond or raceway, kg fish/liter
H_a = heat lost through wall above ground, Btu/hr
H_b = heat lost through wall below ground, Btu/hr
H_c = heat lost by conduction, Btu/hr
H_d = heat lost by thermal radiation, Btu/hr
H_f = heat lost through floor, Btu/hr
H_r = heat lost through roof, Btu/hr
H_s = heat gained by solar radiation, Btu/hr
H_t = total heat lost, Btu/hr
H_v = heat lost by ventilation, Btu/hr
H_w = total heat lost by water hyacinth pond, Btu/hr
I = solar intensity on a horizontal surface
I_d = light intensity at depth d, footcandles
I_i = incident light intensity, footcandles
K = carrying capacity, lb
K_c = $\exp[7.712 + 0.059 (95 - T_d)]$
L = final BOD concentration, ppm
L_0 = initial BOD concentration, ppm
L_t = biochemical oxygen demand concentration, ppm
M = metabolite production (BOD or ammonia nitrogen), kg metabolite/100 fish-day
M_i = moisture of the portion, decimal
M_{mix} = moisture content of the mixture, lb water/lb total
N_A = ammonia nitrogen production, (kg NH_4-N/100 kg fish-day)
ND = number of digester modules
N_i = nitrogen content (as a fraction of total solids), decimal
O_c = oxygen consumption, (kg O_2, 100 kg fish-day)
P = perimeter of water hyacinth ponds, ft
P_A = mass inflow of algae, lb/day
P_{cl} = production of clam meat, lb/day
P_{cr} = production of crayfish, lb/day
P_i = percentage of oxygen saturation at the inlet
P_0 = percentage of oxygen saturation at the outlet
Q = flow rate of influent from the algae pond, ft^3/day
Q_a = flow rate of influent, ft^3/day
Q_{mb} = minimum flow rate to ensure acceptable BOD, L/d
Q_{min} = minimum flow rate, liter/day
Q_{mn} = minimum flow rate to ensure acceptable ammonia nitrogen, L/d
Q_{mo} = minimum flow rate to ensure acceptable dissolved oxygen, L/d
R = air-to-water volume ratio
R_i = carbon:nitrogen ratio (of total solids), decimal
S = Insolation on pond, cal/cm^2-day

S' = total insolation, Btu-ft^{-2}-d^{-1}
SF = safety factor (about 3), dimensionless
S_i = Volatile solids for each component i (as a fraction of total solids), decimal
SRT_{min} = minimum solids retention time, days
T_a = air temperature, °F
T_c = temperature coefficient, decimal
T_d = digester temperature, °F
T_g = ground temperature (to depth of 3 ft), °F
T_h = temperature of thermal effluent entering digester heat exchangers, °F
T_i = temperature of water hyacinth ponds, °F
T_{gw} = ground-water temperature, °F
T_{sw} = surface water temperature, °F
T_w = water temperature in algae pond, °F
V = volume of the pond or raceway, liters
V_{meth} = volume of methane gas produced, measures at 32°F and 14.7 psi, f
V_{wat} = volume of water to be added (removed), ft^3
W_{bact} = dry weight of bacteria, lb
W_i = weight of the portion, lb
W_{mix} = weight of water added to mixture, lb
W_{sludge} = total weight of sludge, lb
W_{slurry} = weight of the slurry, lb
W_{solids} = dry weight of sludge solids, lb
W_{supnat} = weight of the supernatant, lb
W_{vs} = weight of the volatile solids in the slurry, lb
X = quantity of plant biomass, lb
X_0 = weight at time of planting, lb
X_{harv} = weight at time of harvest, lb
a = bacterial conversion constant (approximately 0.04), decimal
b = bacterial mortality constant (approximately 0.015), decimal
c = specific heat of water = 1.00, Btu/lb-°F
d = depth of the algae pond, cm
f = maximum photosynthetic efficiency
h = additional pumping heat required, ft
i = 1, 2, . . . , n = subscript which indexes substances to be added to the digester
k = $3.366\, e^{0.19(T_d - 59)}$, digestion rate factor, day^{-1}
$\dot{m}_d$ = mass flow rate of thermal effluent used to heat the digesters, lb/hr
$\dot{m}_h$ = mass flow rate of thermal effluent used to heat water hyacinth ponds, lb/hr
r = intrinsic rate of natural increase, hr^{-1}
r_{max} = maximum growth rate, hr^{-1}

t = time, hr
t_{harv} = time of harvest, hr
w_a = specific humidity of ambient air, (lb H_2O/lb air)
W_i = specific humidity of air inside enclosure, (lb H_2O/lb air)
α = empirically determined constant (approximately 1.5×10^{-3}), dimensionless
θ = detention time, days
τ = solar radiation transmittance, decimal

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