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NASSER RAZEGHI

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CHAPTER I

INTRODUCTION

Fecal borne diseases have been major health problems in many Asian and African countries as the result of low standards of environmental sanitation. Fifty per cent of the high infant mortality rate in the "developing" nations has been attributable to intestinal disorders caused by the intake of unsanitary water and milk (1, 2). Diseases that have no direct relationship to environmental sanitation display a morbidity reaction corresponding to the incidence of fecal borne diseases. The improvement of environmental health conditions tends to reduce the morbidity of non-sanitation related diseases and the deterioration of environmental sanitation results in an increase in both related and non-related diseases (3). For example, the typhoid death rate has declined significantly in communities provided with safe water supplies, but has risen rapidly when water supplies became contaminated. Non-related diseases seem to follow a parallel pattern (4).

The haphazard disposal of human excreta and other deficiencies of environmental sanitation have fostered the spread of schistosomiasis, typhoid, cholera, and helminthiasis in many communities of the world (1, 3). It has been well recognized that water supply and liquid waste disposal practices have been interrelated factors of community sanitary activities. Inattention to or disregard for sewage disposal will result in hazards affecting the quality of life and the health of all humans so exposed (2, 4). As Bregman (5) so aptly stated: "Today everyone lives in someone else's backyard, everyone lives down wind or down stream from someone else. We can no longer throw our wastes away carelessly and expect them to harm no one".

If water is considered a national resource it follows that the quality of water is of national concern (6). Sewage treatment and disposal are parts of water pollution control and water sanitation programs, and they are directly related to the quality of water and hence to water as a national resource (4, 6). Consequently, decisions on the methods of sewage treatment and disposal are not merely of local importance but must be viewed as national responsibilities (5).

At the present time the economic aspects of sewage treatment are important considerations for communities of the developing nations. Resources vary with the size and composition of the communities and of the countries. It is particularly incumbent upon communities with very limited human and financial resources to discover the most economical methods of effectively treating sewage (7, 8, 9). The developing nations of Asia and Africa are in extreme need of practical solutions to the problems of protecting community health with low cost, efficacious sewage disposal systems (10, 11).

Among these nations are large areas where land is inexpensive and rainfall is low. For such locations an economical solution to the sewage disposal problem may be the utilization of waste stabilization ponds (WSP) (7, 12). This has been recognized as a versatile low-cost method for liquid waste treatment for regions with the characteristics of aridity and low land values (13).

The use of sewage lagoons is not a new method of environmental sanitation but was practiced many centuries ago in Asia (14, 15). In recent years the practice has re-emerged with considerable attention being paid to its improvement. Smallhorst et al. (16) stated that the city of San Antonio, Texas employed some kind of sewage lagoon in 1901. The first systematic attempt at the utilization of waste stabilization ponds occurred in California in 1924. In 1928 sewage lagoons were installed in North Dakota, and by 1948 Maddock, North Dakota was using an apparently effective lagoon system (14, 17). Elsewhere, after 1921, interest increased in this method of sewage treatment. According to Smallhorst (18) a lagoon irrigation system was installed by the city of Abilene, Texas and an experimental pond was developed at Texas A and M College in 1929. Modern sewage lagoon practice is still relatively new with the first installation in Australia, for instance, being completed in 1936.

Iran is representative of those areas of the world for which the sewage lagoon system seems most appropriate. Application to this country will permit focusing on specifics to support the foregoing generalizations. This nation has the factors which were offered as controlling factors in the choice of a lagoon system, namely, inexpensive land and low rainfall (9, 13, 19). At the present time liquid waste treatment in Iran is influenced by the following factors:

a) Iran is a developing nation economically.

b) The financial resources of communities within the 500 to 10,000 population range are very limited. In terms of cost, waste stabilization ponds are the only currently acceptable system for sewage treatment and disposal.

c) Land is available (for lagoons) at reasonable costs.

d) A generally arid condition prevails throughout the nation with low annual rainfall, long days of sunshine and dry air which leads to a high rate of evaporation from bodies of water. Consequently, waste stabilization ponds would increase in total solids and algae concentration, conditions which if not controlled could interfere with the stabilization of organic matter and could lead to the development of other problems such as odor production.

e) There is an inadequate supply of qualified personnel in the field of sewage treatment plant operation. Lack of trained personnel would severely handicap the operation and maintenance of sophisticated methods of liquid waste treatment.

f) There has been a rapid increase in water pollution, particularly in the Caspian Sea, due to the burgeoning of small communities, homes, motels, hotels, and industries discharging raw sewage directly or indirectly into the sea. The Caspian Sea is a source of large quantities of edible fish (including caviar) as well as a recreational area for boating, bathing, and swimming.

g) Currently, most small communities utilize ground water supplies and frequently release their liquid wastes in such a manner that allows contamination of the underground aquifers.

h) Insect-born diseases, such as malaria are very important public health problems in Iran and waste stabilization ponds are looked upon as a mosquito breeding places; therefore, its application and development may be restricted unless effective control procedures can be developed.

CHAPTER II

LITERATURE REVIEW

The biological action in waste stabilization ponds (Figure 1) is believed to be similar to the biological action in the activated sludge and trickling filter processes (20). It involves the conversion of sewage organic matter into bacterial and algal cells which are relatively stable (16). Nemerow (21) indicated that another phase of treatment in waste stabilization ponds is sedimentation, which is more significant around the pond inlet.

McKinney (22) and Gloyna (13) stated that the stabilization of organic matter is achieved by the activity of saprophytic bacteria in the presence or absence of oxygen. In aerobic conditions the oxygen is provided by algal photosynthesis and surface aeration. Canter (23) stated that the main source of oxygen production is algal photosynthesis.

Oswald (24) Varma et al. (25), Nemerow (21), Eckenfelder and O'Connor (26), Canter (27) and Smallhorst et al. (16) described the degradation of organic matter in the pond in the presence of dissolved oxygen as follows:

$$C_{11}H_{29}O_7N + 14\ O_2 + H^+ \rightarrow 11\ CO_2 + 13\ H_2O + NH_4^+$$

$$6(CH_2O)_x + 5\ O_2 \rightarrow (CH_2O)_x + 5\ CO_2 + 5\ H_2O + \text{energy}$$

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$$

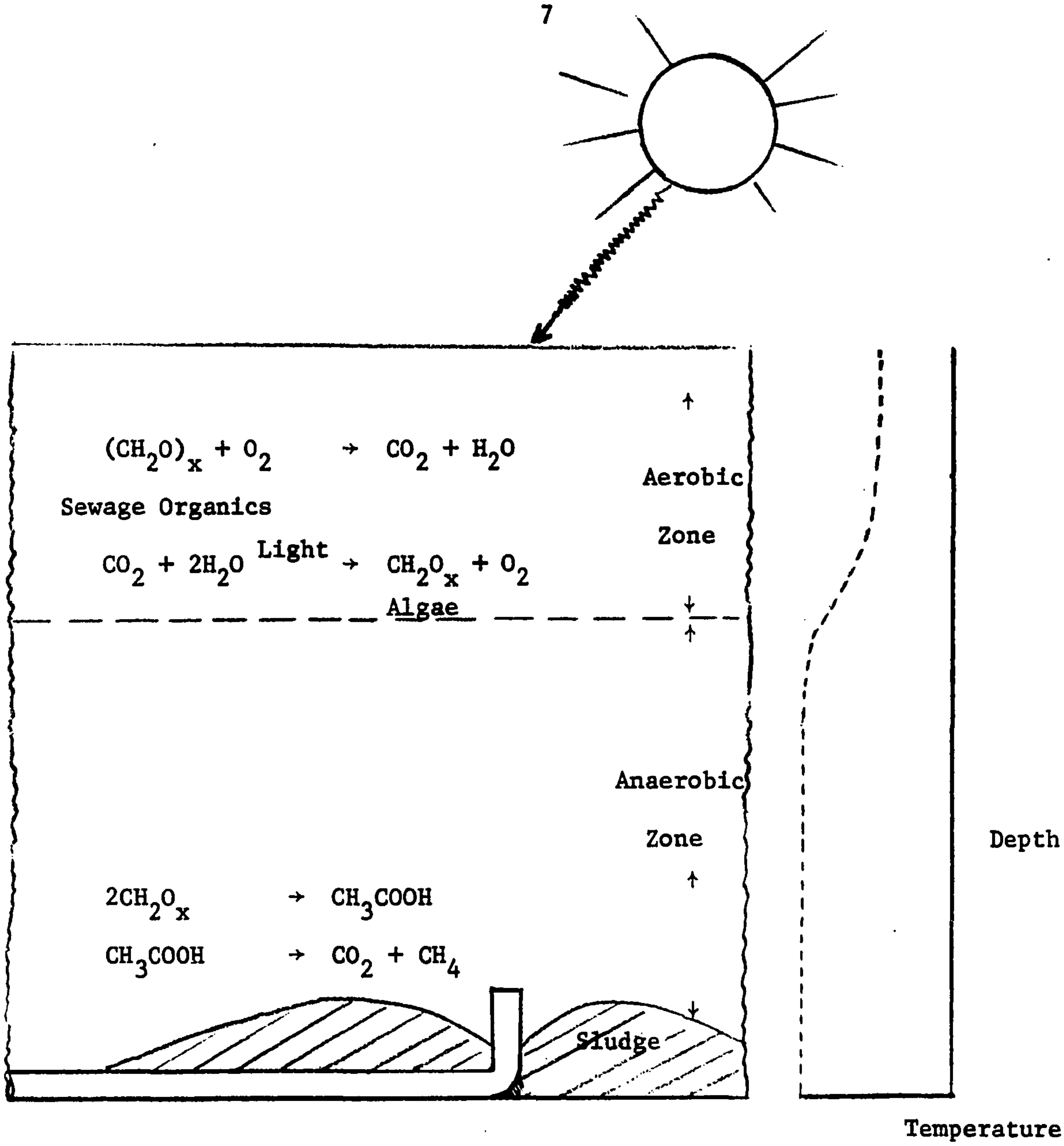

Figure 1--Schematic cross section of a stabilization pond.

Accordingly, the weight of oxygen required to oxidize organic matter is 1.56 times the weight of oxidized organic matter (26). Gloppen in the Federation's 36th Annual Meeting (28) stated that the oxygen requirement for the oxidation pond is 1.5 times the BOD entering the pond. Eckenfelder and O'Connor (26) and McKinney (29) established the following formula for determining the oxygen requirement for the stabilization of organic matters in ponds:

$$\text{lb } O_2 \text{ per day} = a' \text{ (lb } BOD_5 \text{ removed per day)} + b' \text{ (lb MLVSS)}$$

In which:

a' = Oxygen required per unit of organic matter removed

b' = Oxygen required per unit of MLVSS for endogenous respiration

MLVSS = Mixed liquor volatile suspended solid

Oxygen is supplied by algal photosynthesis and surface aeration, (23, 24, 25, 30, 31). The process of photosynthesis and production of oxygen is explained as:

$$(CH_2O)_x + CO_2 \xrightarrow{\text{light + algae}} 2(CH_2O)_x + O_2 + H_2O$$

$$NH_3 + 5.7\ CO_2 + 12.5\ H_2O + \text{light} \longrightarrow C_{5.7}\ H_{9.8}\ O_{2.3}N + 6.25\ O_2 + 9.1\ H_2O$$

$$CO_2 + H_2O \xrightarrow[\text{algae}]{\text{light}} CH_2O + O_2 \longrightarrow \text{energy}$$

$$NH_4 + 7.6\ CO_2 + 17\ H_2O \xrightarrow{\text{algae}} 15.2\ H_2O + H + C_7\ H_{8.1}\ O_{2.5}N + 7.6\ O_2 - 886\ \text{Kcal/gm}$$

$$CO_2 + 2\ H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} CH_2O + H_2O + O_2$$

$$CO_2 + H_2O + \text{inorganic nutrient} + \text{light} \xrightarrow{\text{algae}} (CH_2O)_x + O_2 + \text{energy}$$

$$106\ CO_2 + 90\ H_2O + 16\ NO_3^- + 1\ PO_4 + \text{light} \longrightarrow C_{106}H_{180}O_{45}N_{16}P + 154\ O_2$$

The energy for dehydrogenation of water by Triphosphopyridine Nucleotide (TPN) is supplied by photosynthetic pigments.

$$TPN + 2\ HOH \xrightarrow[\text{chlorophyll}]{\text{light}} TPNH_2 + H_2O_2$$
$$H_2O_2 \downarrow \frac{1}{2} O_2 + H_2O$$

According to formulae by Eckenfelder and O'Connor (26), approximately 3.68 cal are fixed for each mg of oxygen liberated, and about 1.67 mg of oxygen is liberated for each mg of algae synthesized. Canter (23) stated that with optimum illumination, temperature and nutrient, 200 to 250 lbs of oxygen per acre per day will be produced. Also, Canter (27) estimated that algae can supply 125 to 250 lbs of O_2 per acre per day on a practical basis, and according to McKenthum and McNabb (17) the oxygen production by photosynthesis is greater in the upper 2 ft of water.

Canter (23, 27) estimated that the oxygen produced per gm of algae synthesized is 1.55 gm and Rich (32) stated that the ratio of the weight of oxygen produced to the weight of algae cell synthesized is 1.25 to 1.75. Oswald (33) declared that under satisfactory conditions of illumination, temperature and nutrient, photosynthesis may give rise to 200 lbs of oxygen per acre per day. Oswald *et al*. (34) calculated that the amount of oxygen produced during algal photosynthesis is 66 mg per day from that weight of *Chlorella* which contains 1 mg of chlorophyll at a light intensity of 1200 ft-c, and this oxygen is liberated from water molecules and serves as the hydrogen acceptor. Bartsch (35) estimated that in

South Dakota, oxygen production is 3.2 mg/l per hr for 0.46 mg/l of chlorophyll.

Gloyna (13) determined that actually there is 0.7 lb organic matter per lb of ultimate BOD, so stabilization is the conversion of organic matter to live cells and that roughly for each pound of algae produced 749 gm of dissolved oxygen is liberated.

Jayanagaudar (36) found in Ahmedabad stabilization pond that a photosynthetic colored bacteria _Triopedia rosea_ located in the bottom layers could utilize the far infrared light without producing oxygen.

Eckenfelder and O'Connor (26) established the following formula for reaeration in the ponds:

$$R = 0.0271\ (a)(d)\ (D_c)$$

in which:

R = Reaeration in lb O_2 per acre per day,

d = Basin depth in ft

D_c = Mean daily saturation deficit

a = A factor approximately equals to 20

Pipes (37) stated that aeration is the second source of oxygen supply to the pond and could be expressed as:

$$\frac{dD}{dt} = -rD$$

in which:

D = Oxygen deficit $D_s - D_a$

D_s = Oxygen concentration at saturation

D_a = Oxygen concentration at any time

r = Reaeration rate

The reaeration rate (r) is a function of many physical variables such as mixing and wind.

Canter (27) estimated that surface aeration can supply up to 40 lb O_2 per acre per day. Even when the surface layers are supersaturated with dissolved oxygen the dissolved oxygen at the bottom may be zero and the condition may be anaerobic.

Varma et al. (25) expressed the photosynthesis in two steps:

a) Photochemical action and photolysis of H_2O or CO_2 followed by

b) Chemical action and the manufacture of organic substances.

Canter (23, 27) stated that the process of carbohydrate production occurs in three steps:

a) Removal of the hydrogen atom from a water molecule and production of oxygen

b) Transfer of hydrogen from an intermediate compound in the first stage to one in the third stage, and

c) The use of the hydrogen atom to convert CO_2 to carbohydrates

The latter can be shown as follows:

$$2H_2O + 2A \xrightarrow{hr} 2\ AH_2 + O_2 + E_1$$

where

A = Hydrogen acceptor

E = Stored energy

then,

$$2\ AH_2 + CO_2 + E_2 \longrightarrow CH_2O + H_2O + 2A$$

in which:

A = Hydrogen acceptor

E = Energy used for reduction

So it could be shown that

$$CO_2 + H_2O \longrightarrow CH_2O + O_2 + E_3$$

where

$$E + \text{Net energy} = E_1 - E_2 = 112{,}000 \text{ cal per mole.}$$

Later fats, protein and other organic molecules are produced.

Due to thermal stratification which inhibits the mixing and penetration of dissolved oxygen to lower depths, algal stratification occurs and consequently the dissolved oxygen concentration will be different at various levels as the diffusion of oxygen does not extend more than 6.5 ft below surface layer even if the surface is saturated with oxygen (24, 38).

McKinney (22) and Gloyna (13) stated that as long as algae oxygen production plus surface aeration is more than the oxygen required for bacterial degradation of organic matter, the pond will be aerobic. Usually a pond is aerobic at the surface and is anaerobic at the bottom and is called a facultative pond (13, 30). In the absence of dissolved oxygen the biodegradation of organic matter is under anaerobic conditions (24). This has been formulated by Oswald (24) and Canter (27) as follows:

$$5(CH_2O)_2 \longrightarrow (CH_2O) + 2\ CH_3COOH + \text{energy}$$

This is called putrefaction or organic acid formation. Organic acids produced may be decomposed to methane and carbon dioxide by methane bacteria according to the following reaction (24, 27).

$$2\ \frac{1}{2}\ (CH_3COOH) \longrightarrow (CH_2O)_2 + 2\ CH_4 + 2\ CO_2 + \text{energy}$$

This is called methane fermentation.

It was found by Pipes (37) that all factors being equal, the aerobic organisms have a higher rate of metabolic activity than anaerobic organisms and their by-products are more stable and less objectionable. Also, Oswald (24) said that the methane fermentation process is a nuisance-free activity but in shallow ponds, due to temperature variation, pH and oxygen penetration, the process is inhibited. McKinney (22) stated that in an anaerobic environment the oxygen is not the hydrogen acceptor, but some part of the organic matter is oxidized so there is a limitation in the process. According to Gloyna and Malina (39) there were many conflicting environmental conditions for the reactions. Since one single pond can not have all optimum conditions for all reactions, a series of ponds is necessary and consequently it is recommended that multiple cells be used.

BOD Removal, Loading and Detention Time

Oswald (24) found that BOD removal is in direct proportion to detention time so that for a temperature of 15°C and a detention time of 1 day, BOD reduction was 47 per cent and for a detention time of 64 days, BOD reduction was 94 per cent. According to Herman and Gloyna (38) the longer the detention time, the higher will be the BOD and coliform removal.

Hogge and Dobko (40) in their experiments found that in ponds with short detention times, there was a direct relationship between detention time and BOD removal, but Herman and Gloyna (38) found that when the detention time exceeded a certain period the algal cell concentration increased and effluent quality decreased.

According to Oswald (24) BOD reduction is directly in proportion to detention time and temperature as shown in Table 1.

TABLE 1

PERCENTAGE BOD REMOVAL AT INDICATED TIMES AND TEMPERATURES

Time in Days	10 C	14 C	15 C	18 C
0	0	0	0	0
1	23	35	47	33
2	40	61	56	53
4	46	70	67	56
9	57	75	75	81
16	72	89	90	87
32	90	90	95	96
64	94	--	94	--

In a series of BOD analyses from experimental ponds there was a periodicity in BOD removal within a 24-hr period and the gradients depended on prevailing environmental conditions (41). A survey by Canter (23) showed that northern states had an average detention time of 117 days; whereas, the central and southern states have a mean detention time of 82 and 31 days respectively.

Neel et al. (42) found the average BOD removal to be 80 per cent. Eckenfelder and O'Connor (26) developed the following formula for BOD removal in waste stabilization ponds:

$$\text{Percentage BOD removal} = \frac{100}{1-0.04\ L^{0.54}}$$

in which

L = lb of BOD per acre per day discharged into the pond.

Other experiments (26) correlated loading to percentage BOD removal as:

$$100 - 0.05\ L$$

Other works (43) related detention time and loading to BOD removal as:

$$E = 0.859\ (y)^{-0.082}\ (T)^{+0.121}$$ in which:

E = Percentage BOD removal

y = Loading in lbs of BOD per acre per day and

T = Detention time in days

Neel et al. (42) found in their experimental ponds that WSP with loadings over 60 lb BOD per acre per day would produce odor after 36 days of ice cover. Also, Herman and Gloyna (38) in their experimental ponds found that when the loading was low, the ponds contained dissolved oxygen even during night period, but when the pond was overloaded anaerobic conditions will exist during the night period.

Canter (23) in his lagoon survey found that the mean design loading rate in the north was 26 lb BOD per acre per day, or an average of 124 persons per acre per day, and that central states between 37° and 42° latitude had a mean design loading of 33 lb BOD per acre per day, or an average of 189 persons per acre. Hopkins (44) stated that the loading of lagoons in the Missouri basin was 10 to 34 lb BOD per acre per day with satisfactory results and, according to Carl and Kalda (45), the loading was around 20 lb of BOD per acre per day in South Dakota with a BOD removal of 70 per cent during the winter and approximately 99 per cent in the summer. Generally speaking, BOD loadings varied from 20 to 40 lb BOD per acre per day or an average of 200 people per acre per day (15).

Gloppen in the Federation's 36th Annual Meeting (28) stated that experiences at Washington State University showed that under controlled conditions the load on a pond could be 150 lb of BOD per acre per day without objectionable results, and Canter (23) recorded that in experimental stabilization ponds, loadings as high as 200 lb BOD per acre per day gave satisfactory results. Also, McKinney (7) found that even in mild climates a lagoon could handle raw domestic sewage BOD loadings up to 100 lb per acre per day with satisfactory results; however most California ponds are designed for BOD loadings of only 40 to 50 lb per acre per day (33).

According to Cooley and Jennings (46) experiments with an average loading of almost 400 persons per acre per day indicated that the overall average BOD reduction for the period from March 1959 through October 1959 was 80 per cent in each pond.

Sometimes there are variations in BOD removal and according to El-Barouli and Moawad (47) this periodic high and low rate of BOD reduction might be due to toxic substances produced by organisms present in the ponds. However Pipes (37) indicated that variations in BOD removal were due to overgrowth of secondary and tertiary heterotrophs. Herman and Gloyna (38) found that the BOD of the filtered pond effluent was about 50 per cent of the unfiltered effluent. Varma et al. (25) found that due to the presence of algae in pond effluents the BOD analyses gave different results whether incubation was in a dark environment or not. Gloyna (13) noted that in ponds receiving low organic loads the algae were usually consumed by planktonic phagotrophes such as daphnia or cyclops and that in quiescent ponds the settling factor was favorable for the production of low BOD effluents. Oswald et al. (34) gave a similar statement to the effect that the higher the organic load the higher will be the algal population.

Another favorable result of the waste stabilization pond is its ability to remove coliform bacteria from sewage (48). McKinney (29) indicated that this rapid die-off of coliform bacteria was due to the production of antibiotics by algae or other bacteria. Oswald (24) and Klock and Durham (49) found that temperature was more effective than time in the reduction of the most probable number (MPN) of bacteria as winter conditions and the short circuiting of influent warm waste caused a higher coliform count in the effluent. Canter (23) maintained that the destruction process of pathogens in ponds was not clear, but that competition for nutrients between saprophytes and pathogens is very important, and the reduction of viruses is probably due to the long detention time. Loehr and Ruf (50) found that during the period in which the pond operation was optimum the coliform reduction was 99.0 to 99.8 per cent. In another series of experiments, coliform reduction was found to be 90 per cent for 90 per cent of the time (46). Gloyna (13) studied the relation between detention time, number of cells and coliform reduction and found that for a detention time of 30 to 40 days in multiple cells the coliform count of the effluent was reduced to drinking water standards.

According to experiments by McKenthum and McNabb (17) there was a high percentage of coliform reduction in waste stabilization ponds and this percentage was found to be over 98 per cent for more than 87 per cent of the time. Another experiment showed that this reduction was 90 per cent (40). Additionally, Canter (23) reported that Marais found that 99.9 per cent of the coliform and 100 per cent of salmonella enteric bacteria were destroyed in waste stabilization ponds and the empirical formula for pathogen removal was:

$$100 - P.R. = \frac{100}{KR + 1}$$

in which:

P.R. = Percentage of pathogenic organisms remaining

K = Removal constant for coliform (about 2 per day)

R = Detention time in days

For a series of two ponds the formula would be

$$100 - P.R. = \frac{100}{(KR_1 + 1)(KR_2 + 1)}$$

in which:

K = 2.0 for _Echerichia_ _coli_ and 0.8 for _salmonella typhi_,

R = Detention time in days

P.R. = Percentage removal of pathogens

Hogge and Dobko, (40) and Nel _et al_. (42), found that coliform reduction in ponds was 99.9 and 90 per cent respectively. Considering that the most probable number of coliform organisms in the raw sewage ranged from 4×10^6 to 1.1×10^8, even with a 99.9 per cent reduction there would still be 1×10^5 to 4×10^5 organisms per 100 ml remaining.

Algae and Other Life in Waste Stabilization Ponds

Steffen (51) and Canter (27) concluded that for optimum operation of ponds, the necessary algal populations are a minimum of 10^5, an optimum of 10^7 and a maximum 10^8 per ml, which are very similar to the total count of 10^7 found by Gann _et al_. (52).

According to Herman and Gloyna (38), Varma _et al_. (25), Oswald et al. (34), and Nemerow (21), as detention time increases, the algal cell concentration increases so the effluent BOD will be higher due to algal cells. On the other hand, Bartsch (35) found that this rapid growth of algae associated with the consumption of elemental nutrients had a reducing effect on the growth rate of algae. Gloyna (13) also agreed that nitrogen and phosphorous had an important effect on algal synthesis and the required ratios of BOD to P and BOD to N were around 100 to 1 and 20 to 1 respectively.

Due to this increase of algal growth in ponds Kappe (53) and Canter (23) showed considerable resistance to the idea that lagoons produce effluents as good as conventional sewage treatment in term of BOD removal because of the presence of algae in the effluents and Raschke (54) believed that BOD determinations of filtered effluent permits a better judgment of effluent quality. However, Herman and Gloyna (38) found that when the pond was quiescent, the difference between filtered and unfiltered effluent samples was insignificant and according to Varma and DiGiano (55), the algal cells which settle after decomposition give simple amino-acids which are used by bacteria for cell synthesis.

The concentration of algae has been formulated as being inversely proportional to the lagoon depth as follows (23, 27):

$$dC_c = 2000$$

in which:

d = Depth of pond in ft

C_c = Algal concentration in mg/l and is maximum in depths of 8 to 12 in.

McKinney (22) indicated that the higher the load, the higher will be the algal concentration.

According to Bogan (56) the growth rate of algae was:

$$N_t = N_o e^{kt}$$

in which:

N_t = Number of algae at time "t"

N_o = Number of algae at original time, and

k = Rate constant and is equal 0.2 to 2.0 per day for algae, 1.0 to 4.0 per day for protozoa and 2.0 to 60 per day for bacteria.

t = Time in days

On the other hand Rich (32) related the algal growth to oxygen production according to the equation.

$$W_{o_2} = PW_a$$

in which:

W_{o_2} = Net weight of oxygen produced in gm per day

P = Oxygenation factor and

W_a = Net weight of algae synthesized in gm per day

In another calculation it was found that an oxidation pond receiving 2 MGD of sewage would produce 600 lb of algae per day on a dry weight basis (16). Pipes (37) concluded that the nutritional requirement for microorganisms are:

a) Energy source,

b) Macronutrients such as, C, H, O, N, P, K,

c) Micronutrients such as, Fe, Ca, Mg, Zn, and

d) Certain organic structures.

Gloyna (13) indicated that the majority of algae species use only free carbon dioxide in their photosynthesis process, but there are some indications that a few algae utilize bicarbonate ions. Pipes (19) stated that algae can utilize some organic compounds as a carbon source. In so far as nitrogen is concerned, Canter (27) stated that algae can utilize inorganic nitrogen in the form of NH_3, NO_2 or NO_3, but it seemed that nitrate forms were most conducive to algal growth.

According to Bogan (56), the direct method of utilization of algae for recovering nutrients appeared to be the use of oxidation ponds followed by a process of harvesting. Absorption and coagulation are two possible harvesting processes, while a third potential method of harvesting is by screening.

Reid and Assenzo (57) determined that algae can reduce nutrients from sewage and according to Cooly and Jennings (46) the overall ammonia reduction would be 80 per cent. As algae are high in protein they can be used for cattle feeding (16).

Similar species of algae have been found in waste stabilization ponds all over the world, but the predominant algae depends on environmental factors (27, 34).

The process of sewage treatment and nutrient removal in waste stabilization ponds is a function of algae concentration since sewage organic matter is changed to algal cell materials (20, 58). Consequently, the removal of organic matter and nutrients is proportional to the production of algal cells, (20). The ratio of carbon to nitrogen and phosphorous in algal mass has been determined to be C:N:P = 106: 16:1 (20). Some general composition formula of algae are:

$$C_{7.62}H_{8.08}O_{2.53}N$$

$C_{5.7}H_{9.8}O_{2.3}N$

$C_5 H_8 O_2 N$

$C_{106}H_{180}O_{45}N_{16}$

$C_7 H_{8.1}O_{2.5}N$ (23, 26, 27, 56).

Analytical works of Sawyer (59) showed that since algae contain nitrogen, they can be used for nutrient removal from sewage.

Pipes (37) reported that there were two groups of heterotrophs; the first group feed on organic matter introduced to the pond and the second group, the secondary and tertiary heterotrophs, feed on the cells of the primary heterotrophs. According to McKinney (22), the predominant bacteria in the pond are Pseudomonas, Flavobacterium and Alcaligenes.

It has been reported that rotifers, cladocera, daphnia and cyclops are predators of algae (23). Daphnia and longispina, known as water fleas, feed on algae and can cause an almost complete disappearance of algae in the pond. Algae may settle to the bottom of the pond and be consumed by Chironomus larvae (27).

It has been reported that ducks, fish, rodents and insects make use of ponds for feeding, resting, nesting and breeding (23). It has also been proven that if a pond is designed, loaded and operated properly it can support fish life (16).

Light

The required solar energy to be utilized in the process of photosynthesis by algae can be derived only from light having a wave length of 4000 to 7000 Å, which comprises about 40 per cent of the total energy of solar radiation. This range comprises the red portion of the visible spectrum (23, 27, 32). In terms of intensity, the process of photosynthesis increases up to a point, with increasing light intensity; thereafter, at certain higher intensities, the photosynthesis process decreases. This range is generally from 500 to 5000 ft-C and depends on the various species of algae. For example, it is 24 to 600 ft-C for Chlorella pyrenoidosa (13, 17, 23, 37).

The availability of light as a source of energy is a function of latitude, season, elevation and cloud cover (23). The light effect on algal photosynthesis is highly influenced by the light saturation point (13, 23, 32). The light saturation point is the light intensity at which the algal photosynthesis rate is maximum, but this intensity is not the same for all species of algae. According to Gloyna (13) it is 600 ft-C for Chlorella, but the range is 400 to 600 ft-C (14). Beyond this range the rate of photosynthesis remains constant (13) and it was concluded that at 24 ft-C the rate of oxygen production through photosynthesis for Chlorella is equal to the rate of oxygen use.

Bogan (56) stated that the minimum light requirement is around 100 to 200 ft-C for optimum photosynthesis. According to Canter (23), Copeland and Dorris (31), Varma and DiGiano (55), and Bartsch (35) the efficiency of conversion of solar energy to useable energy as chemical energy is 1.0 to 3.6 per cent divided between the following functions:

a) To split water molecules into hydrogen and oxygen atoms, and
b) to form high energy phosphate bonds such as adenosine diphosphate (ADP) to adenosine triphosphate (ATP) in the chloroplast of algal cell (23, 27, 32).

The penetration of light in waste stabilization pond is not very deep because of the existence of algae and other particulate matter which absorbs the light (13, 35). Gloyna (13) and Canter (23) concluded that the penetration of light in waste stabilization ponds follows Beers-Lambert law which is expressed as:

$$I = I_o e^{-kcd}$$

in which:

k = Absorption coefficient

c = Concentration of algal cells

d = Depth of the pond

I_o = Original light intensity

I = Light intensity after passage through depth of "d"

Bartsch (35) found that in South Dakota 99 per cent of the light was absorbed in the upper 50 to 70 cm of the pond; consequently, at the depth where 0.5 per cent of the surface light intensity is available the oxygen production by algal photosynthesis is not enough for respiration of the biological system. Figure 2 shows photosynthesis versus depth of WSP.

Gloyna (13) stated that because of light absorption the intensity reduces with penetration into the pond; at a certain level the intensity will be just equal to saturation so the efficiency of light utilization at that level is higher.

Rich (32) stated that the highest fraction of available light utilized is up to 2000 ft-C and lowest is around 10,000 so the efficiency will vary within a broad range of values from 0.02 to 0.09 with an average of 0.04.

The fraction of light utilized according to Gloyna (13) and

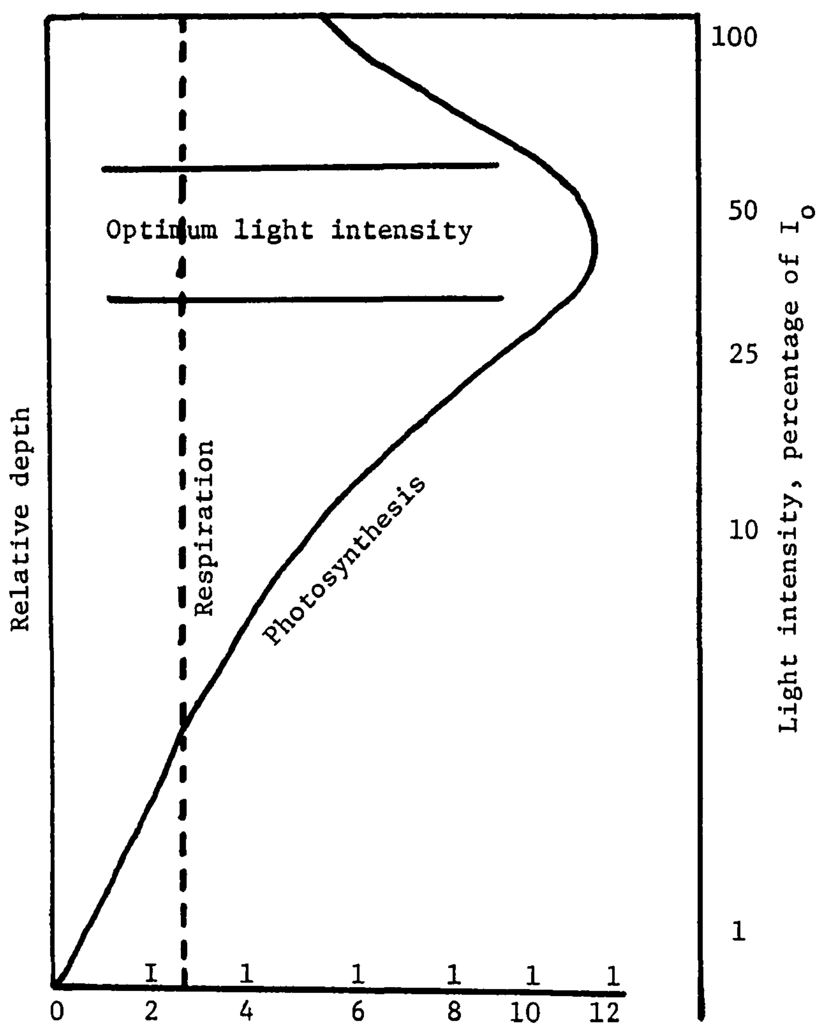

Figure 2--Photosynthesis from surface to depth of penetration of 1 per cent of surface light.

Rich (32) is expressed as:

$$f = \frac{I_s}{I_o} (L_n \frac{I_o}{I_s} + 1)$$

in which:

f = Fraction of light

I_s = Saturation intensity

I_o = Original light intensity

I = Light intensity after passage through some depth

The rate of utilization of solar energy per cm^2 of pond surface area is expressed by Rich (32) as:

$$hW_a = ESA$$

in which:

h = Unit heat of combustion, cal per gm

W_a = Net weight of algal synthesis, gm per day

E = Efficiency of energy conversion

S = Solar radiation in langleys, cal per cm^2 per day

A = Surface area of the pond

The unit heat of combustion is developed as:

$$h = 127\ R + 400$$

in which:

R = A value expressing the degree of reduction and equals

$$\frac{100\ (2.66)(\%C) + 7.99\ (\%H) - (\%O)}{398.9}$$

Percentages of carbon, hydrogen and oxygen to be used in the above equation should be computed on an ash-free weight basis. The unit heat of combustion for algae grown on sewage has been found to be 6 k cal/gm.

Light variation during summer and winter brings changes in algal species (54, 60). Gloyna (13) stated that the diurnal cycle and the oxygenation of a pond were probably more influential on the variation in algal population than the variation in light intensity. The penetration of light and its availability for photosynthesis was an important factor and according to Eckenfelder and O'Connor (26) and Williford and Middlebrooks (61) the depth of pond leads to different types of ponds. Fortunately, it is not necessary to keep the total pond aerobic; otherwise, the maximum depth of ponds should be limited to about 35 cm. This is why, according to Oswald (24) and Mills (10), the BOD reduction and coliform removal, nitrate and nitrite reduction are not affected by changes in depth.

Temperature

Generally speaking, effluent quality or pond efficiency is a function of air temperature (13, 47, 53). According to Gloyna (13) temperature affects photosynthesis and oxygen production and any other biological activity in the pond as:

$$\frac{t}{t_o} = e^{c(T_o - T)}$$

in which:

t = Reaction time, in days, required at any temperature (T)

t_o = Original time, in days, for reaction at an original temperature T_o

c = Energy-Temperature characteristic of Van't Hoff-Arhenius equation = 0.0693

T_o = Original temperature

The rate of biological activity in ponds is doubled for each

10°C rise in temperature within the range of 3 to 35°C (13, 23, 37). Results from pilot plants showed that a drop of 12°C decreased the deoxygenation "K" from 0.112 to about 0.056 per day (10). Gloyna (13) and Canter (27) concluded that the optimum oxygen production from algal photosynthesis was at 20°C and the range was 4°C to 35°C. It was found that when the temperature of the pond exceeded 30°C the dominant microorganisms were Eugelenophceae, and that gasification of the bottom sediment caused floating sludge mats and the development of blue-green algal on the mats (13, 27). This was why the performance and efficiency of ponds in summer and winter were significantly different (17, 42).

Bartsch (35) found that during the winter the rate of reproduction of algae decreased and that some organisms settled, alive but dormant, to the bottom so at this phase they exerted BOD on the pond. Ling (14) showed that the BOD removal per unit volume of lagoon per unit of time was lower in winter than summer. Nemerow (21) commented that cold winter temperatures cause an ice cover on the pond, thereby reducing light intensity for algal photosynthesis and preventing mixing and reaeration due to the wind effect. This is why in cold climates ponds receiving loads as low as 20 lb per acre per day, would be anaerobic when covered by ice (23). An additional factor was that during the cold season incoming sewage which was warmer and thus lighter than the balance of the pond liquid, formed a thin layer and moved toward the outlet thereby causing short circuiting and resulting in less contact time with a consequently high effluent coliform content (49). With the coming of warm weather the rate of bio-degradation is increased; photosynthesis and reaeration can not supply sufficient dissolved oxygen and the pond becomes anaerobic, (13, 47, 49, 50). In this case odor may be an operational problem; otherwise, if the pond is not highly loaded there should be no odor even with ice cover (23, 45).

Temperature causes thermal stratification of the pond which can cause a change in dissolved oxygen, BOD, and pH at different levels of the pond; because of this and the winter induced anaerobic conditions, pond design should be based on winter conditions (23, 62, 63).

pH

The pH of domestic waste water is usually near neutral. As decomposition ensues, the CO_2 produced from the decomposition of organic matter tends to lower the pH; however, the process of photosynthesis consumes all the CO_2 and, as a result, the pH in the pond actually rises (13, 23, 64). According to Gloyna (13) the rate of carbon dioxide absorption and oxygen production by algae may be 20 times the rate of CO_2 production so the pH might be raised. Canter (23) stated that the pH might rise as high as 10 or 11 during the day light hours but would fall to lower values at night; consequently, there is a diurnal cycle of pH (61, 65). The best pH for biological activity is 6.5 to 10.5 and if the pH increased to 10 the algal activity decreases thus affecting the BOD removal (23, 27).

McKinney (7) found that the change in pH from day to night was accompanied by a drop in the carbon dioxide content in the upper layers of the pond with little change in CO_2 content and pH at the pond bottom (7, 52, 61).

During the cooler months the pH difference between bottom layers and surface layers becomes insignificant (61). Pipes (64) and McKinney

(7) suggested that since the rate of CO_2 consumption by algae during the day time was more than CO_2 production by degradation of organic matter there would be a shift in the carbonate and bicarbonate system of the pond.

$$2\ HCO_3^- \rightleftharpoons CO_2 + CO_3^= + H_2O$$

or

$$HCO_3^- \rightleftharpoons CO_2 + OH^-$$

A decrease in the concentration of bicarbonate ion is accompanied by an equivalent increase in the concentration of either $CO_3^=$ or OH^-, so the total alkalinity remains constant; therefore, Pipes (64) suggested the following reaction:

$$CO_3^= + H_2O \rightleftharpoons CO_2 + 2\ OH^-$$

With this formula there is still no change in alkalinity of the water. Canter (23) said that the process was according to the following reaction:

$$HCO_3^- \rightleftharpoons CO_2 + OH^-$$

According to this, the pH is increased and may reach to 10 or 11 during the day. The absorption of CO_2 from air was considered insignificant.

Efficiency of Waste Stabilization Ponds

Gloyna (13), Herman and Gloyna (38) and McGoodwin (15) stated that stabilization ponds have had sufficient study and development to be classified as one of the major types of waste treatment systems. According to McKinney (22) the waste stabilization ponds originally were used for secondary treatment of sewage but today they are used for complete treatment. McKinney (7, 22) wrote that it was also used following other methods of waste treatment for achieving more polished effluents.

But according to Wilson (60), Hopkins (44) and Gloyna (13) it could be used as the sole and permanent sewage treatment method for receiving either raw or treated sewage and treating the sewage effectively under the usual climatic conditions. Even in cold climates it was reported to function satisfactorily (60).

In areas with available land, low rainfall, ample sunlight, and relatively small populations, waste stabilization ponds are an acceptable method for sewage treatment (9, 15, 23). Also, due to their functional flexibility, lower cost and minimal need for operational control, ponds are rapidly gaining popularity (50, 66, 67).

If waste stabilization ponds are designed on sound basic environmental factors and are well operated, they will produce good effluents, but if they are overloaded, they will not function properly (7, 8, 38, 44).

Gloyna (13) stated that even though the design procedure for waste stabilization ponds involves an empirical approach, the success of this method of sewage treatment has been recognized.

McGoodwin (15) concluded that the use of the oxidation pond for polishing the sewage was the most efficient and most useful procedure for reducing the BOD of the final effluent from standard sewage treatment plants, provided that initial BOD was high.

It was found that conventional sewage treatment removes a fraction of the nitrogen and phosphorous from sewage influent, but sewage lagoons with loading of 13 to 150 lb BOD per acre per day could remove nitrogen and phosphorous from 30 to 95 per cent and, consequently, were very effective in the prevention of nutritional pollution (41, 68).

Gloyna and Eckenfelder (20) found that almost 67 per cent of the total nitrogen could be removed from sewage regardless of the method of harvesting the algae. By denitrification processes occurring at the bottom of the pond, nitrogen gas may be released from the pond so that nitrogen removal from sewage can be significant in the WSP.

Other experiments indicated that ammonia nitrogen might be reduced up to 90 per cent, phosphorous 96 per cent, and potassium up to 20 per cent (35).

Assenzo and Reid (68) found that for the nutritional removal in terms of loading, the optimum was 11.23 to 19.66 lb of BOD per acre-ft per day. Bogan (56) stated that, for 80 to 90 per cent removal of phosphorous from most sewage, retention times of 14 to 28 days would be required.

Application of Waste Stabilization Ponds

Surveys showed that in 1957, 27 states of the U.S. had approximately 430 ponds serving a total population of 760,000 persons but by 1962 this number had increased to 1300 ponds in 39 states serving a population of 2 million. In addition, 31 industrial groups were using waste stabilization ponds for their sewage. In 1966 more than 1200 municipal and industrial ponds were in operation in the State of California alone (23).

According to Gloyna and Malina (39) ponds in conjunction with pretreatment have been used for petrochemical waste and achieved 99 per cent BOD removal.

Eckenfelder (11) found that ponds have been used for the meat and poultry, dairy, textile and sugar industries with 45 to 95 per cent

BOD reduction. According to McKinney (7) waste entering ponds should contain oil of less than 20 mg/l, sulfide of less than 15 mg/l and phenol of less than 7 mg/l.

Other surveys showed waste stabilization ponds have been used by many industries such as canning, meat, poultry, chemical, paper and petroleum with satisfactory results (43, 44, 69).

Voege and Stanley (70) reported the satisfactory results of utilization of waste stabilization ponds by many industries in Canada.

It has also been reported that waste stabilization ponds with loading of 20 lb BOD per acre per day used for treating the sewage of slaughter houses and packing plants gave satisfactory results (70). Another survey by Herman and Gloyna (71) showed that 99 per cent of the communities using waste stabilization ponds recommended this method of sewage treatment and 86 per cent described the effluent of the ponds as appearing clear. Ponds have been recommended by consulting engineers, mayors and many others (72). A relatively new modification of WSP is a series of anaerobic-aerobic ponds which have been used by meat packing plants and many other industries (48).

Modification of Ponds and Design Consideration

According to Fair *et al*. (73) and Eckenfelder (11) oxidation ponds, in terms of operation, are of three types:

a) Aerobic and/or facultative ponds

b) Anaerobic ponds

c) Mechanically aerated ponds and oxidation ditches.

Eckenfelder (11) has presented the design criteria for different kinds of ponds (Table 2).

TABLE 2

DESIGN FACTORS FOR WASTE STABILIZATION PONDS

	Aerobic	Facultative	Anaerobic	Aerated
Depth, ft	0.6-1	2-5	8-10	6-15
Detention time, days	2-6	7-30	30-50	2-10
BOD loading, lb/acre/day	100-200	20-50	300-500	
BOD removal, percentage	80-90	75-85	50-70	55-90
Algae concentration mg/l	100	10-50	nil	nil

Aerobic Ponds

Since aerobic pond operation depends upon algae to provide enough oxygen for satisfaction of the BOD of the suspended and dissolved degradable materials by aerobic microorganisms, such ponds have been limited to those wastes which are not toxic to algal growth (11, 13, 26, 33).

Eckenfelder (11) found that to maintain the aerobic conditions in the sludge of aerobic pond the mixing of the sludge with supernatant for a few hours each day was necessary.

Facultative Ponds

Facultative ponds have aerobic conditions at the surface layers and anaerobic conditions at the bottom (11, 13, 33, 61). Studies have shown that the aerobic layers of such ponds have diurnal variations in temperature, oxygen and pH (13, 52, 61, 63).

Aerated Lagoons

According to Svore (74), aerated lagoons are growing in popularity for domestic wastewater treatment. In this type of lagoon the oxygen is supplied by diffused air or mechanical aeration systems (11, 67) and field experiments showed that the capacity of such lagoons for handling sewage is greater than that for non-aerated ponds (67). According to Svore (74) odor problems were minimized when the loading was around 20 lb BOD per acre per day and that one major advantage of aerated lagoons in cold climate was a higher dissolved oxygen content in the pond.

Anaerobic or Deep Ponds

The deep pond is like the septic tank or Imhoff tank and is more efficient in warm climate (75, 76). Fair et al. (73) stated that in this system, degradation of organic matter was accomplished by anaerobic microorganisms in the absence of dissolved oxygen. According to Loehr (75), as the ratio of surface area to volume is smaller, light utilization is decreased and evaporation is minimized. Therefore in warm climates deep ponds are actually good digesters because they accumulate more heat and radiate less (13, 24, 75).

The process of BOD reduction in deep ponds is accompanied by the production of methane, carbon dioxide and nitrogen and the amount of gas produced has been estimated to be 10 to 12 cu ft of gas per lb of BOD applied. Anaerobic ponds have been shown to be an efficient method of stabilization for meat, textile and sugar industrial wastes (11, 24, 50).

Loading experience showed that 7.9 lb BOD per day per 1,000 cu ft gave 80 per cent BOD reduction (51). Eckenfelder (26) reported that a loading of 0.11 to 0.15 lb BOD per day per cu ft for ponds 8 to 17 ft deep was satisfactory. Other reports showed that ponds with depths of 15 ft and loadings up to 20 lb per day per 1,000 cu ft of pond volume were a very "efficient" and economical method of treating meat packing waste (76, 77). According to Steffen (51), 90 per cent BOD removal could be achieved by this method.

The BOD of the anaerobic pond effluent might be around 200 mg/l so it needs further treatment (75, 78). According to Gloyna (13) reductions in summer and winter were reported to be 65 to 80 per cent and 45 to 65 per cent respectively. Sludge removal was necessary where suspended solids content of the sewage was high.

Loehr and Ruf (50) described the anaerobic lagoon as a unit in which surface reaeration and photosynthesis were not able to provide the necessary oxygen for bio-degradation of organic matter. According to Parker and Skerry (78) there was interaction between sludge and raw influent, and other experiments showed that the mixing of sludge and raw influent gave better results (37, 50, 76).

Experiments with slaughterhouse waste showed this kind of pond was very efficient (76, 79, 80).

Wachs (81), in experiments with extra-deep ponds (5 mt), found that during the period of March through May, when the BOD loadings were about 100 kg per hectare per day, the BOD removal on the basis of "unfiltered" effluent was about 60 per cent. Porges (69) in his study of 168 aerobic and anaerobic ponds in the United States and the median loading was 72 lb BOD per acre per day. Also another survey on industrial waste stabilization ponds in 1962 showed there were 197 anaerobic ponds treating industrial waste (69).

Design

The beginning point in designing a stabilization pond is to study all the environmental conditions namely, winter and summer temperatures, duration and intensity of sunlight, rainfall and evaporation and soil conditions (12, 13, 26, 66, 73). Some authors recommended that the mean temperature in the coldest winter month be used as the critical condition (13, 66). Generally, in spite of widespread and increasing use of sewage lagoons, there are no basic processes and principles of design and operation (16).

The existing formulae for design of waste stabilization pond is based either on empirical or semi-empirical techniques (66). In the design of stabilization ponds Fair et al. (73) utilized the following formula:

$$T_d = \frac{hy_o \Theta^{35-T}}{5.8\ ES} \qquad \text{and}$$

$$C = 5.3 \times 10^{-8} pqy_o \frac{(1.072^{35-T_c})}{ES}$$

in which:

T = Water temperature in °C

p = Population discharging their waste into the pond

T_d = Detention time in days

h = Depth of the pond in ft

y_o = BOD of the waste in ppm

C = Capacity of the pond in acre-feet

q = Gallons per capita per day (gqcd)

E = The efficiency of conversion of light energy into chemical energy which ranges between 2 to 6 per cent

S = Visible light energy in langleys (Calories per day per square centimeter)

Θ = Temperature factor = 1.072

Eckenfelder and O'Connor (26) utilized a similar equation for application to ponds having depths of 2 to 3.5 ft.

$$V = (5.37 \times 10^{-8})\ N_q Y \times 1.072^{35-T}$$

in which:

V = Lagoon volume in acre-ft

N_q = Sewage flow in gallon per day

Y = Influent BOD in ppm

T = Temperature in °C

$$D = \frac{hC_c d}{E\ 1000\ S}$$

in which:

D = Detention period in days

h = Unit heat of combustion of algae in cal per mg

d = Depth of lagoon in ft

E = Efficiency of solar energy conversion

S = Solar insolation expressed in gm per cal per cm^2 per day

C_c = Algal concentration in mg/l

and

$$W_{o_2} = PW_a$$

in which:

W_{o_2} = Net weight of oxygen produced in gm per day

P = Oxygenation factor

W_a = Net weight of algae synthesized in gm per day

Now by substituting these two equations and solving for pond surface area,

$$A = \frac{hW_{o_2}}{PES}$$

If design equations could be based on sound scientific principles designers would be more likely to use more stabilization ponds for sewage treatment (66).

Considering the process of organic equilibrium sought in stabilization ponds it is well recognized that all environmental conditions cannot be optimal in single pond (39). Many scientists have recommended the two cell unit operation for various reasons (42, 44). Hopkins (39) contended that the effluent from the secondary unit will have a much lower algae concentration. In another series of experiments by Hogge and Dobko (40), BOD and coliform reduction in a one cell unit was 80 per cent and 90 per cent, respectively, but with a three cell unit, operating in series, BOD and coliform reduction was 90 per cent and 100 per cent, respectively.

According to Hopkins (39), the design for lagoons operated in series should take into consideration the application of the entire load initially into the primary unit. Carl and Kalda (45) recommended that the BOD loading should not exceed 15 to 20 pounds per acre per day for the total pond surface area.

Problems Associated with Waste Stabilization Pond Operation

According to a survey by Canter (23) odor may be an operational problem in overloaded ponds and in areas with ice cover formation will probably be more severe right after winter and at the beginning of spring. However, if the pond is not highly loaded, there will be no odor even with ice cover (45).

Oswald (24) indicated that in deep ponds or in sludge areas of facultative ponds; sometimes the accumulation of sludge was faster than the rate of methane production, consequently, there would be an accumulation of organic acids which would disturb the activity of the methane bacteria. Odors of H_2S gas were also associated with long periods of anaerobic conditions (17).

In some cases during the hot summer there may be a development of blue-green algae which, after dying, can produce noticable odors (15).

The location of the lagoon with reference to the community is of importance with regard to odor (15, 44). Babbitt and Baumann (58) suggested a distance of 0.5 mile or more to the nearest residence with due regard to prevailing wind.

The effluent of the oxidation pond will carry algal cell in addition to the end products of the biological activity of the pond (55). Canter (23) stated that a high BOD due to algal cells may be a serious problem. Kappe (53) indicated that as lagoons age the concentration of nutrients in the effluent increases and recommended that analysis of pond effluent should be conducted on unfiltered samples in which the algae have been killed and the sample bottles incubated in darkness.

Another problem which has been shown to be a potential danger has been seepage from ponds and the eventual contamination of ground water (15). Chemical pollution, including detergents, is a threat to ground water and needs special consideration with regard to the location of the lagoon (44). Fortunately, nitrate, phosphate and alkyl benzene sulfonate (ABS) in traveling through the ground are very sharply reduced in concentration by what is believed to be absorption and biological action (82).

Existing data on the operation of waste stabilization ponds indicate that mosquito problems can become very important (15, 83). According to Canter (23), Myklebust and Harmston (12), Beadle and Rowe (83) and McGoodwin (15), mosquito problems are associated at least in part with the presence of weeds and floating debris, with the intensity of the mosquito infestation being directly proportional to the extent of the weed growth and the amount of surface solids. Weed problems can be minimized by mechanical removal, by eliminating shallow areas, and by treatment with herbicides (40, 84, 85). The latter should be undertaken with great care since many such chemicals have potentially harmful effects on pond performance.

Other mosquito control procedures that have been recommended are aimed at destroying the larvae. According to Babbitt and Baumann (58), mosquito breeding may be prevented by introducing top-feeding species that are compatible with the pond environment. Scovill (84) has reported that a concentration of 0.25 to 0.49 ppm of Baytex (Bayer 29493) could destroy mosquito larvae, but the operational problem would be to attain a good distribution.

Covering the surface of stagnant water with oil or a combination of oils is a very old practice in malaria eradication programs and is still practiced (86, 87, 88, 89). Kerosene is a very light petroleum derivative which is highly toxic to mosquito larvae and penetrates the trachae rapidly, but its spreading power is low and its volatility is high. In order to overcome these disadvantages, it is frequently mixed with diesel oil (No 37) which is relatively non-volatile at room temperatures (88). In this form, it can be quite easily and economically applied to the surface of practically any body of water for effective mosquito control. Unfortunately, the effects of such a larvicide on the performance of waste stabilization ponds is largely unknown.

Since malaria is considered a significant public health problem in Iran, the potential hazards of any kind of stagnant water as a breeding place for mosquitoes, can not be overlooked (86, 87). In view of this, the application of stabilization ponds as the principal waste treatment process in Iran must be undertaken with mosquito control procedure in mind. It is imperative, then, that the effects of such procedures on pond performance be investigated.

Evaporation Control

Foster (90), Linsley et al. (91) and Mead (92) defined evaporation as a process by which liquid water absorbs heat energy and changes to a gaseous state. It is a very important process in arid areas and should be carefully and accurately determined and controlled (90, 92, 93). Actually the process of evaporation is in two stages, one is evaporation or escape of water molecules to the layers of air close to water surface and the second stage is the removal of the water vapor from the vicinity of the body of water, so that recapture does not occur (90). Water vapor is only 0.6 times the weight of dry air, so it tends to rise and be carried away (93). In turbulent air, the "carry-off" rate is increased, consequently, the evaporation rate is higher than for still air (93). For each gm of water evaporated 600 cal is the maximum input if the water is to be maintained at a fixed temperature (91).

As the sun rises and the temperature of the air increases, relative humidity decreases, but the vapor pressure, which is the actual moisture in the air, remains practically constant (93). Thus, saturation by evaporation is related to air temperature (90).

Linsley et al. (91) stated that evaporation from a body of water was in direct proportion to the wind speed over the water surface and vapor pressure of the air in contact with the water. When the wind is colder than the water and the amount of heat taken from the body of water by the wind is greater than that replaced by solar radiation, evaporation is reduced. According to Linsley et al. (91) a change of 10 per cent in wind speed will change the evaporation rate by 1 to 3 per cent.

Wisler and Brater (94) found that another factor was the depth of the lake. In deep lakes much of the heat, instead of being used for evaporation, can be, due to seasonal overturn, used to warm the entire volume of the water. In deep lakes summer evaporation was less and winter evaporation was higher than in shallow lakes.

As it has been said evaporation is the loss of water molecules at a rate greater than the rate of re-capture. When the air is saturated with water the two processes are equal and there will be no water loss (90, 93). When the relative humidity is 100 per cent, if the temperature of the water is higher than the air temperature, evaporation will take place (93). When the temperature of the water and the air are equal, the vapor pressure gradient, which determines the process of evaporation, will be in proportion to the saturation deficit of say, 100 per cent minus the relative humidity.

Evaporation is reduced in proportion to the amount of salt in solution so that evaporation from the ocean is about 2 to 3 per cent less than from fresh water (93).

Evaporation is expressed according to following formula (93):

$$E = C\ (V - \upsilon)(1 + \frac{W}{10})$$

in which:

E = Evaporation in inches of water for a given unit of time

V = Saturation vapor pressure in inches of mercury at the water temperature

υ = The actual vapor pressure in inches of mercury in the air 25 ft above the ground

W = Wind velocity in miles per hour measured at 25 ft above the ground

C = Coefficient

In the above equation it is necessary to use data related to air temperature and because air temperature fluctuates it must be approximated.

Foster (90) after considering many different experiments developed a complete formula for evaporation:

$$E = 0.771(1.465 - 0.0186\ B)(0.44 + 0.118\ W)(e_s - e_d)$$

in which:

E = Evaporation in inches per 24 hours

B = Mean barometer reading in inches of mercury at 32°F

W = Wind velocity in miles per hour

e_s = Vapor pressure of saturated air in inches of mercury at the temperature of the water surface

e_d = Mean vapor pressure of air in inches of mercury above the water surface

Butler (95) recommended the collection of field information with an evaporation pan but when such collection was not feasible that the following formula be used:

$$E = (e_o - e_2)(0.068 + 0.00246\ V_4)$$

in which:

E = Evaporation in inches per day

e_o = The saturation vapor pressure in inches of mercury at the temperature of the surface of the body of water

e_2= Vapor pressure at a height of 2 mt above the water surface on the upwind side of the water

V_4= Wind in miles per day at a height of 4 meters

Wisler and Brater (94) approached evaporation with another formula as follows:

$$E = C\ (P_w - P_a)$$

in which:

E = Rate of evaporation in inches per day

P_w= Vapor pressure in the film of air near the surface of water

P_a= Vapor pressure in the air above the surface

C = Coefficient that depends on wind velocity

It was reported in 1920 that certain chemicals, by producing a monomolecular film on the surface of water, can reduce evaporation (96, 97). According to Chow (98) the most effective organic compounds that can produce a layer on the surface of the water in order to reduce evaporation were long-chain fatty alcohols called octadecanol, hexadecanal, or ethyl alcohol.

These compounds are composed of hydroxyl (OH) or hydrophylic ions at one end and hydrocarbon or hydrophobic ions at the other end. The molecule is oriented and makes a monomolecular film on the surface of the water (96, 98). According to Franzini (96) the water molecules escaping from a body of water to the atmosphere must pass between the film molecules and this requires additional energy to the end that evaporation is hindered.

Chow (98) stated that oxygen and carbon dioxide were passed through the film but water molecules were impeded. Franzini (96) found that the oxygen content in bodies of water treated with suppressants was not changed significantly from bodies of water with large surface areas, and that this perhaps was due to the presence of spots without suppressants.

Hexadecanol, CH_3- $(CH_2)_{15}$-OH spreads on the water surface easily, but octadecanal, CH_3- $(H_2)_{17}$ OH, does not spread very well (98). A mixture of these two with the help of a solvent such as petroleum ether facilitates the spread, and subsequently the solvent evaporates leaving the suppressant.

Theoretically only 0.02 lb of chemical is necessary to produce a film of 10^{-5} inches on the surface of water (96). It has been shown that certain bacteria feed on these chemicals so the area covered may be gradually reduced (96).

Another problem is the wind which moves the film and so reduces its effectiveness. Consequently the use of a wind-break has been recommended wherever possible (96). For film detection the use of powdered talc was recommended as the talcum would spread if the film was not present. Also in the early morning the moisture rising from uncovered areas could be observed (96, 98). Experiences in Australia, Africa, U.S.A., Israel, Japan and India demonstrated that evaporation was reduced up to 70 per cent (98).

As pointed out above evaporational losses from stabilization ponds located in arid climates can be extensive and, as a result, can have serious effects on the quality of the treated effluent. It is important, then, that those designing and operating ponds in such climates employ evaporation control procedures.

One procedure which merits study is the use of multi-cell ponds designed to reduce the surface area and to minimize the wind and wave action which accelerates evaporation. Another procedure which holds considerable promise is the use of surface films. Kerosene, mentioned earlier as a larvicide, is not chemically very different from the materials used for evaporation control and should be studied for its potential application as both a larvicide and evaporation suppressant.

CHAPTER III

PURPOSE AND SCOPE

In the foregoing discussion, attention was focused on the operation of waste stabilization ponds and their application in countries which economically, demographically and climatically favor this type of process for domestic waste treatment. In arid countries such as Iran, waste stabilization ponds appear to be the optimum treatment process; however, potential problems exist in (a) controlling excessive evaporation in order to minimize the subsequent increases in minerals, suspended solids and algae and in (b) eliminating the waste stabilization ponds as a potential breeding place for mosquitos, a vector of considerable public health significance in Iran.

A survey of the literature indicates that the WSP has been the subject of a large number of field and laboratory investigations under a wide range of loading, lighting and depth considerations; however, no studies have been reported, to date, which were designed to investigate, on a comparative basis, mosquito and evaporation control procedures and their effects on pond performance. It was this need that provided the purpose of this investigation.

Specifically, this investigation was designed to elucidate the effects of kerosene, a larvicide, on controlling the evaporational losses from laboratory waste stabilization ponds and on the efficiency of waste treatment as measured by the BOD and total nitrogen in the effluents of such ponds.

Additionally this research was to study the treatment efficiencies of one and two cell laboratory ponds functioning under the same operational parameters.

Finally, as the presence of algae in the pond effluent has been a matter of question regarding the quality of the treated effluent, this research was undertaken in an effort to investigate the effects of effluent algae on BOD and total nitrogen in centrifuged and uncentrifuged samples from both one and two cell ponds.

CHAPTER IV

EQUIPMENT AND PROCEDURES

The experimental ponds were constructed from glass aquaria arranged into three treatment units. Units hereafter numbered 1 and 2, each consisted of a single tank 23.5 inches long, 12 inches wide and having 14 inches of liquid depth; thus providing 1.96 sq ft of surface area and 2.29 cu ft of volume. Unit number 3 consisted of two tanks (in series) each being 19.5 inches long, 10 inches wide and having 10.25 inches of liquid depth, thus providing a total of 2.70 sq ft of surface area and 2.30 cu ft of volume.

The inlets to the ponds were made of 0.5 inch (internal diameter) polyvinylchloride tubing inserted at a height of 2 inches above the liquid surface. Plexiglass inlet baffles were placed 1 inch from the inlet tube and extended 1 inch below the surface of the ponds.

To maintain the liquid levels listed above, a 0.5 inch diameter outlet, designed as a circular overflow weir, was inserted through the bottom of each tank at a distance of 2 inches from the end wall. Each outlet was equipped with a 1-inch diameter circular baffle extending 1 inch below the surface.

Light was provided by eight 4-ft Westinghouse, 40-watt, "Plant Gro" fluorescent tubes (No 40/GRO) which were installed 6 inches above all liquid surfaces. These lights were operated on a 12-hour on, 12-hour off cycle (6 AM to 6 PM) and provided an average illumination of 250 ft-C during the daylight hours.

Start-up and acclimation of the ponds was initiated by introducing 4 gal of digested sludge from the Oklahoma City Southside Sewage Treatment Plant (a 25-MGD trickling filter operation) to each tank. The remainder of the tank was filled with supernatant from the Choctaw, Oklahoma, Waste Stabilization Pond, a multi-cell WSP serving a community of 4,000. Initially, daily feeding of each pond was accomplished with two 0.5-ℓ doses of raw domestic sewage obtained from the Southside Sewage Treatment Plant. Acclimation continued for 2 weeks during which time analyses for pH were performed in order to monitor the progress toward equilibrium.

When acclimation was achieved, a step-wise program of varying the organic loading rate was initiated in order that the optimum operational parameters might be determined. The results of the BOD, COD, dissolved oxygen and pH determinations conducted during the 15- and 45-lb per acre per day regimens indicated the optimal loading rate for the ponds to be 30 lbs per acre per day. At an influent BOD of 300 mg/l, the detention times were 32.4 days for units 1 and 2 and 23.4 days for unit 3. In order that the detention times as well as the organic loading rates might be equitable for all three units, the influents of units 1 and 2 were diluted with tap water so that the detention times for all three units were equal to 23.4 days.

Experience with continuous feeding utilizing various types of "peristaltic" low discharge pumps indicated that, due to clogging problems resulting from the high suspended solids content of raw domestic sewage, loading rates could not be accurately and uniformly controlled. Consequently feeding of the ponds was accomplished in four to six doses spread over a 4- to 6-hour period.

The larvicide was applied to the surface of unit 2 at an amount equal to 100 gal per acre and was maintained through the 4-months of the investigation. Unit 1 was established as a normal single-cell pond functioning under recommended loading rates, and as such, provided the reference necessary for evaluating both evaporation losses and treatment efficiency.

Evaporational losses from units 1 and 2 were determined by capturing the effluents, correcting the volumes retained for the amount of samples withdrawn and comparing these values with the respective feed rates.

In order to provide a reference for evaluating evaporational losses from the experimental ponds, an additional tank having dimensions identical to tanks 1 and 2, was filled with water, placed in the laboratory environment and observed daily for evaporational losses.

The relative humidity values at which the various evaporation rates were observed was determined by the wet bulb - dry bulb technique and were confirmed utilizing a calibrated hygrometer.

Air movement in the laboratory was provided by an electric fan which furnished an air velocity of 15 to 25 fpm over the surface of the ponds.

Pond performance and treatment efficiencies were evaluated by determining (99) and comparing the BOD, COD, and organic nitrogen content of the influent and effluent of all three experimental ponds. Samples for BOD analysis were taken two to three times each week for the entire 20 weeks of the study while samples for COD analyses were taken three to four times per week for the first 8 weeks after acclimation was achieved. The organic nitrogen values of the influent and all three effluents were determined 2 times weekly for the last 2 months of the study.

Since the effects of the presence of algae on the results of the BOD, COD and nitrogen tests were of concern, part of each sample was centrifuged at 1,135xg for 20 min and the analyses were repeated.

Pond performance was also monitored by observing the pH of the supernatant of each pond. Samples were taken at least once daily (10:00 AM and/or 2:00 PM) from 2 inches below the surface near the outlet of each unit and were analyzed utilizing a Beckman Expanded Scale pH meter.

CHAPTER V

RESULTS AND DISCUSSIONS

15-lb Loading Rate

The results of the BOD and COD analyses conducted during this phase of the investigation are summarized in Table 3. A study of this table along with Table 8 in the Appendix reveals that both single-cell ponds (units 1 and 2) achieved BOD and COD reductions of approximately 55, and 49 per cent, respectively, on an uncentrifuged basis.

TABLE 3

BOD AND COD REDUCTIONS DURING THE
15-lb LOADING RATE

	Percentage Reduction in BOD		Percentage Reduction in COD	
	Centrifuged	Uncentrifuged	Centrifuged	Uncentrifuged
Unit 1	86.8	55.3	93.7	48.5
Unit 2	87.2	54.9	93.7	48.8
Unit 3	87.5	75.5	93.8	64.2

The marked increase in BOD and COD reduction reflected in the centrifuged samples suggests that the algae leaving these ponds had a major influence on the quality of the effluent and that unles the viability of these organisms is maintained, they will exert an appreciable BOD in the receiving stream.

The results of the analyses conducted on the two-cell pond (unit 3) indicates that, on the basis of centrifuged samples, this pond achieved treatment efficiencies comparable to units 1 and 2. However, a comparison of the results observed on uncentrifuged samples reveals that the two-cell unit produced a superior quality effluent. This increase in treatment efficiency might be attributed to a reduction in effluent algae from the second cell of the two-cell pond.

During this phase of the study the pH varied between 8.5 and 9.5 and the dissolved oxygen content never fell below 7 mg/l during the daylight hours, thus indicating that the ponds were functioning normally in the laboratory environment and were well below their maximum loading rates.

45-lb Loading Rate

As may be seen in Table 4 below and Table 9 in the Appendix, the BOD and COD analyses conducted on centrifuged samples indicate lower treatment efficiencies for all three units than those observed at the 15-lb loading rate.

TABLE 4

BOD AND COD REDUCTIONS DURING
THE 45-lb LOADING RATE

	Percentage Reduction in BOD		Percentage Reduction in COD	
	Centrifuged	Uncentrifuged	Centrifuged	Uncentrifuged
Unit 1	79.4	67.9	81.4	54.6
Unit 2	74.7	63.5	80.9	57.0
Unit 3	79.7	68.8	83.4	64.1

This suggests that the higher loading rate was marginal with respect to pond stability and probably would result in a gradual progression of acid phase, anaerobic decomposition.

This is supported by the results of the BOD and COD analyses of the uncentrifuged effluent samples. Even though there was an apparent increase in treatment efficiency at this loading rate, this can not be interpreted as a true increase in pond performance but rather as a decrease in the algae in the effluents of all three units. Such a decrease indicates a deteriorating environment in the pond.

The eminent failure of the pond as an aerobic process was also indicated by the pH values which, after only three days into this phase of the study, averaged only 7.5 at midday, (6 hours of light). In addition the dissolved oxygen concentrations in all three units were always below 1.0 ppm even after 9 hours of illumination.

These analyses together with the subjective observations on odor and gas production at the lower level in the ponds, indicated the optimum loading rate for continued operation to be 30 lbs per acre per day which, incidently, is the standard loading recommended for field ponds.

It is interesting to note, however, that under marginal loading conditions there were no apparent advantages to a two-cell versus a one-cell design.

It was also noted at this point that COD as an analytical technique for monitoring the efficiency of an aerobic biological treatment process, was limited. As the data indicates, the ratio of BOD to COD of the various samples was quite variable and could result in misleading interpretation.

30-lb Loading Rate

The results of the BOD, COD and organic nitrogen determinations are presented in Table 10 in the Appendix and the treatment efficiencies are shown in Table 5.

TABLE 5

PERCENTAGE BOD, COD AND ORGANIC NITROGEN REDUCTIONS DURING THE 30-lb LOADING RATE

		Unit 1	Unit 2	Unit 3
BOD	Centrifuged	96.3	83.8	98.0
	Uncentrifuged	86.09	73.0	91.42
COD	Centrifuged	----	----	----
	Uncentrifuged	73.6	71.0	67.5
Organic Nitrogen	Centrifuged	39.0	39.8	57.62
	Uncentrifuged	30.0	37.47	46.27

By comparison with Tables 3 and 4, it may be seen that the performance, of the ponds at this loading was satisfactory and in general, was superior to that observed at either the higher or lower loading rates studied in the preliminary phases of this investigation. It may also be noted that unit 3, the two-cell pond, was more efficient than units 1 and 2, the single cell ponds, in removing BOD and organic nitrogen measured on both a centrifuged and uncentrifuged basis. However, the COD analyses indicate a higher reduction in the single cell ponds.

A comparison of units 1 and 2, reveals that the pond containing the larvicide achieved a somewhat lower BOD reduction than did its counterpart without the kerosene. This trend was supported by the COD values but was reversed by the organic nitrogen analyses. This leads to the observation that the larvicide had a definite effect on certain parameters of pond performance but in spite of these effects, the pond still performed acceptably.

Visual observations indicated that the algae concentration was quite high in the first cell of unit 3 but was very low in the second cell. This compares with the low effluent algae concentrations observed during the previous studies and is consistent with the high pH values and BOD reductions achieved by this unit.

Other observations on unit 2 indicated that at the interface between the pond liquid and the kerosene, a layer of white microorganisms intermingled with colonies of red organisms gradually developed. This layer reduced the penetration of light and, consequently, lowered the algal activity. This, in turn, contributed to the lower dissolved oxygen content, pH and BOD reduction discussed above.

Isolation and identification of these organisms by Ernest D. King, microbiologist, and Graduate Fellow, Department of Environmental Health, University of Oklahoma, revealed that the white layer was composed of genus Providence, group A and B. Associated bacteria were Actinobacillus actinomycetemcomitans, Chromobacterium janthinum and Pseudomonas aeruginosa. On several occasions, a yeast-like organism identified as Candida krusi was found associated with the bacterial population. The red colonies, which eventually dominated the layer, were identified as a pigmented bacteria, Rhodopseadomonas palustris. According to Breed (100),

<u>Chromobacterium janthinum</u> is found in water and soil and can cause a fatal septicemia in both animals and man.

As may be seen in Table 6, the pH for all three units was 8.1 to 8.7 during the first month of this phase of the investigation. As the study progressed, unit 1, the single cell pond without the larvicide, and unit 3, the two-cell pond, both maintained their original values ± 0.4 pH units with unit 3 being slightly higher on each occasion. On the other hand, unit 2, the pond with the kerosene experienced transient pH conditions before stabilizing at 7.9, a somewhat low but acceptable level.

TABLE 6

AVERAGE pH VALUES OBSERVED DURING
THE 30-lb LOADING RATE

	October	November	December	January
Unit 1	8.6	8.2	8.2	8.3
Unit 2	8.1	7.8	7.9	7.9
Unit 3				
Cell 1	8.7	8.3	8.4	8.4
Cell 2	8.5	8.3	8.5	8.5

The evaporation data presented in Table 7 indicate that the evaporational losses from the waste stabilization ponds were lower than from a comparable body of water. This observation is in direct opposition to the theory that ponds, due their higher suspended solids content, would absorb more radiant energy and therefore would experience higher rates of evaporation.

TABLE 7

MONTHLY AVERAGE EVAPORATIONAL LOSSES
IN INCHES OF WATER PER 24 HOURS

	October	November	December	January
Unit 1	0.137	0.144	0.218	0.258
Unit 2	0.031	0.026	0.042	0.021
Water Tank	-----	0.209	0.269	0.308
Relative Humidity	54.2	47.9	40.6	32.9

It may also be seen that the rate of water loss from both unit 1 and the control tank were inversely proportional to the relative humidity. By comparison, unit 2- the pond with the larvicide- exhibited a much lower rate of evaporation and that these observed rates were apparently independent of the relative humidity. These observations indicate that kerosene, an effective larvicide, can significantly reduce evaporational losses from waste stabilization ponds.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This research was designed to investigate the effects of kerosene, a larvicide extensively employed in mosquito control programs, on the operational performance and on controlling the evaporational losses from waste stabilization ponds operated at 30-lbs of BOD per acre per day under laboratory conditions. Evaporation control was evaluated and compared with a similar pond not containing the larvicide and with a body of water of identical geometry. The effects on pond performance were evaluated by determining the BOD, COD and organic nitrogen reductions along with the dissolved oxygen and pH of the pond with the larvicide and comparing these with similar analyses on both single and two-cell laboratory ponds.

Based on the results of these analyses the following conclusions have been drawn.

1. Waste stabilization ponds operated at standard loading rates and treated with kerosene at levels up to 100 gal per acre can achieve, somewhat reduced, but satisfactory levels of BOD satisfaction (73 per cent) and organic nitrogen removal (37 per cent), and can maintain acceptable dissolved oxygen and pH levels.
2. For stabilization ponds operating in arid to semi-arid regions where evaporation control is desirable, kerosene can function as

both a larvicide and an evaporation suppressant. Evaporational losses can be cut by factors of four to ten depending on the relative humidity.

3. The presence of algae in the effluent from waste stabilization pond can increase the residual BOD by factors as high as 400 per cent and, consequently, can have a significant effect on the quality of the effluent and on the receiving stream.

   It is recommended that future investigation be undertaken in an effort to develop practical and economical procedures for removing algae from pond effluents. Such procedures would not only improve the quality of the flow leaving the pond as well as the receiving stream but also could provide a readily available source of protein.

4. When operated under identical conditions of organic loading, detention time, depth and light, two-cell ponds compared to their one-cell counterparts can achieve and maintain higher reductions in BOD and organic nitrogen as well as higher dissolved oxygen and pH levels. Such increases in treatment efficiency may be due, in part but not totally, to a reduction in the concentration of effluent algae. It is recommended that two-cell ponds be further investigated in order to ascertain the influence of design on evaporational losses and that such studies be expanded to include an evaluation of monomolecular films on controlling evaporation.

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APPENDIX

TABULATED DATA--RESULTS OF BOD, COD, ORGANIC NITROGEN AND EVAPORATIONAL LOSSES DURING THE INVESTIGATION

TABLE 8

MEAN CONCENTRATION AND STANDARD DEVIATION OF INFLUENT AND EFFLUENT BOD AND COD DURING THE 15-lb LOADING RATE

			Influent mg/l	Effluent, mg/l		
				Unit 1	Unit 2	Unit 3
BOD	Centrifuged	$\bar{x}$	--	37	36	38
		s	--	2.2	2.8	1.7
		n	--	4	4	4
	Uncentrifuged	$\bar{x}$	282	126	127	69
		s	40	6.2	5.1	3.6
		n	4	4	4	4
COD	Centrifuged	$\bar{x}$	--	58	58	57
		s	--	3.6	7.3	7.5
		n	--	7	7	7
	Uncentrifuged	$\bar{x}$	921	474	471	329
		s	18	124	120	78
		n	8	8	8	8

$\bar{x}$ = Mean

s = Standard deviation

n = Number of observations

TABLE 9

MEAN CONCENTRATION AND STANDARD DEVIATION OF INFLUENT AND EFFLUENT BOD AND COD DURING THE 45-lb LOADING RATE

			Influent mg/l	Effluent, mg/l		
				Unit 1	Unit 2	Unit 3
BOD	Centrifuged	$\bar{x}$	--	66	81	65
		s	--	15	14	19
		n	--	8	8	8
	Uncentrifuged	$\bar{x}$	321	103	117	100
		s	32	14	12	15
		n	8	8	8	8
COD	Centrifuged	$\bar{x}$	--	155	159	138
		s	--	6.6	14	8.8
		n	--	8	8	8
	Uncentrifuged	$\bar{x}$	834	378	358	299
		s	241	33	16	43
		n	9	7	7	7

TABLE 10

MEAN CONCENTRATION AND STANDARD DEVIATION OF INFLUENT AND EFFLUENT BOD, COD AND ORGANIC NITROGEN DURING THE 30-lb LOADING RATE

			Influent mg/l	Effluent, mg/l Unit 1	Unit 2	Unit 3
BOD	Centrifuged	$\bar{x}$	--	11	42	5.8
		s	--	6.3	15	3.0
		n	--	10	9.0	8.0
	Uncentrifuged	$\bar{x}$	296.3	41.2	80.0	25.4
		s	70.0	10.2	14.3	15.6
		n	27	30	30	30
COD	Centrifuged	$\bar{x}$	--	--	--	--
		s	--	--	--	--
		n	--	--	--	--
	Uncentrifuged	$\bar{x}$	1314	344	380	403
		s	1065	82	215	92
		n	13	19	19	22
Organic Nitrogen	Centrifuged	$\bar{x}$	--	38.0	37.5	26.4
		s	--	5.3	5.8	6.0
		n	--	13	12	12
	Uncentrifuged	$\bar{x}$	62.3	43.59	38.94	33.47
		s	2.8	4.5	2.7	4.1
		n	11	15	10	17

TABLE 11

MEAN AND STANDARD DEVIATION OF EVAPORATIONAL LOSSES

	$\bar{x}$	Inches/day	0.255
Control Tank	s		0.127
	n		60
	$\bar{x}$	Inches/day	0.178
Unit 1	s		0.070
	n		93
	$\bar{x}$	Inches/day	0.039
Unit 2	s		0.028
	n		87
	$\bar{x}$		45.7
Relative Humidity	s		11.1
	n		97