PHYSICAL CHARACTERISTICS OF PILOT-SCALE PONDS

Technical Report

to the

Federal Water Pollution Control Administration

by

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ABSTRACT

The purpose of this study was to determine the physical characteristics of three waste stabilization pond systems. The total detention time and loading of three pilot plants were the same. However, the physical arrangements of the pretreatment anaerobic pond and facultative ponds were different. Each of the three systems included a maturation pond as the final polishing unit.

Physical characteristics were evaluated by measuring diurnal fluctuations in pH, dissolved oxygen (DO), temperature and suspended solids. The experiments were conducted under different climatic conditions.

A well-defined thermal stratification appeared in each pond during the middle of the day. High pH, DO and temperature were observed above the thermal barrier during the day. Below the thermal barrier the pond was essentially void of oxygen, also pH and temperature remained relatively constant.

A deeper aerobic zone was found to exist during the cooler periods. However, there was no significant reduction in suspended solids during the cooler months. A higher influent BOD removal was also obtained in winter.

CONCLUSIONS

1. Anaerobic conditions are more likely to occur in summer than in winter because the intense fermentation in the sludge layer exerts a high oxygen demand in the lower strata. The existence of thermal stratification also prevents mixing between the upper and lower layers.

2. A deeper aerobic zone exists in winter than in summer. Thus light intensity, if above saturation level, is not necessarily the critical a factor in pond performance.

3. High pH values caused by algal blooms should not be overlooked in design because these high pH conditions may curtail some bacterial activity.

4. In semi-tropical areas, it is suggested that the design loading should consider summer condition when nuisance conditions are more likely to occur. It is also suggested that when designing facultative ponds the aerobic and anaerobic zones should be considered separately due to the intense stratification which occurs in these ponds.

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I. INTRODUCTION

Waste stabilization ponds have been employed successfully in the treatment of domestic and industrial wastewaters. In areas where land is reasonably priced and moderate climatic conditions prevail, the waste stabilization pond is an efficient and economical method of wastewater treatment.

In waste stabilization ponds, the treatment process depends upon the effective use of bacteria and algae. The degradation of putrescible organic material occurs as a result of aerobic, facultative and anaerobic microorganisms. The successful operation requires an aerobic environment near the surface, but the normal transfer of oxygen across the air-water interface either by diffusion or by natural mixing is inadequate. Therefore, for successful operation of a pond system it is necessary to employ the photosynthetic action of algae.

It is well known that the principal products of aerobic bacterial oxidation of organic matter are ammonia, carbon dioxide and water; which except for solar energy are the requirements for algal photosynthesis. In the presence of sunlight, algal growth occurs in ponds with conversion of carbon dioxide into organic compounds and free oxygen, which in turn, is used by the bacteria to oxidize the wastes. As long as the algae, in conjunction with natural surface aeration, can provide an excess of oxygen above that required by the aerobic or facultative bacteria, a relatively aerobic environment will be maintained in some sections of the pond.

Algae use carbon dioxide in their photosynthetic activity, and their removal of carbon dioxide is responsible for the relatively high pH conditions. Algae can also reduce the free carbon dioxide concentration below its equilibrium concentration with air and consequently, can cause an even greater increase in pH.

During the period of warm, calm weather, algae tend to accumulate in such numbers as to form visible "blooms". The solar energy absorbed by algae cause the upper layer of the pond to warm readily. The relatively warm surface waters resist mixing with the cooler bottom waters and consequently thermal stratification occurs. The covering of the water surface by these algal mats also shuts off the sunlight essential for photosynthesis in the deeper layer, thereby preventing continued reoxygenation of the deeper waters.

In the absence of free oxygen, conversion of carbohydrates to bacterial cells occurs with formation of organic acids and related compounds. The organic acids may be decomposed anaerobically to methane and carbon dioxide during growth of methane-forming bacteria. This production of organic acids may depress the local pH within the lower strata of the pond.

Several trace elements are required for algal metabolism. Generally, in waste treatment there is no problem in maintaining an adequate level of trace elements. However, nitrogen and phosphorus are frequently deficient in industrial wastes. The lack of these two elements retards the formation of protoplasm and reduces the rate of stabilization.

1-1 Objective

The purpose of this study was to evaluate the physical characteristics of the three pilot-plant pond systems at the Govalle Sewage Treatment Plant in Austin, Texas. It was hoped that an evaluation of the physical characteristics of these experimental ponds would yield valuable information to help improve the present design criteria of waste stabilization ponds.

Mixing appears to be of prime importance in the successful performance of waste stabilization ponds, and by observing the more important physical parameters, it was intended to determine the effect of stratification upon the degree of mixing.

1-2 Scope

The experiment was limited to diurnal measurement of temperature, DO, pH and suspended solids at various depths. These pond systems were designed to treat the domestic sewage at a loading of 70 lb BOD_5/acre/day. Other parameters, including light intensity, wind velocity were measured to support the primary objective.

II. LITERATURE REVIEW

Successful pond operation depends on bacterial decomposition of wastes, mostly under aerobic conditions. In some types of ponds, aerobic conditions can be maintained by the natural photosynthetic process of algae which may provide the required oxygen more economically than mechanical devices.

2-1 Bacterial-Algal Commensalism

As shown in Figure 1, bacterial-algal commensalism is the mechanism responsible for waste stabilization. Bacteria oxidize the organic constituents of the waste. The soluble nutrients produced, primarily ammonia and carbon dioxide, are utilized by algae which, with energy from sunlight, liberate oxygen by photosynthesis. The oxygen produced in many cases is sufficient to meet the bacterial demand in upper pond segments. Anaerobic action in the lower layers and aerobic activity in the surface layers proceed simultaneously resulting in what is termed as facultative system.

As described by Oswald (1966), four principal biological transformations are of concern in ponds. The first of these is the aerobic conversion of dilute solutions of carbohydrates in wastes into bacterial solids, carbon dioxide and water. This reaction probably occurs as follows:

$$6(CH_2O)_x + 5O_2 \longrightarrow (CH_2O)_x + 5CO_2 + 5H_2O + \text{energy} \qquad (2\text{-}1)$$

In the presence of sunlight, algae are responsible for the conversion of carbon dioxide into organic compounds and free oxygen through the process

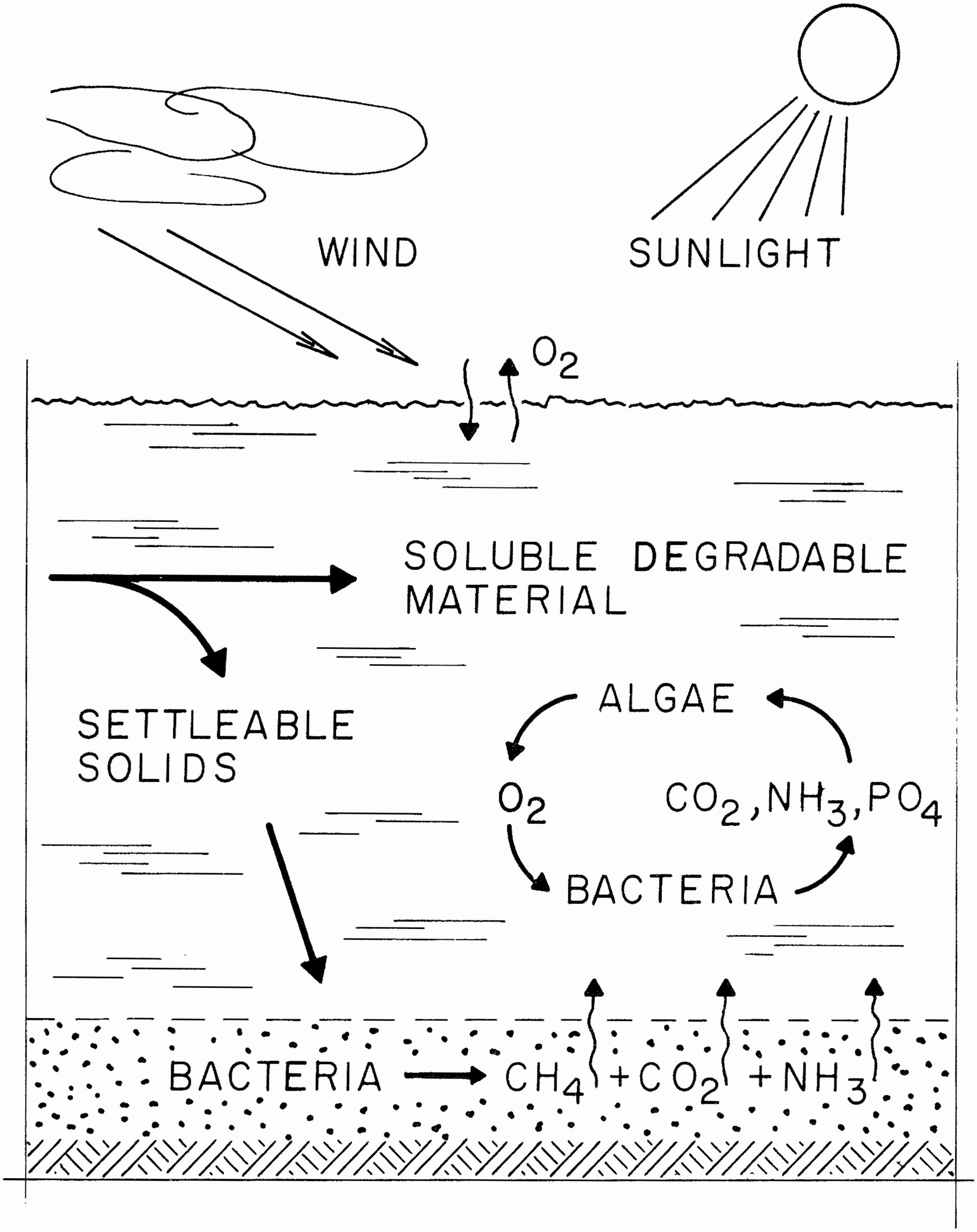


FIG. I
STABILIZATION POND PROCESS

of photosynthetic oxygenation. This reaction is essentially the reverse of aerobic oxidation:

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

The third biological transformation of concern is the organic acid formation. This reaction converts carbohydrates to bacterial cells with the formation of organic acids in a benthal environment void of oxygen:

$$5(CH_2O)_x \longrightarrow (CH_2O)_x + 2CH_3COOH + \text{energy} \quad (2\text{-}3)$$

Once produced, organic acids may be decomposed to methane and carbon dioxide through the action of methane-forming bacteria. In this case, the reaction is:

$$2\ 1/2\ CH_3COOH \longrightarrow (CH_2O)_x + 2\ CH_4 + 2\ CO_2 + \text{energy} \quad (2\text{-}4)$$

2-2 Photosynthesis

Photosynthesis and consequently solar radiation has been termed the most important factors in determining the course and effectiveness of the stabilization process. Studies indicate that only a negligible amount of oxygen is contributed to the liquid by surface reaeration. Mills (1961) reported that no oxygen could be found in facultative ponds two hours after sunset; even though, the pond recovered quickly each morning. Oswald concluded that without vertical mixing caused by wind, atmospheric reaeration will introduce less than 40 pounds of oxygen per acre per day even under anaerobic conditions.

During the period of algal blooms, strong photosynthetic activity tends to produce much greater amounts of oxygen than required by bacteria in oxidizing the organic matter. Krauss (1956) stated that the algae may release twenty times as much oxygen in photosynthesis as they utilize in metabolism.

As a result of photosynthetic action supersaturation of dissolved oxygen may occur. DO values as high as 34 mg/l have been observed in South Africa by Marais (1966), and 250 pounds of oxygen per acre per day have been reported (Mackenthum 1964). During the periods of supersaturation there is a loss of oxygen to the atmosphere. This deaeration can often be observed to occur in the form of visible bubbles of oxygen.

Specifically, photosynthetic oxygenation is a two-phase process. The first phase consists of the absorption of light energy, the removal of hydrogen atoms from water with production of molecular oxygen and the formation of high energy phosphate compounds by the conversion of adenosine diphosphate (ADP) to adenosine triphosphate (ATP). The second is a chemical phase which involves the use of hydrogen atoms, along with the stored energy, to chemically reduced carbon dioxide. The energy absorbed is used to split water molecules into hydrogen and oxygen atoms and to form high energy phosphate compounds in the chloroplasts of the algal cells (Varma & Talbot, 1965).

2-3 Algae

Over 15,000 species of algae have been catalogued, but only four major groups of algae are of importance in the study of waste stabilization ponds (Jackson 1965). Of particular significance are the commonly found green and blue-green algae.

It is recognized that changes in temperature, vitamins, dissolved salts, light intensity, dissolved gases, trace amount of nutrients, geometry of the container, etc. have a marked effect upon the periodicity of algal blooms. However, the interaction of these various factors is extremely complex and not well understood (Fogg 1965). Therefore, it is of importance to examine critically these environmental factors which affects the growth rates; namely temperature, nutrient condition, pH and light intensity.

2-4 pH

The continuous removal of carbon dioxide from the water by algal photosynthesis tends to change the pH of the water. If oxygen is made available through photosynthesis and the pH is favorable, aerobic decomposition occurs with production of carbon dioxide and ammonia. This stimulates further algal growth which in turn boost the pH. The pH will increase up to 10 or more as the algae increase their photosynthetic activity during daylight hours (Neos 1966).

As the pH increase, the alkalinity forms change, with the result that carbon dioxide can be extracted for algal growth both from bicarbonates and carbonates in accordance with the following equilibrium equations.

$$2HCO_3^- \rightleftharpoons CO_3^= + H_2O + CO_2 \quad (2\text{-}5)$$

$$CO_3^= + H_2O \rightleftharpoons 2OH^- + CO_2 \quad (2\text{-}6)$$

Thus, the removal of carbon dioxide by algae tends to cause a shift in the form of alkalinity present from bicarbonate to carbonate, and from carbonate to hydroxyl until an inhibitory pH is reached (Sawyer 1967). Increase pH may also result in deposition of phosphates and inhibition of bacterial oxidation which ultimately leads to a decrease in nutrients for photosynthesis.

At night photosynthesis and uptake of carbon dioxide by the algae greatly decreases, while absorption of carbon dioxide from the atmosphere continues, as a result, the carbonate equilibrium may be shifted to the left and the pH adjusted until equilibrium is reached.

Energy from light is absorbed by the chlorophyll, a green pigment in algae, and through a series of reactions, is transformed into chemical energy which is stored in the molecules of algae. The demonstration of photosynthesis during dark periods indicates that the algae have considerable capacity for storing energy obtained during light periods and can metabolize heterotrophically for some time following the onset of a dark period by converting organic matter to protoplasm.

2-5 Illumination

Variation in light intensity with depth is largely determined by algal density which varies seasonally from pond to pond. One study on light penetration showed that 99 percent of incident light was observed in less than 20 inches of depth. In contrast to this, the depth for absorption of 99 percent of incident light in a nearby artificial lake was almost 21 feet. Towne, et al. (1957) while studying ponds in the Dakotas, found that only one percent of surface light penetrated the pond's upper six inches.

The light intensity in a homogeneous Chlorella Pyrenoidosa suspension decreases according to concentration and depth in compliance with Beer-Lambert Law

$$I = I_o e^{-Kcl} \tag{2-7}$$

where

I = light intensity after passage through some medium

I_o = original light intensity

K = absorption constant

c = concentration of algal cell

l = depth

Algae are capable of withstanding wide variation in light intensity. Beginning at a saturation level for some algae on the order of 500 foot-candles and increasing to 5,000 foot-candles, the photosynthetic rate is independent of light intensity. At an intensity less than saturation the rate decreases, while above 5,000 foot-candles, oxygen production is completely inhibited (Steila, 1968). An expression deriving the fraction of light utilized has been developed by Hermann and Gloyna (1958) is represented as:

$$f = \frac{I_s}{I_o} \left(\ln \frac{I_o}{I_s} + 1 \right) \qquad (2\text{-}8)$$

where

f = fraction of light utilized

I_s = saturation intensity

I_o = original light intensity

2-6 Temperature

Temperature affects photosynthetic oxygen production as well as other biological reactions. However, different species undoubtedly have different temperature and light requirement and it could be that a particular species predominates at a particular season because the prevailing temperature and light conditions favor it.

The optimum oxygen production for some species is obtained at 20°C. Limiting lower and upper value appear to be about 4°C and 37°C, respectively. Yet, the occurrence of blue-green algae in certain situations may be directly attributable to their tolerance of high temperatures. Also, some algae have been observed growing well under a cover of clear ice.

As previously noted, algae use only a small percentage of the solar energy for photosynthesis and the remainder is absorbed as heat; therefore the upper layers of a pond is readily warmed. The resulting relatively warm, less dense surface waters resist mixing with the cooler, denser waters beneath and thermal stratification occurs. Above the thermocline, the temperature increases to the maximum of the day. Below the thermocline, the temperature drops quickly to approximately ground temperature. A difference of 11°C between the surface and four meters depth has been measured during the summer in Israel (Wachs and Berend, 1968). Temperature lapses near the surface of a pond at a rate of 2°C or more per foot have been reported by Oswald (1968), but these rarely continue downward for more than two feet.

Using a continuous type of reactor and a soluble milk compound as substrate, yield a rate constant and temperature relationship (Suwannakarn and Gloyna, 1963).

$$K_T = K_{35} (1.085)^{(T-35)} \qquad (2\text{-}9)$$

where

K_T = reaction rate at temperature T

K_{35} = reaction rate at 35°C

T = temperature in °C

Studies by Oswald (1964) and Marais (1966) on the temperature effects of sludge fermentation indicate there is approximately a sevenfold increase in gas evolution for each rise in temperature of 5°C, over a temperature range of 8°C to 24°C. The observed increase in gas evolution rate for a rise in temperature is probably a compound effect of an increase in metabolic activity plus an increase in the number of active organisms.

Temperature influences are also indicated by the types of organisms present. Cairns (1955) observed that a given type of organism usually had a definite temperature range at which optimum growth occurred. A change in temperature could, therefore, affect the competitive position of a species and their relative distribution in a population. Consequently, the overall rate of oxidation may be influenced.

2-7 Nutrients

It is well known that algal cells which are deficient in nutrients are unable to utilize light as efficiently as cells having unlimited access to nutrient. McCombie (1960) in a discussion of temperature, light and nutrient effects on the green algae, states that temperature acts as a typical controlling factor governing the rate of growth by determining the rate of metabolism. The concentration of nutrient salts shifts the temperature optimum for growth.

Neil (1957) reported a heavy algal bloom in Sturgeon Lake in 1954 when the sunlight was diminished and temperature cool, but when the phosphate content was also relatively high (soluble 0.149 ppm and total 0.165 ppm). He also stated that of all the nutrients necessary in algal metabolism the most critical are often found to be nitrogen and phosphorus.

Gotaas and Oswald (1957) have collected considerable evidence indicating that the species of algae which are effective in photosynthetic oxygen production utilize ammonia as the principal source of nitrogen. Gerloff and Skoog (1957) considered nitorgen to be even a more critical factor in limiting algal production in natural waters since phosphorus is stored in plankton as excess and may approach ten times the actual need. Sylvester and Anderson (1964) reported that Green Lake in Washington has offensive algal blooms, yet the concentration of phosphorus is seldom above 0.01 mg/l.

Aside from nitrogen and phosphorus, magnesium and potassium are essential to algal growth. Magnesium is essential because it is an integral part of chlorophyll molecules and potassium because salts of this metal are prime constituents of algal cell sap.

The majority of algal species use only free carbon dioxide and nutrients in photosynthesis (Neilsen, 1955). However, there is some indication that a few algae utilize the carbonate ion (Osterlind, 1948). Generally, the 0.03 percent of CO_2 normally found in air is sufficient to permit an optimum rate of photosynthesis (Davis, 1953).

Bacteria in the presence of ample amount of organic matter can supply as much as 20 mg/l of CO_2 in a supersaturated state. Logarithmic growth rates of bacteria under favorable conditions can deliver large amounts of CO_2 required for algal bloom development. It should be pointed out that while either aerobic or anaerobic bacteria degrade organic matter and produce high concentration of CO_2 locally, thermal stratification hinders the transfer of this nutrient to all areas of the pond.

III. EQUIPMENT AND PROCEDURES

This research was conducted on a set of pilot-plant scale pond systems specifically constructed for this purpose at the Govalle Sewage Treatment Plant of the City of Austin. These pond systems were designed such that the location of the anaerobic zone was different in each case, since it was felt that the anaerobic zone played a major role in the stabilization of wastewaters. A description of the three different pond systems, as well as the feeding and sampling schedule, test procedure, and instrumentation follows.

3-1 Pilot-Plant Pond

The total detention time and loading of the three systems were the same. System I consisted of an anaerobic pond, a facultative pond and a maturation pond. System II consisted of a facultative pond with a deep trench in the middle of the pond and a maturation pond. System III was similar to that of System II except there was no sludge trench in the facultative pond. The facultative ponds and the maturation ponds were equal in surface area. Figure 2 shows the general layout of the three pond systems.

3-2 Feeding Schedule

Sewage was pumped at a rate of ten gallons per minute (gpm) from the grit chamber into the three pond systems by three automatically controlled pumps. A circular screen was provided around each influent

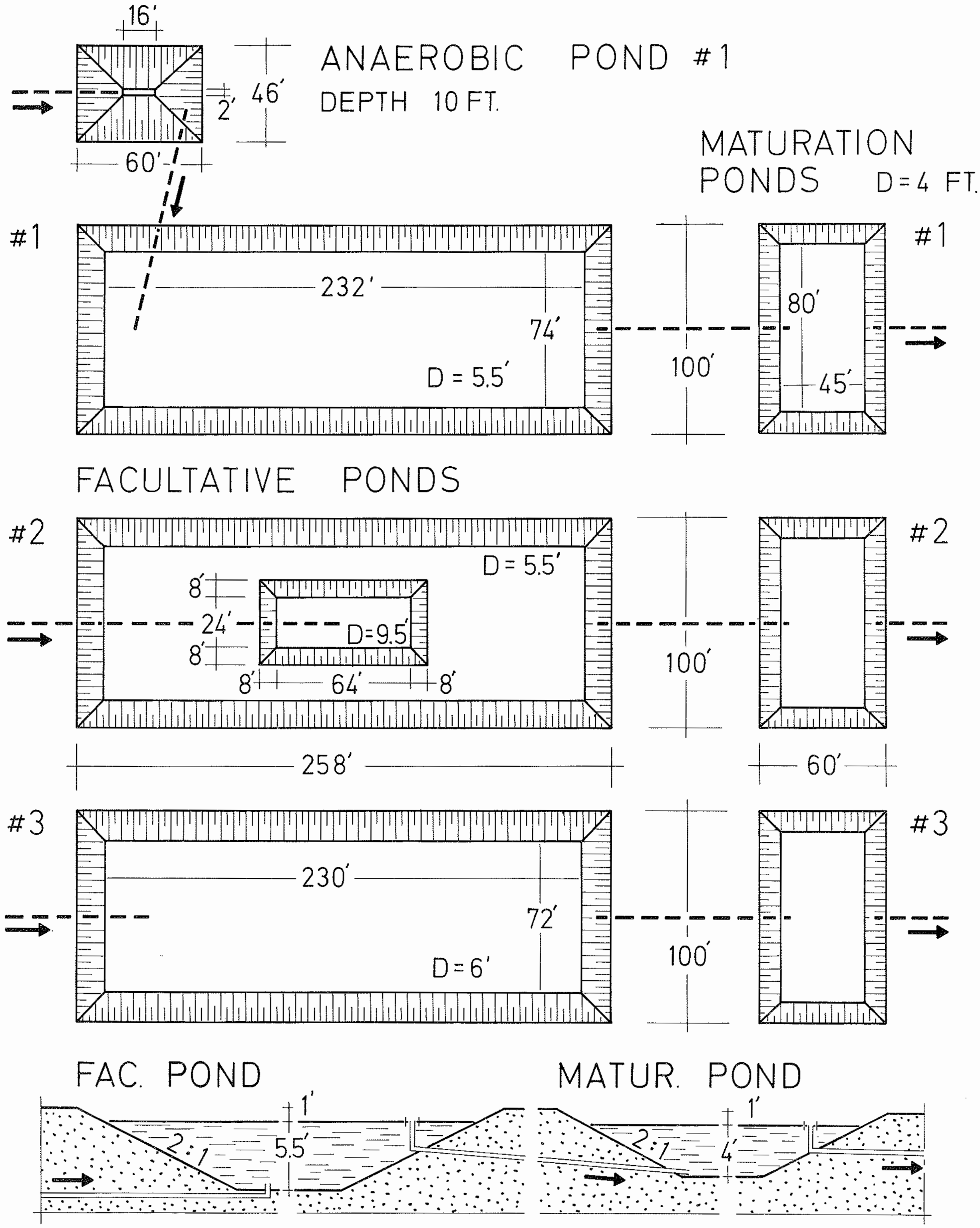


FIG. 2
PILOT WASTE STABILIZATION PONDS

line to prevent clogging of inlet line by large particles. These screens were cleaned daily in order to obtain a more representative sewage. Facultative Pond II and Facultative Pond III both received an average load of 70 lb BOD_5/acre/day while the Anaerobic Pond in System I receives 640 lb BOD_5/acre/day.

3-3 Sampling and Test Procedure

Sampling stations were located at the mid-point of each pond. During the profile studies, a rubber raft was used. The location of the raft was controlled by several stakes which were set near the edge of each pond. Diurnal measurements were conducted once a week for several weeks. Each test was started early in the morning and continued every two hours until relatively stable conditions were observed.

3-4 Instrumentation

The various pond parameters were measured with a minimum of instruments in order to simplify analyses. The pH was determined with a Beckman Electromate pH Meter. Dissolved oxygen was determined by a Galvanic Cell Oxygen Analyzer and Azide Modification of the Winkler Method (Standard Methods). An adjustable thermistor was used to determine the temperature. Millipore Filters (HAWG 047 So) were used to measure suspended solids.

IV. EXPERIMENTAL RESULTS

Pond performance was established on the basis of temperature, pH, dissolved oxygen and suspended solids profile. Experimental results obtained from these studies will be discussed in this chapter.

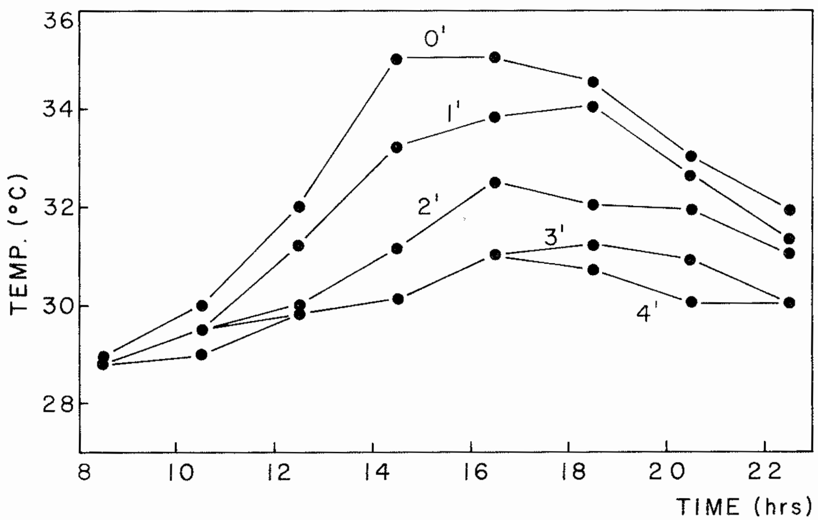
4-1 Temperature

The diurnal temperature profiles, Figure 3, show that thermal stratification appeared in each pond during the middle of the day. Temperatures as high as 38^{o}C were observed near the surface layer; the temperature then dropped quickly to a bottom temperature of about 30^{o}C and remained relatively constant.

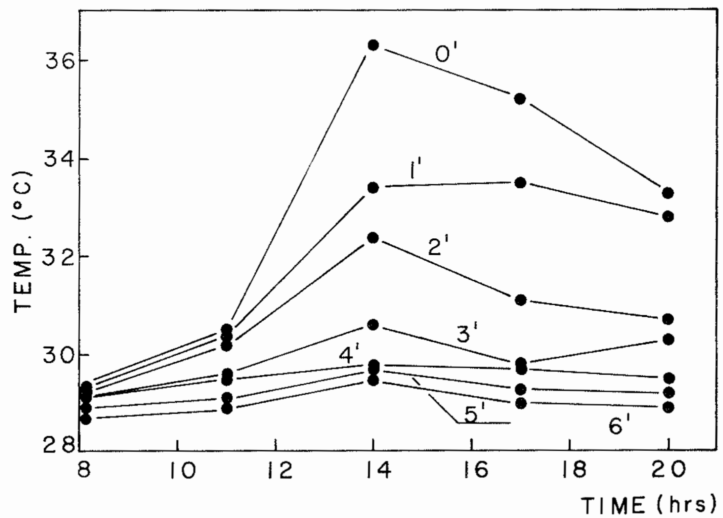
Early in the morning when wind mixing occurred, the temperature was uniform throughout the pond. As the sunlight intensity increased, the temperature increased gradually due to the absorption of solar energy.

The excess heat absorbed by algal expidited the formation of thermal stratification. The temeprature near the surface layer increased rapidly to the maximum of the day while below the warm water layer the temperature remained practically constant at 30^{o}C due to the fact that heavy algal density reduced the availability of the light in the deeper layers.

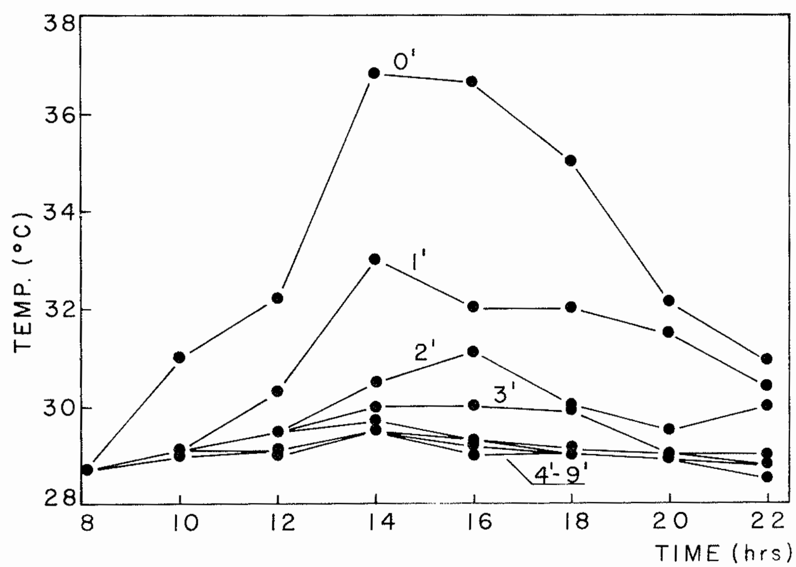
In the evening, when the ambient air temperature was lower than the water temperature, the excess heat on the top layer dissipated away into the atmosphere. As a result, the temperature on the top layer was less than the lower layer.



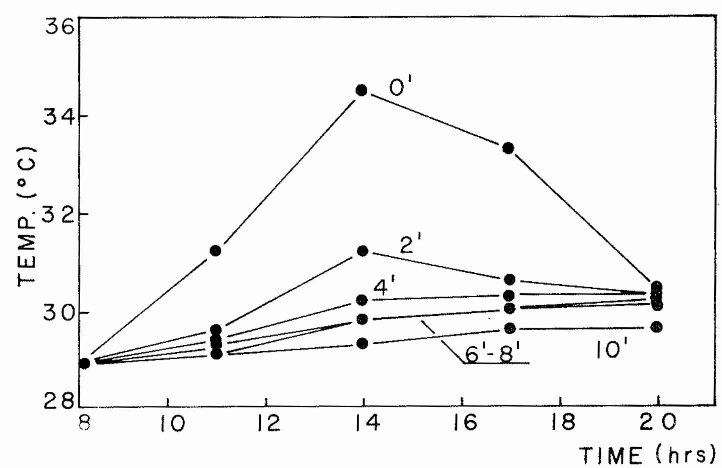
3a: MATURATION POND III (8-10-69)



3c: FAC. POND I (7-21-69)



3b: FAC. POND II (8-12-69)



3d: ANAEROBIC POND I (7-21-69)

FIG. 3 DIURNAL TEMPERATURE PROFILE

The sink of the cooler top layer induced mixing. Thus, the temperature decreased gradually with depth. As long as the air temperature was lower than the water temperature on the top layer, this mixing as a result of overturning continued until a uniform temperature throughout the depths was obtained.

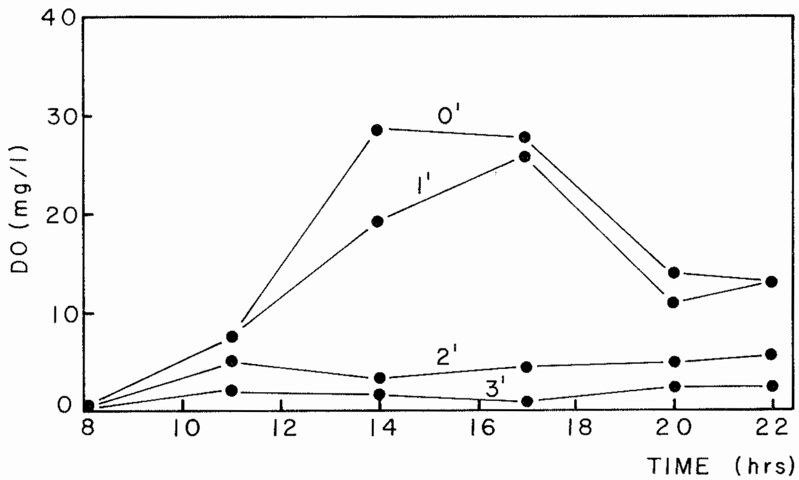
The duration of stratification and degree of mixing depended mainly on the air temperature, water temperature, geometry of the pond and wind conditions. During some summer nights, when the air temperature was relatively high, cooling by radiation was not sufficient to mix the pond and thermal stratification persisted for longer periods.

The stratification tended to inhibit the mixing of the upper layers of water with the lower layers because of density differences. This inhibition of mixing also brought about a stratification in other physical characteristics of the water, namely DO, pH and suspended solids.

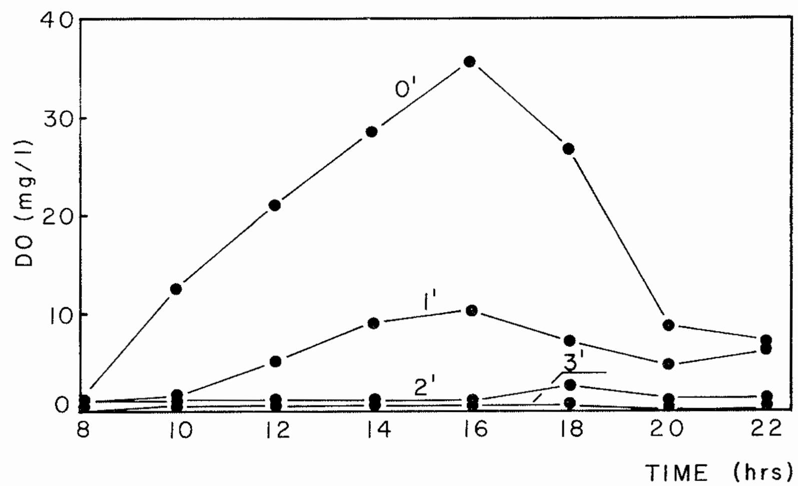
It was found that a higher average temperature was recorded for the deeper pond than the shallow pond even though the shallow pond may temporarily have had higher temperature near the surface during the day. Excess heat was quickly dissipated from the shallow pond at night whereas it seemed to be retained in the deeper pond. Besides, the deeper pond may not have been completely mixed as the shallow pond.

4-2 Dissolved Oxygen

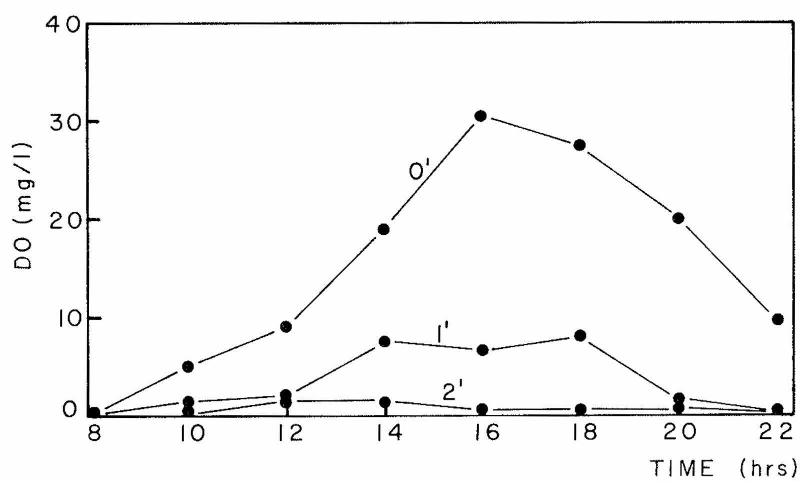
Diurnal variation of dissolved oxygen are illustrated in Figure 4 and coincided with the thermal gradient. Aerobic condition developed



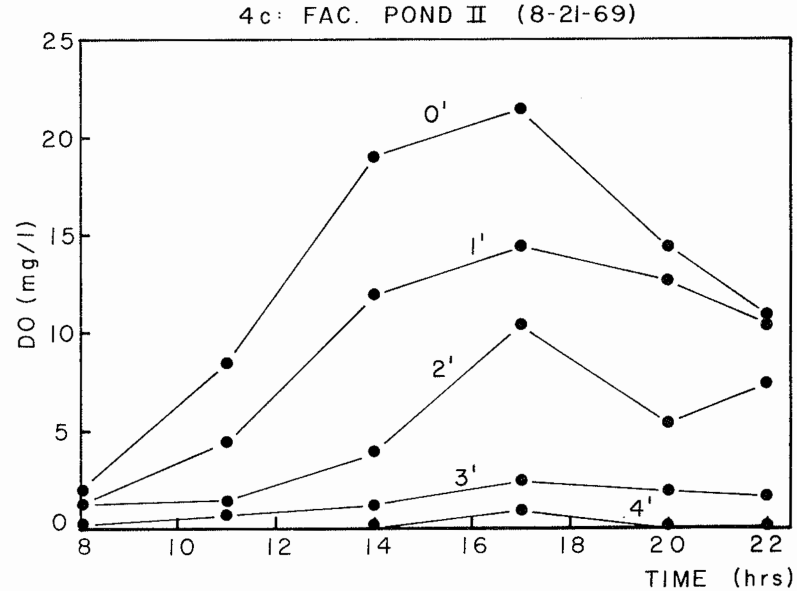
4a: FAC. POND I (7-21-69)



4c: FAC. POND II (8-21-69)



4b: MATURATION POND II (8-12-69)



4d: MATURATION POND I (7-21-69)

FIG. 4 DIURNAL DO PROFILE

near the top layers during the day with dissolved oxygen varying from minute amounts to supersaturation. Below the zone of solar heating the pond remained void of oxygen in this zone.

The presence of excess dissolved oxygen in a pond indicated that oxygen was being produced by algae at a greater rate than it was being utilized by both bacteria and algae.

The amount of oxygen present depends on the algal density as well as light penetration. In general, oxygen produced by algal photosynthesis was greatest in the surface layers and decreased with increasing depth. In some cases when the algae concentrations were highest at deeper depths, higher oxygen concentrations were also observed at this depth.

One study on Maturation Pond III was conducted when the algal density was relatively low. This low turbidity allowed the sunlight to penetrate into the full depth. As a result, aerobic condition prevailed throughout the depth of the pond although no supersaturation was observed. It is interesting to point out that the highest suspended solids concentration appeared at the two-foot depth in the same study when the maximum dissolved oxygen concentration and pH also existed at the same depth. This phenomenon illustrates that at this light intensity, the photosynthetic rate depends on the amount of algal cells present. These parameters are plotted versus depth in Figure 5.

The water temperature, wind velocity and relative humidity

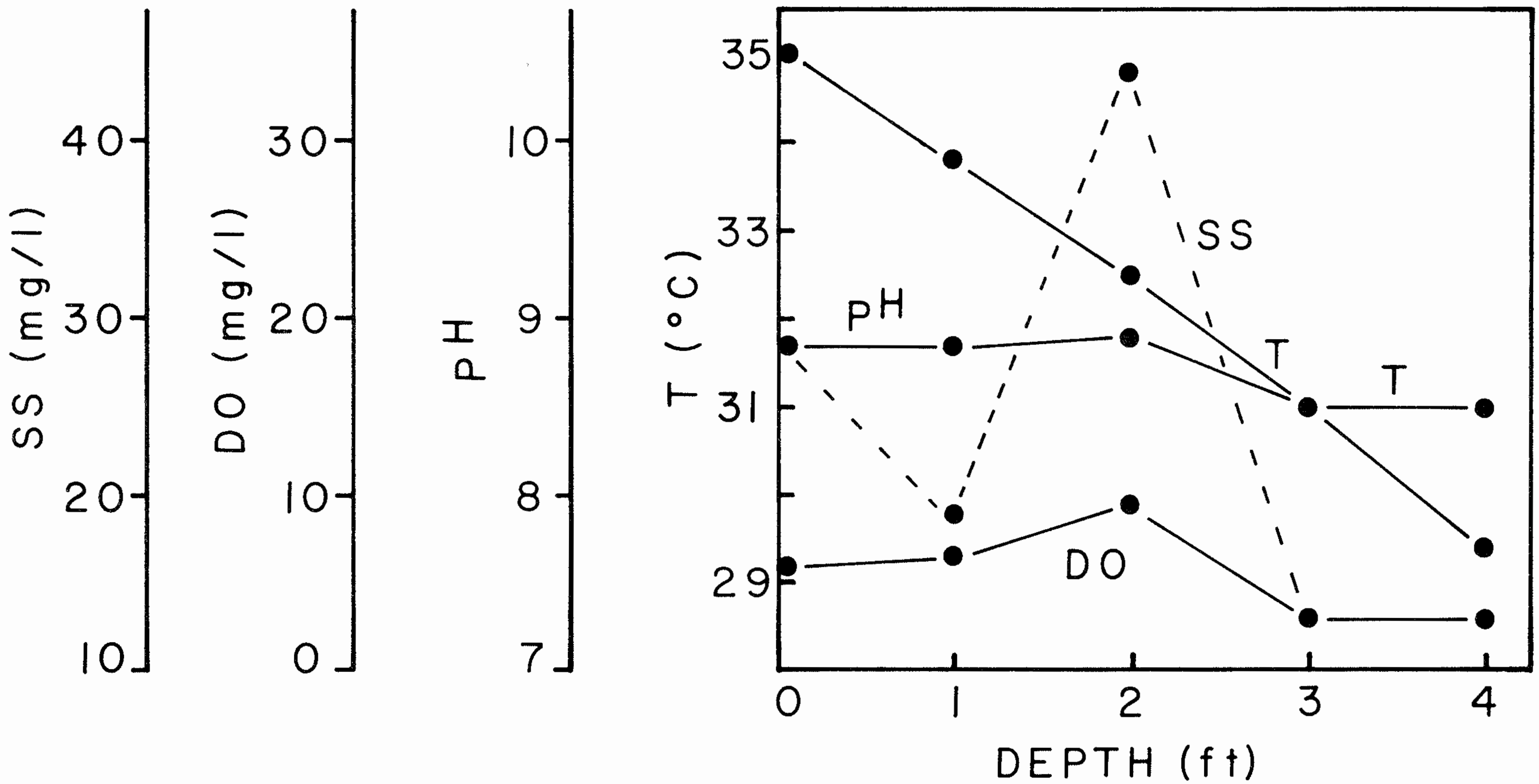


FIG. 5 PROFILE STUDY ON MATURATION POND II
(8-10-69)

of the ambient air determine the amount of oxygen escaping from the surface. In the evening when solar radiation decreased, the amount of oxygen produced by photosynthesis was less than that which escaped from the surface and an overall reduction in the dissolved oxygen concentration in the pond occurred. The reduction in dissolved oxygen concentration continued as respiration requirements exceeded the input of photosynthetic oxygen.

Some measurable dissolved oxygen was also present near the surface of the Anaerobic Pond. Figure 6 shows that some oxygen was present during the middle of the day.

A deeper aerobic zone was found to exist during the cooler periods. However, these appeared to be no significant reduction in suspended solids during the cooler months. Therefore, light penetration and photosynthesis was not a critical factor under this condition. Although bacteria utilized oxygen at a lower rate in breaking down organic matter during the cooler months. The high oxygen demand of the gas products from the bottom by active fermentation during the warmer periods should not be overlooked. Considering the effect of the temperature on anaerobic fermentation, it would seem that an additional depth should be provided in order to maintain a deeper section of the pond under aerobic environment.

4-3 pH

Algae utilize CO_2 as a carbon source resulting in an increase in the pH. A typical diurnal pH profile, Figure 7, shows a difference

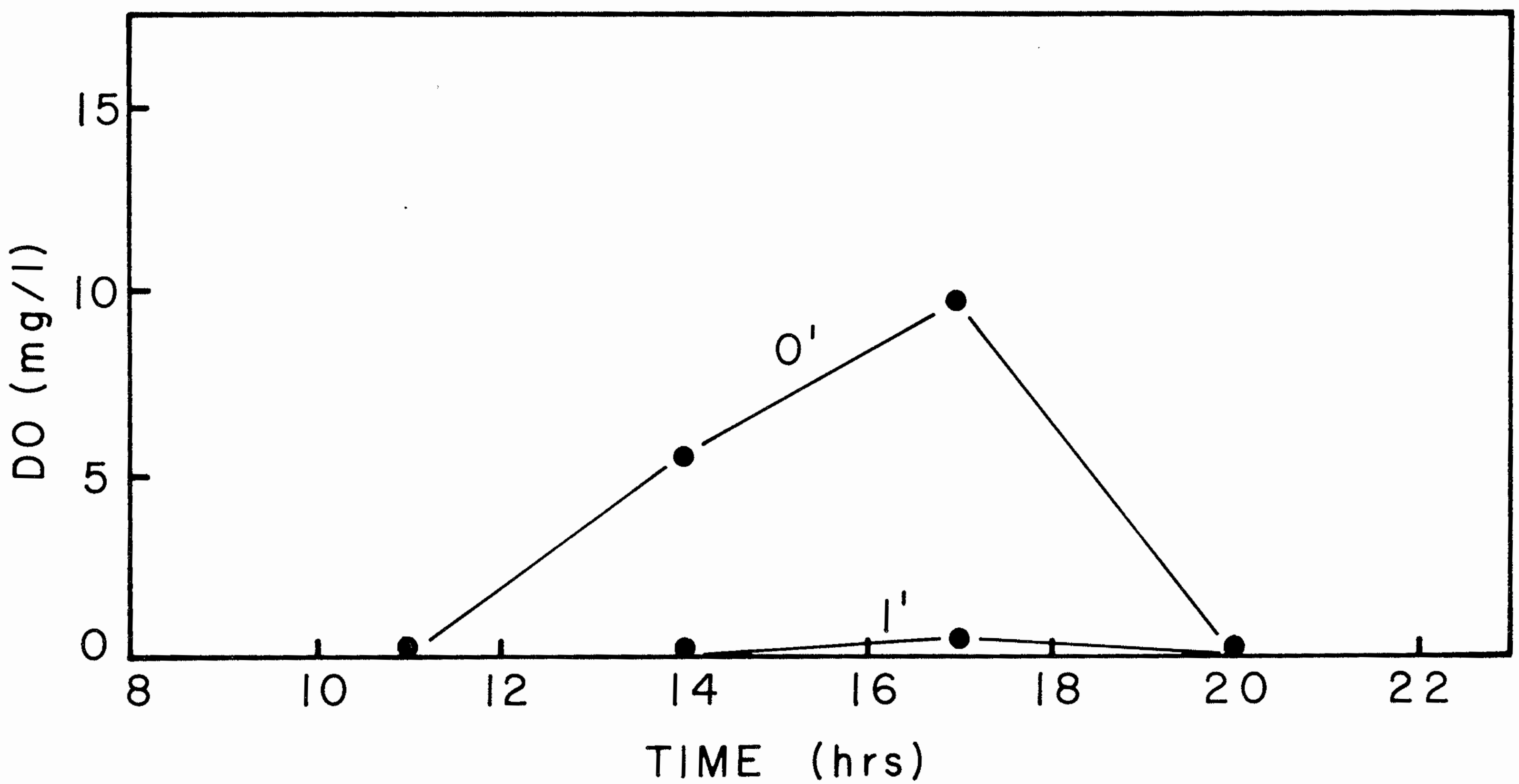
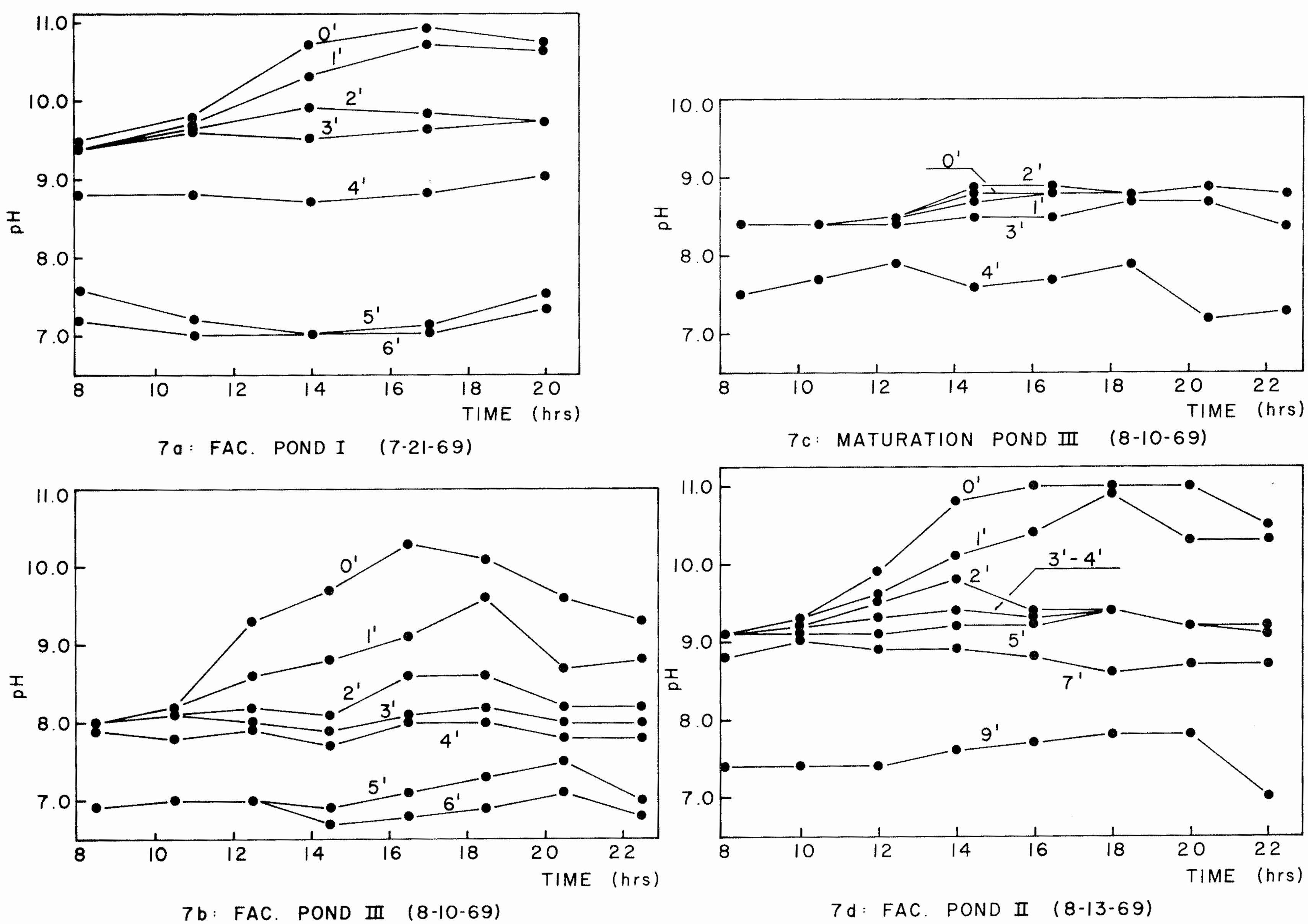


FIG. 6 DO PROFILE ON ANAEROBIC POND I
(7-21-69)



7a: FAC. POND I (7-21-69)

7c: MATURATION POND III (8-10-69)

7b: FAC. POND III (8-10-69)

7d: FAC. POND II (8-13-69)

FIG. 7 DIURNAL pH PROFILE

between the upper layer and the lower layer of the water which relates well to the thermal stratification. A rise in pH to about 9 or higher caused by the uptake of CO_2 by the algae can be seen in the upper layer during the day. Below this layer the pH was uniformly low.

Although CO_2 is produced by bacteria continuously, the algae rapidly use the CO_2 resulting in the elimination of CO_2 from the water. Carbon can also be extracted for algal growth from bicarbonate and carbonate with the result of a further increase in pH until an inhibitory effect on algal photosynthesis occurs. According to the data observed, it seemed that the maximum tolerable value is in the neighborhood of pH 11, (Figure 7), although it is possible that the inhibitory pH values varies with algal species.

The activity of most bacteria is reduced significantly as pH rises above 9. The relatively high pH values near the surface caused by vigorous photosynthesis during the daytime hinders the production of CO_2 by bacteria.

The existence of thermal stratification also blocks the source of CO_2 and organic acid from the lower strata which may neutralize the high pH water on top. Consequently the dissolved oxygen and pH remain high until mixing occurs as a result of an overturn. After this overturn mixing destroys the existence of stratification, a more uniform pH and dissolved oxygen level will exist in pond.

The diurnal variation in pH in the Anaerobic Pond were similar to the dissolved oxygen observations. A pH of 8.5 was observed near the surface and values of about pH 7.0 were noted throughout the rest of the pond.

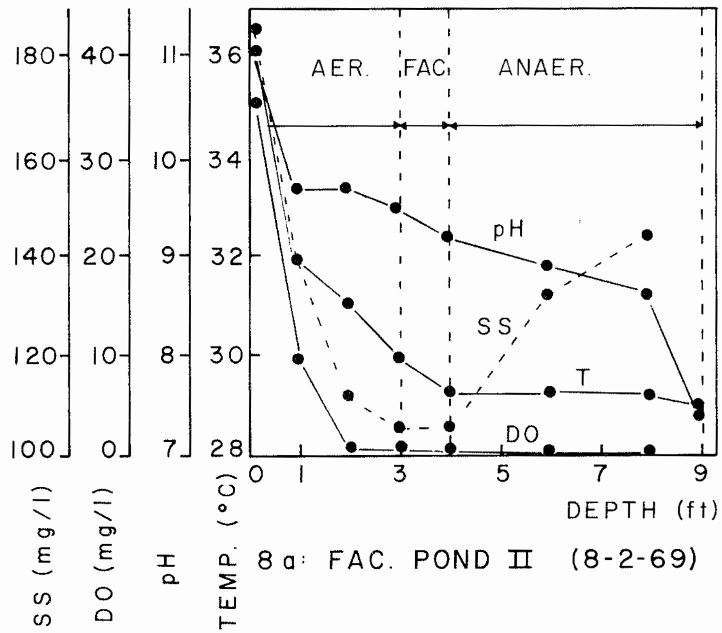
4-4 Suspended Solids

A plot of dissolved oxygen, pH, temperature and suspended solids versus depth at the mid-day for each pond is presented in Figure 8. The suspended solids concentration decreased with increasing depth above the thermal boundary, but it increased with increasing depth. The existence of thermal stratification divided the pond into an aerobic zone and an anaerobic zone.

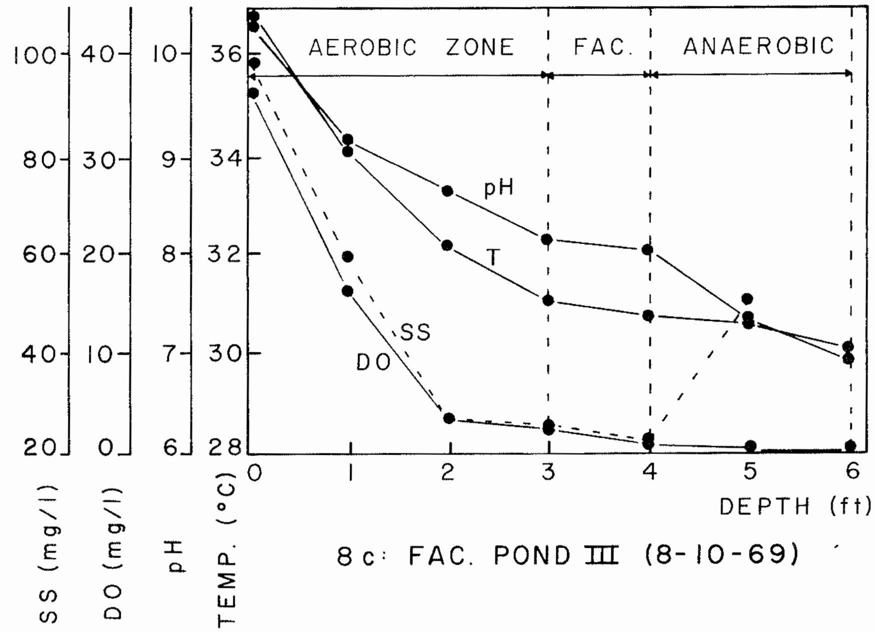
In the aerobic zone the suspended solids were predominately algal cells. This decrease in concentration with depth might be expected on the basis of light penetration. However, there is always some mixing which occurs as a result of thermal and wind driven currents.

The saturation level for the photosynthetic process and algal growth is much less than the light provided at Austin during the summer. The excess radiant energy provided by intense sunlight may actually be detrimental to cell growth. Under such conditions, the motile algae on the surface tend to move downward where the light is more favorable for growth.

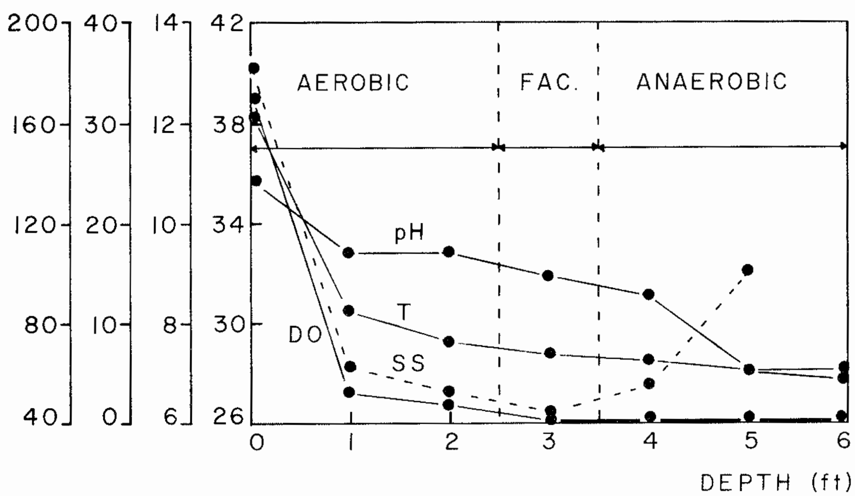
The optimum temperature for algal growth varies from species to species. The distribution of algal cells in ponds depend largely on the optimum temperature of the dominant species. In summer, filamentous



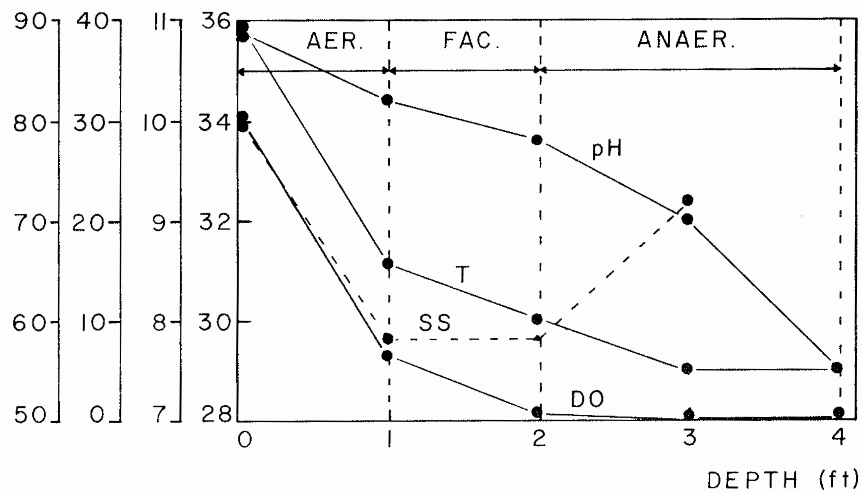
8a: FAC. POND II (8-2-69)



8c: FAC. POND III (8-10-69)



8b: FAC. POND I (8-22-69)



8d: MATURATION POND II (8-2-69)

FIG. 8 VARIATION OF DO, pH, TEMP, AND SS WITH DEPTH blue-green algae were predominant and were frequently found floating near the surface.

The presence of thermal stratification at the middle section of the pond prevented mixing between the upper layer and the lower layer. In the transition zone the dissolved oxygen concentration was low and curtailed the production of algal nutrients by aerobic bacteria. The lack of nutrients and light penetration resulted in a low algal cell concentration in this zone.

The suspended solids measured in the anaerobic zone may consist of benthic algae and suspended sludge particles in addition to the live algal cells. It is possible that the increasing suspended solids with depth was due to colloidal solids and other debris buoyed up by gasification resulting from anaerobic decomposition.

A summary of the experimental results under different climatic conditions is presented in Table 1. It is apparent that pond performance was not as effective in summer as during the cooler periods although the higher temperature in summer was more favorable for bacterial action. High pH above the thermal gradient during the summer appeared to inhibit aerobic action although there was excess oxygen available. The intense anaerobic fermentation in the lower strata also created a large load on the aerobic or facultative zone.

During the cooler periods, little degradation took place in the sludge layer and the pond bottom became primarily a settling zone.

TABLE 1

SUMMARY OF INFLUENT BOD REMOVALS

Pond System	% BOD Removal		Avg. Temp.* (^{o}C)		Avg. pH**	
	Summer	Winter	Summer	Winter	Summer	Winter
System I	96	97	30	12.6	9.8	8.1
System II	95	96	30	12.4	9.7	8.5
System III	95	97	30.5	12.7	9.2	8.4

* Average temperature from 8 a.m. to 10 p.m.

** Average pH in upper layer thermally stratified pond from 8 a.m. to 10 p.m.

The relatively deeper aerobic zone and optimum pH facilitated the aerobic bacterial break-down of organic matter.

Generally, the degradation rate in summer was high, but the BOD feedback from the bottom sludge was also high. In winter, the degradation rate was low, but a low BOD load was received from the sludge. Thus, the two processes tended to balance out and decrease the cyclic variation in effluent BOD.

V. DISCUSSION

Marais (1964) applied the concept "time of explosure" with temperature and degradation action for designing a plug flow process where the influent was assured as a slug of BOD. The effluent BOD for continuous flow was given by:

$$Y_t = \frac{Y}{(V/Q)} \cdot \int_{t=0}^{\infty} e^{-k_1 t} e^{-(Q/V)t} dt \qquad (5-1)$$

where

Y_t = effluent five-day BOD (mg/l)

Y = influent five-day BOD (mg/l)

t = retention time

V = volume of process

Q = flow per day

K = degradation rate constant

Resolving Equation (5-1) and solving in terms of a retention factor, it is possible to develop Equation (5-2).

$$Y_t = \frac{Y}{K_T t+1} \qquad (5-2)$$

where

K_T = degradation rate at temperature T

As indicated in the typical BOD decay relationship for a batch system, the influent BOD is degraded according to Equation (5-3).

$$Y_t = Y e^{-K_T t} \qquad (5-3)$$

Thus, for a fixed percentage reduction it can be shown that for a single pond the ratio of the degradation constants are equal to the ratio of the retention time.

$$\frac{K_{35}}{K_T} = \frac{t_T}{t_{35}} = \Theta^{(35-T)} \qquad (5-4)$$

where

K = reaction rate for various temperatures

t = retention time

T = temperature ($^{\circ}C$)

Studies on a series of laboratory-scale ponds operated at a different temperature, Suwannakarn and Gloyna (1963) indicated that $\Theta = 1.085$ and $K_{35} = 1.2$. The Θ value is close to the Θ 1.072 value that was accepted by Hermann and Gloyna (1958).

Marais and Shaw (1961) noted that for a given liquid depth, there appears to be an upper limit to BOD in a pond which must not be exceeded if aerobic conditions are to be maintained, namely

$$P = \frac{750}{0.6d + 8} \qquad (5-5)$$

where

P = maximum BOD allowed

d = depth

The inhibition of chlorophyll sythesis and the suppression of photosynthetic oxygenation due to the presence of toxic compounds have been studied by Huang and Gloyna (1967). A toxicity factor is suggested to be added to the design equation.

$$V = 1.54 \times 10^{-8} \, Q Y \Theta^{(T_o - T)} \, t_o \, e^{K\left(\frac{C_o}{K_o t_o + 1}\right)} \tag{5-6}$$

where

V = designed volume of the pond, acre-ft

Q = quantity of influent flow, gal/day

Y = 5-day BOD, mg/l

Θ = temperature coefficient

T_o = observed maximum temperature, ^oC

T = expected minimum temperature, ^oC

t_o = reaction time

K = toxicity coefficient

C_o = original concentration, mg/l

K_o = observed rate constant

Marais (1966) considered the influence of the sludge layer and assumed the anaerobic degradation of the sludge to be a first-order reaction. A modified equation is expressed as follows:

$$P_u = \frac{P_{ui}}{Kt + 1} (f_p + c_p f_s) \tag{5-7}$$

where

P_u = ultimate BOD in a pond, mg/l

P_{ui} = ultimate BOD in influent, mg/l

K = degradation constant, 1/day

t = retention time, day

f_p = fraction of influent BOD in pond liquid

f_s = fraction of influent BOD in sludge layer

c_p = fraction of fermentation products from sludge layer entering pond liquid

Equation (5-7) considers the whole liquid depth under aerobic conditions. However, it is difficult to maintain the whole pond under an aerobic environment without employing mechanical devices, especially during the summer when intense stratification occurs.

Past designs are based on an effective aerobic depth and in order to maintain the original design depth under aerobic conditions an additional depth would be required. The BOD reduction obtained below the thermal barrier through anaerobisis has been neglected.

In tropical areas where nuisance conditions are more likely to occur during the summer, facultative pond design should be based on summer rather than winter values. Therefore, it is suggested that pond design should be divided into two separate phases. An aerobic section above the thermal barrier and an anaerobic section for the rest of the pond depth.

Assuming a mean effective depth in the pond, the retention time required for a certain degree of treatment can be calculated from the following equation:

$$Y_t = \frac{Y}{Kt_1 + 1} \qquad (5\text{-}8)$$

where

$Y = $ influent soluble BOD, mg/l

$Y_t = $ effluent BOD, mg/l

$t_1 = $ retention time in aerobic section

$K = $ aerobic degradation rate

This equation can be modified for anaerobic processes by the incorporation of an anaerobic degradation rate constant as follows:

$$Y_t = \frac{Y_o}{K_s t_2 + 1} (f_p + c_p f_s) \qquad (5\text{-}9)$$

where

$K_s = $ anaerobic degradation rate

$t_2 = $ retention time in anaerobic section

A total retention time can be obtained through mass balance by assuming aerobic depth (d_1) and anaerobic depth (d_2).

$$t = \frac{d_1 t_1 + d_2 t_2}{d_1 + d_2} \qquad (5\text{-}10)$$

where

$t = $ total retention time

$d_1 = $ aerobic depth

$d_2 = $ anaerobic depth

The above equations are based on the assumption that aerobic and anaerobic processes take place without any mixing. Although the mixing does occur as a result of overturning mixing and may cause a complete mixing in ponds, it is believed that the total BOD removal will remain unchanged.

Usually the occurrence of algal blooms and the resulting high pH are overlooked in practical designs. Yet, these blooms do occur and the efficiency decreases. Algal cells leaving the pond also contribute to the total effluent BOD.

The commonly recommended design depth is four to five feet. However, additional depth, particularly where settleable solids are present, provides added flexibility. A shallow pond provides better dilution and disperse of nutrient solids, but it is also too sensitive to changes in environmental conditions. By keeping the ponds sufficiently deep, some periodically occurring nuisance conditions can be prevented. A deep pond also may be a more economical design, although light energy may not penetrate to the full depth, the latter may not be a major significance nor desirable.

APPENDIX

TABLE 2

PROFILE CHARACTERISTICS

ANAEROBIC POND I
July 21, 1969

depth (ft)	8:00	11:00	14:00	17:00	20:00
		Temp. (°C)			
0	28.9	31.2	34.5	33.3	30.4
2	28.9	29.6	31.2	30.6	30.3
4	28.9	29.4	30.2	30.3	30.3
6	28.9	29.3	29.8	30.0	30.2
8	28.9	29.1	29.8	30.0	30.1
10	28.9	29.1	29.3	29.6	29.6
		pH			
0	7.2	7.3	7.5	7.9	7.2
2	7.2	7.3	7.3	7.2	7.1
4	7.2	7.2	7.2	7.2	7.1
6	6.9	7.2	7.1	7.2	7.1
8	6.9	7.2	7.1	7.1	7.1
10	6.8	7.1	6.9	6.9	6.9
		Dissolved Oxygen (mg/l)			
0	0	0	5.6	9.8	0
2	0	0	0	0.5	0
4	0	0	0	0	0
6	0	0	0	0	0
8	0	0	0	0	0
10	0	0	0	0	0

FACULTATIVE POND I
July 21, 1969

depth (ft)	8:00	11:00	14:00	17:00	20:00	22:00
			Temp. (°C)			
0	29.4	30.5	36.3	35.2	33.3	--
1	29.3	30.4	33.4	33.5	32.8	--
2	29.2	30.2	32.4	31.1	30.7	--
3	29.1	29.6	30.6	29.8	30.3	--
4	29.1	29.5	29.8	29.7	29.5	--
5	28.9	29.1	29.7	29.3	29.2	--
6	28.7	28.9	29.5	29.0	28.9	--
			pH			
0	9.5	9.8	10.7	10.9	10.7	--
1	9.4	9.7	10.3	10.7	10.6	--
2	9.4	10.0	9.9	9.8	9.7	--
3	9.4	9.6	9.5	9.6	9.7	--
4	8.8	8.8	8.7	8.8	9.0	--
5	7.6	7.2	7.0	7.1	7.5	--
6	7.2	7.0	7.1	7.0	7.3	--
			Dissolved Oxygen (mg/l)			
0	0.4	7.4	28.3	27.4	13.6	12.8
1	0.4	7.3	19.1	25.3	10.5	12.8
2	0.2	5.0	3.1	4.2	4.4	5.1
3	0.2	1.9	1.7	0.2	2.0	1.9
4	0	0	0	0	0.9	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0

MATURATION POND I
August 22, 1969

depth (ft)	9:00	11:00	13:00	15:00	18:00	21:00
			Temp. (^{o}C)			
0	29.0	34.0	36.1	38.3	36.5	--
1	28.7	29.4	29.8	30.9	31.6	--
2	28.6	28.7	28.7	29.0	29.1	--
3	28.0	28.2	28.2	28.5	28.2	--
4	27.5	27.6	27.6	27.8	27.8	--
			pH			
0	9.3	10.3	10.4	10.5	10.7	--
1	9.5	9.5	9.6	9.6	9.5	--
2	9.2	9.3	9.1	9.2	9.2	--
3	9.2	9.2	8.6	8.2	8.8	--
4	7.5	7.7	7.7	8.2	8.0	--
			Dissolved Oxygen (mg/l)			
0	0.1	23.0	22.6	27.8	24.0	5.0
1	0	2.6	5.3	10.5	5.0	0
2	0	0	0.3	1.3	0.5	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0

FACULTATIVE POND II
August 2, 1969

depth (ft)	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
	Temp. (^{o}C)							
0	28.7	31.0	32.2	36.8	36.6	35.0	32.1	30.9
1	28.7	29.1	30.3	33.0	32.0	32.0	31.5	30.4
2	28.7	29.1	29.5	30.5	31.1	30.0	29.5	30.0
3	28.7	29.1	29.5	30.0	30.0	29.9	29.0	29.0
4	28.7	29.1	29.5	29.7	29.3	29.1	29.0	28.8
6	28.5	29.1	29.1	29.5	29.3	29.0	28.9	28.8
8	28.5	29.0	29.1	29.5	29.2	29.0	28.9	28.5
9	28.5	29.0	29.0	29.5	29.0	29.0	28.9	28.5
	pH							
0	8.8	10.1	10.7	11.0	11.1	11.0	10.8	10.2
1	8.8	9.2	9.6	10.2	10.5	10.3	10.2	9.7
2	8.8	9.2	9.4	9.5	9.7	9.3	9.3	9.3
3	8.8	9.1	9.3	9.4	9.5	9.2	9.2	9.1
4	8.8	9.1	9.2	9.2	9.2	9.1	9.1	9.1
6	8.5	8.8	8.9	8.9	8.9	8.9	8.8	8.9
8	8.1	8.4	8.4	8.6	8.6	8.6	8.5	8.5
9	7.3	7.4	7.8	7.9	7.4	7.7	7.6	7.2
	Dissolved Oxygen (mg/l)							
0	1.1	12.7	2.9	28.4	35.6	26.5	8.3	7.2
1	1.1	1.6	5.0	9.0	10.2	6.8	4.5	6.0
2	0.8	0.8	0.9	1.1	1.1	2.5	1.3	1.0
3	0	0.4	0.5	0.7	0.3	0.2	0	0
4	0	0.4	0.4	0.6	0.5	0.4	0.5	0
6	0	0	0	0	0.3	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0

MATURATION POND II
August 13, 1969

depth (ft)	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
				Temp. (°C)				
0	27.7	29.0	31.0	35.5	37.0	36.1	34.0	31.0
1	27.7	28.5	29.8	30.5	32.0	32.5	32.3	30.8
2	27.6	28.0	28.3	29.8	29.1	29.2	29.0	28.9
3	27.5	28.0	28.3	28.6	28.8	29.0	28.5	27.8
4	27.3	28.0	28.3	28.5	29.0	29.0	28.0	27.6
				pH				
0	9.5	9.8	10.1	10.9	11.0	11.0	11.0	10.7
1	9.5	9.6	10.1	10.3	10.3	10.5	10.7	10.5
2	9.4	9.3	9.2	10.1	9.6	9.6	9.8	9.8
3	8.4	7.8	8.0	7.7	7.5	8.3	8.3	7.8
4	6.7	6.8	6.7	6.7	7.3	6.8	6.7	6.8
				Dissolved Oxygen (mg/l)				
0	0	6.1	8.3	25.3	28.5	28.8	25.5	10.6
1	0	2.2	4.4	4.1	5.0	5.7	6.5	5.2
2	0	0	0.2	0.7	0.5	1.3	0.2	0.6
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0

FACULTATIVE POND III
August 10, 1969

depth (ft)	8:30	10:30	12:30	14:30	16:30	18:30	20:30	22:30
	Temp. (^{o}C)							
0	29.5	30.0	33.0	35.5	36.8	36.0	33.0	32.0
1	29.4	29.8	32.0	32.5	34.0	34.8	32.0	31.9
2	29.4	29.7	31.0	31.0	32.1	32.0	30.8	30.5
3	29.4	29.7	30.5	30.8	31.0	31.0	30.0	30.0
4	29.1	29.5	29.8	30.0	30.7	30.3	29.8	29.8
5	29.0	29.0	30.0	29.8	30.5	29.8	29.2	29.0
6	29.0	29.0	29.8	29.6	30.0	29.8	29.0	28.7
	pH							
0	8.0	8.2	9.3	9.7	10.3	10.1	9.6	9.3
1	8.0	8.2	8.6	8.8	9.1	9.6	8.7	8.8
2	8.0	8.1	8.2	8.1	8.6	8.6	8.2	8.2
3	8.0	8.1	8.0	7.9	8.1	8.2	8.0	8.0
4	7.9	7.8	7.9	7.7	8.0	8.0	7.8	7.8
5	6.9	7.0	7.0	6.9	7.1	7.3	7.5	7.0
6	6.9	7.0	7.0	6.7	6.8	6.9	7.1	6.8
	Dissolved Oxygen (mg/l)							
0	2.2	4.3	13.9	13.7	36.0	12.3	12.8	7.4
1	2.2	4.2	15.0	11.6	16.0	8.0	12.4	7.3
2	2.1	4.4	4.2	6.4	3.1	1.6	1.3	1.6
3	2.4	2.9	3.1	3.0	2.2	1.4	1.4	0.6
4	0.8	1.0	0.9	0.4	0.3	0.9	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0

MATURATION POND III
August 10, 1969

depth (ft)	8:30	10:30	12:30	14:30	16:30	18:30	20:30	22:30
				Temp. (^{o}C)				
0	29.0	30.0	32.0	35.0	35.0	34.5	33.0	31.9
1	28.8	29.5	31.2	33.2	33.8	34.0	32.6	31.3
2	28.8	29.5	30.0	31.1	32.5	32.0	31.9	31.0
3	28.8	29.5	29.8	30.1	31.0	31.2	30.9	30.0
4	28.8	29.0	29.8	30.1	31.0	30.7	30.0	30.0
				pH				
0	8.4	8.4	8.5	8.8	8.8	8.8	8.9	8.8
1	8.4	8.4	8.5	8.7	8.8	8.8	8.9	8.8
2	8.4	8.4	8.5	8.9	8.9	8.8	8.9	8.8
3	8.4	8.4	8.4	8.5	8.5	8.7	8.7	8.4
4	7.5	7.7	7.9	7.6	7.7	7.9	7.2	7.3
				Dissolved Oxygen (mg/l)				
0	0.5	1.1	2.3	5.2	5.8	5.8	5.3	4.7
1	0.8	1.0	2.3	4.5	6.3	6.9	4.9	4.6
2	0.7	0.8	2.0	6.6	9.5	7.6	5.4	4.5
3	0.9	0.6	1.0	1.9	3.1	3.0	2.5	1.0
4	0	0	0.4	1.1	3.1	0.3	0	0

February 8, 1970

Weather condition - Windy

Temp. (°C)

depth (ft)	A-1	F-1	M-1	F-2	M-2	F-3	M-3
0	19.8	17.2	18.2	16.5	17.8	17.0	17.2
1	18.5	17.0	18.0	16.2	17.5	16.8	16.8
2	17.0	17.0	14.2	15.0	13.2	16.2	13.2
3	16.5	13.6	12.1	12.5	12.0	13.0	12.0
4	16.5	11.5	11.2	12.0	11.2	12.0	11.2
5	16.2	11.0		12.0		11.2	
6	16.2			11.5		11.2	
7	16.0			11.4			
8	16.0			11.2			

pH

depth (ft)	ANA	F-1	M-1	F-2	M-2	F-3	M-3
0	7.4	8.2	8.6	8.9	9.4	9.4	9.4
1	-	8.2	8.6	8.9	9.2	9.2	9.3
2	7.4	8.1	8.2	8.3	8.7	9.0	9.0
3	-	7.7	7.8	8.2	7.8	8.8	8.9
4	7.3	7.6	7.3	8.0	7.4	8.7	8.6
5	-	7.4		7.7		8.5	
6	7.3			7.6		8.3	
7	-			7.5			
8	7.3			7.0			

Dissolved Oxygen (mg/l)

depth (ft)	ANA	F-1	M-1	F-2	M-2	F-3	M-3
0	1.3	9.0	15.2	14.0	16.7	17.8	16.7
1	0.5	10.5	12.8	13.8	15.7	17.6	15.0
2	0	7.6	8.1	5.3	4.6	10.2	8.1
3	0	2.7	2.7	3.6	0.7	1.9	1.7
4	0	0.3	0	1.1	0	1.3	0
5	0	0		0.2		0.2	
6	0	0		0		0	

BIBLIOGRAPHY

1. Cairns, J., Jr., "Effects of Increased Temperature on Aquatic Organisms," Proceedings: 10th Industrial Waste Conference, Purdue University, 346 pp. (1955).

2. Davis, E. A., et al., In: Carnegie Institute of Washington Publication 600, pp. 105-153 (1953).

3. Fogg, G. E., Algal Cultures and Phytoplankton Ecology, The University of Wisconsin Press, Madison, Wisconsin (1963).

4. Gerloff and Skoog, "Nitrogen as a Limiting Factor for the Growth of Microcystis Aeruguinosa in South Wisconsin Lakes," Ecology, 38:4, p. 561 (1957).

5. Gotaas, H. B., and Oswald, W. J., "Photosynthesis in Sewage Treatment," A.S.C.E. Proc. Separate #686, Trans. A.S.C.E. 81 (1957).

6. Hermann, E. R., and Gloyna, E. F., Waste Stabilization Ponds III Formulation of Design Equations, Sewage and Industrial Wastes, 30, pp. 963-975 (1958).

7. Huang, J. C., and Gloyna, E. F., "Effects of Organic Compounds on Photosynthetic Oxygenation," Dissertation presented to The University of Texas at Austin (1967).

8. Jackson, H. W., Types of Algae In: Aquatic Biology for Engineers (USPHS Training Course Manual) Cincinnati, Ohio, Robert A. Taft Sanitary Engineering Center (1965).

9. Krauss, R. W., "Photosynthesis in the Algae," Industrial and Engineering Chemistry, 48, pp. 1449-1458 (1956).

10. Mackenthum, K. M., "Biology of Waste Stabilization Ponds," Bio-Oxidation of Industrial Wastes (Course Manual USPHS) (1964).

11. Marais, G. V. R., "New Factors in the Design, Operation and Performance of Waste Stabilization Ponds," Bulletin of World Health Organization, pp. 737-763 (1966).

12. Marais, G. V. R., and Shaw, V. A., "A Rational Theory for

Design of Sewage Stabilization Ponds in Central and South Africa," Transaction South Africa Institution Civil Engineers, 3, p. 205.

13. McCombie, A. M., "Actions and Interactions of Temperature, Light Intensity and Nutrient Concentration on the Growth of the Green Alga Chlamydomonas reinhardi Dangeard," Journal Fish Research Board, Canada, 17, p. 871.

14. Mills, D. A., "Depth and Loading Rates of Oxidation Ponds," Water and Sewage Works, 108, p. 345 (1961).

15. Neil, J. H., "Problems and Control of Unnatural Fertilization of Lake Waters," Proceedings of the 12th Purdue Industrial Waste Conference, 94, p. 301 (1957).

16. Neilsen, E. S., "Carbon Dioxide as Carbon Source and Narcotic in Photosynthesis and Growth of Chlorella Pyrenoidosa, Physiologia Plantarium, 8, p. 317 (1955).

17. Neos, C., and Varma, M. M., "The Removal of Phosphates by Algae," Water and Sewage Works, 113, p. 456 (1966).

18. Osterlind, S., "The Retarding Effect of High Concentrations of Carbon Dioxide and Carbonates Ions on the Growth of a Green Alga," Physiology Plantarium, 1, p. 170 (1948).

19. Oswald, W. J., "Advances in Stabilization Pond Design," Proceedings of the 3rd Sanitation Engineering Conference, Vanderbilt University, Nashville, Tennessee (1964).

20. Oswald, W. J., Basis for Waste Stabilization Pond Designs, In: Special Lecture Series in Water Quality Improvement, University of Texas Press (1966).

21. Oswald, W. J., "Advances in Anaerobic Pond Systems Design," Advances in Water Quality Improvement, University of Texas Press, p. 409 (1968).

22. Sawyer, C. N., Chemistry for Sanitary Engineers, McGraw-Hill, New York, N.Y., p. 338 (1967).

23. Streila, Donald, "The Waste Stabilization Pond: A Recent Cultural Innovation," Unpublished paper (1968).

24. Suwannakarn, V. and Gloyna, G. F., "Temperature Effects on Waste Stabilization Pond Treatment," Dissertation presented to The University of Texas at Austin (1963).

25. Sylvester, R. O., and Anderson, G. C., "A Lake's Response to Environment," Journal of Sanitary Engineering Division of American Society of Civil Engineers, 90:1, (1964).

26. Towne, W. W., Bartsch, A. F., and Davis, W. H., "Raw Sewage Stabilization Ponds in the Dakotas," Sewage Industrial Wastes, 29, p. 337 (1957).

27. Varma, M. M., and Talbot, R. S., "Reaction Rates of Photosynthesis," Proceedings of the 20th Purdue Industrial Waste Conference, pp. 146-174 (1965).

28. Wachs, A. M., and Berend, A., "Extra Deep Ponds," Water Quality Improvement, The University of Texas Press (1968).