

AERATED LAGOONS—A REPORT ON THE STATE OF THE ART

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Aerated lagoons are a relatively new innovation in the wastewater treatment field. Until recently, aerators were used almost exclusively to alleviate existing nuisance problems in heavily loaded oxidation ponds and to improve effluent qualities. It was found, however, that because of turbidity, turbulence, and other factors, normal algae growths were retarded or eliminated in the oxidation ponds when aerators were added, thus the birth of the aerated lagoon. The aerated lagoon was found to provide good biochemical oxygen demand (BOD) removals with a significantly shorter detention time than the oxidation pond.

An aerated lagoon is generally defined as a basin, usually 6 to 15 ft (1.8 to 4.6 m) deep in which oxygenation is accomplished by mechanical or diffused aeration units and by induced surface aeration. From the process point of view, aerated lagoons are of two types—the aerobic lagoon and the aerobic-anaerobic or facultative lagoon.

The aerobic lagoon is designed with sufficient power input to create a turbulence level high enough to maintain solids in suspension. Generally, the power input levels are not as high as those for activated sludge. The aerobic lagoon is analogous to an activated sludge with extended aeration and no

sludge return. However, the aerobic lagoon is more sensitive to temperature than activated sludge because of the lack of sludge recycle. The aerobic lagoon requires power levels in the magnitude of 100 hp/mil gal. (0.02 kw/cu m) of basin volume.

The aerobic-anaerobic or facultative lagoon is designed with only sufficient power input to create turbulence levels adequate to insure uniform dissolved oxygen (DO) dispersion throughout the liquid in the lagoon. The bulk of the solids are not maintained in suspension but settle to the bottom of the lagoon where they are decomposed anaerobically. Some solids are maintained in suspension and are carried out in the effluent. Sedimentation may be employed to provide a more clarified effluent. Power input to the facultative lagoon is in the magnitude of 15 to 20 hp/mil gal (0.003 to 0.004 kw/cu m) of basin volume.

The facultative lagoon is used almost exclusively rather than the aerobic lagoon because a good effluent can be produced with a low power input. The remainder of this paper will deal with the facultative lagoon.

Because the active biological solids level in the facultative lagoon is low, BOD removal is primarily a function of detention time, temperature, and nature of the waste.

Eckenfelder¹ suggests the following formulation to describe BOD removal in a facultative aerated lagoon:

$$\frac{L_e}{L_0} = \frac{1}{1 + Kt} \quad (1)$$

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where

L_e = effluent BOD,
 L_o = influent BOD,
 t = time in days, and
 K = facultative lagoon BOD removal rate coefficient.

It should be noted that the K in Equation 1 is not the same k that describes the BOD reaction in the classical equation $y = L_a(1 - 10^{-kt})$. The K in Equation 1 is a number that describes the BOD removal rate for a particular waste and a particular lagoon design. Therefore, there can be a wide variation of K values for similar wastes. For domestic wastewater K values have been reported¹⁻³ from 0.3 to greater than 1.0.

Another reason for the wide variation in reported K values could result from the assumptions made in the derivation of Equation 1. The BOD removal formulation is derived from the following steady-state mass balance.

$$\frac{\text{lb influent BOD}}{\text{day}} - \frac{\text{lb effluent BOD}}{\text{day}} = \frac{\text{lb BOD removed}}{\text{day}}$$

If rainfall, evaporation, and percolation are small, the steady-state mass balance may be written as follows:

$$L_oQ - L_eQ = rV \quad (2)$$

where

L_o = influent BOD,
 L_e = effluent BOD,
 Q = waste flow per day,
 V = lagoon volume, and
 r = BOD removal rate.

The BOD removal rate is considered to be a first order reaction; therefore, the removal rate is proportional to the concentration remaining:

$$\frac{dC}{dt} = KC \quad (3)$$

where

K = removal rate coefficient,
 C = concentration, and
 t = time.

If the turbulence level produced by the aerators is sufficient to maintain a completely mixed flow regime, then the BOD concentration throughout the lagoon is equal to the BOD of the effluent. When the system reaches equilibrium KL_e may be substituted for r in Equation 2:

$$L_oQ - L_eQ = KL_eV \quad (4)$$

Since $V = Qt$, Qt may be substituted for V in Equation 4:

$$L_oQ - L_eQ = KL_eQt$$

Simplifying:

$$\begin{aligned} L_o - L_e + KL_e t \\ L_o &= L_e + KL_e t \\ L_o &= L_e(1 + Kt) \\ \frac{L_o}{L_e} &= (1 + Kt) \\ \frac{L_o}{L_e} &= \frac{1}{1 + Kt} \end{aligned} \quad (1)$$

It may be seen readily that if a completely mixed flow regime is not maintained with respect to dissolved BOD, Equation 1 will not be completely valid. There is also some question as to the validity of Equation 1 where a significant portion of the BOD in the waste is in the form of suspended solids (SS) because the bulk of the SS is not maintained in suspension. The BOD removal coefficient K in this instance would also be a function of the rate at which the solid portion of the waste was liquefied by anaerobic decomposition.

Equation 1 is based on steady-state conditions; therefore, the use of Equation 1 to evaluate lagoon performance before steady-state conditions are reached would result in error. It may take several years for a facultative lagoon to reach steady state with respect to solids. Until this condition

is reached, BOD removal rates will be enhanced because of the sedimentation of the bulk of the solids and a portion of the limited biomass. The sedimentation occurs in the relatively quiescent portions of the lagoon away from the high turbulence areas near the aerators. A net increase in settled solids will occur even though a portion of the settled solids will be liquefied by anaerobic decomposition. The net increase in settled solids causes a decrease in the liquid volume in the basin, thus causing the zone of high turbulence surrounding the aerators to increase with respect to the total liquid volume in the lagoon. Therefore, more solid material will be maintained in suspension where it will be decomposed aerobically. When the rate of sedimentation equals the rate of resuspension, the lagoon has reached steady-state conditions. After initial acclimation of the lagoon's limited biomass, the BOD removal rate, in all probability, will decrease steadily until a steady-state condition is reached with respect to solids deposition. The wide range of K values reported in the literature could, in part, result from the evaluation of BOD removal rates before a steady-state condition is reached.

Field and laboratory studies have verified the temperature dependence of the BOD removal rate in facultative lagoons. The variation of K with respect to temperature can be determined through the relationship

$$K_T = K_{20^\circ\text{C}}\theta^{T-20} \quad (5)$$

where

K_T = BOD removal rate coefficient at temperature T ,

$K_{20^\circ\text{C}}$ = BOD removal rate coefficient at 20°C ,

T = temperature, $^\circ\text{C}$, and

θ = temperature coefficient.

Eckenfelder^{1,4} has reported values of θ ranging from 1.06 to 1.09 for a temperature range of 10° to 30°C . To illustrate this temperature dependence, assume a K value of 0.5 at 20°C and a θ of

1.09. If the temperature were dropped by 10°C to 10°C , the K would be decreased to 0.212, which represents a 57.5 percent decrease in the BOD removal rate K .

It is apparent that at the present experimental confirmation of the temperature coefficient θ is desirable, especially if the lagoon temperature will be below 10°C . When determining the detention time required for a given BOD removal efficiency, winter conditions will control because the detention time required for a given removal efficiency increases with a decrease in temperature. To illustrate further the temperature dependence of facultative aerated lagoons with respect to other treatment processes, Wuhrmann⁵ has reported θ to be 1.0 for activated sludge, Howland⁶ has reported θ to be 1.035 for trickling filters, and Sawyer⁷ has reported θ to be 1.035 for aerobic lagoons.

The liquid temperature in a facultative aerated lagoon depends on the heat balance resulting from changes in waste temperature and ambient temperature. If influent waste temperature is low and the detention time in the lagoon is long, the liquid temperature in the lagoon approaches ambient temperature. The lagoon temperature can be calculated by the following equation suggested by Eckenfelder¹:

$$T_w = fA(T_w - T_a)(T_i - T_o)Q \quad (6)$$

where

A = lagoon surface area,

Q = waste flow,

T_i = influent temperature to the lagoon, $^\circ\text{F}$,

T_o = effluent temperature to the lagoon, $^\circ\text{F}$,

T_w = lagoon temperature, $^\circ\text{F}$,

T_a = air temperature, $^\circ\text{F}$, and

f = factor containing the heat transfer coefficients, the surface area increase from aeration equipment, wind, and humidity effects. When Q is in mgd and A is

in sq ft, f has an approximate value of 12×10^{-6} for the central portion of the U. S.

If a completely mixed flow regime exists with respect to the liquid in the lagoon, $T_o = T_w$. Therefore, Equation 6 can be re-expressed as follows:

$$(T_i - T_w) = \frac{(T_w - T_a)fA}{Q} \quad (7)$$

Equation 7 can be re-expressed in terms of depth D and detention time t to yield

$$T_w = \left(T_a + \frac{T_i D}{ft} \right) \left(\frac{1}{1 + D/ft} \right) \quad (8)$$

where

$f = 1.6$,

D = depth of lagoon, ft, and

t = detention time, days.

In computing estimated lagoon temperature, local weather bureau records should be used to define air temperature. If the waste stream already exists, influent temperatures may be determined by measurement. If the waste stream is not in existence, influent temperature may be estimated from existing waste streams of a similar nature under similar climatic conditions. Calculating the estimated lagoon temperature requires a trial and error solution. A lagoon temperature must first be assumed. The K for that temperature is calculated and used to determine detention time. Having calculated the detention time and assuming a lagoon depth, the lagoon temperature can then be calculated using Equation 8. Agreement between the assumed lagoon temperature and calculated lagoon temperature usually can be reached in two or three attempts.

Because the level of active biological solids is low in the facultative aerated lagoon, the normal biological oxygen requirement can be related to BOD removal according to the relationship

$$NOR = L \times P \times D \quad (9)$$

where

NOR = normal oxygen requirement, lb/hr,

L = ratio of ultimate BOD to 5-day BOD,

D = 5-day BOD, lb/hr, and,

P = decimal fraction of BOD removal.

The actual rate of oxygen transfer to the lagoon is dependent on liquid temperature, relative DO saturation, and the oxygen transfer ratio α . The determination of the actual oxygen transfer rate to be expected in the lagoon may be calculated from the following relationship:

$$R_s = R_a \frac{(C_{sw} - C_L)}{9.17} 1.024^{T-20} \alpha \quad (10)$$

where

R_s = actual rate of transfer of oxygen to wastewater in $\frac{\text{lb}}{\text{hp-hr}}$,

R_a = rate of transfer of oxygen by aerator under standard test conditions of water with a saturation value of 9.17 mg/l at 20°C, devoid of oxygen, at one atmosphere of pressure in $\frac{\text{lb}}{\text{hp-hr}}$,

C_{sw} = saturation value in mg/l of wastewater at lagoon operating temperature,

C_L = concentration of DO in lagoon, mg/l,

T = lagoon operating temperature, °C, and

α = the ratio of oxygen transfer in wastewater to that in tap water.

Because the DO saturation value in water decreases with an increase in temperature and because the BOD removal rate K increases with an increase in temperature, the determination of the rate of transfer of oxygen to the wastewater should be predicated on summer conditions. The determination of the lagoon temperature representing summer conditions may easily

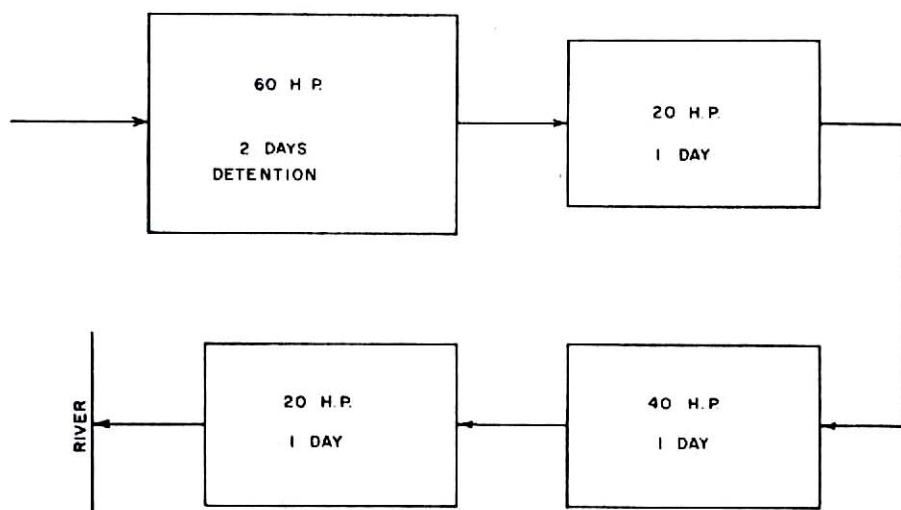


FIGURE 1.—The aerated lagoon installation studied. ($\text{Hp} \times 0.7457 = \text{kw.}$)

be determined using Equation 8 because all factors are known except lagoon temperature T_w .

The actual horsepower required to satisfy the BOD of the waste may be calculated as follows:

$$\text{HPS} = \frac{\text{NOR}}{R_s} \quad (11)$$

where

HPS = horsepower rating of aeration equipment required.

For proper functioning of a facultative lagoon, there must be sufficient power input to maintain turbulence levels high enough to insure uniform DO dispersion throughout the basin. Eckenfelder^{1,4} indicates that aerators spaced up to 200 ft (61 m) on centers with power inputs of 15 to 20 hp/mil gal (0.0030 to 0.0039 kw/cu m) of basin volume are sufficient to accomplish this. Generally, the horsepower required to satisfy the BOD is less than the horsepower required for mixing; therefore, the horsepower required for mixing should be determined and compared with the horsepower required for BOD satisfaction and the larger value used.

Operational Data

In order to evaluate critically some of the previously presented theories

and formulations, particularly those pertaining to temperature prediction and effects, considerable operational data were obtained from a full-scale aerated lagoon installation. The observed lagoon system consisted of a series of four lagoons as shown in Figure 1, and it was used to treat 0.7 mgd (2,650 cu m/day) of wastewater from a textile-finishing plant during the period of study. Thus, the first and largest lagoon had a power input of 43 hp/mil gal (0.008 kw/cu m) of basin volume, a figure somewhat higher than that typical of a facultative lagoon but considerably less than that required for an aerobic lagoon. The power input of the three remaining lagoons was 28.6, 57, and 28.6 hp/mil gal (0.006, 0.011, and 0.006 kw/cu m) of basin volume, respectively. In addition, the effluent from Lagoon 1 was sprayed into Lagoon 2 through a slotted pipe.

The waste entering the first lagoon had been previously treated with lime for color removal and subsequently neutralized to pH 7.5 with sulfuric acid. The influent BOD typically had a value of 300 to 400 mg/l and was very low in SS.

Observations during the warm summer months showed that the lagoon system was operating at a very high efficiency. At temperatures of 60°F (15.5°C) and above, it achieved an

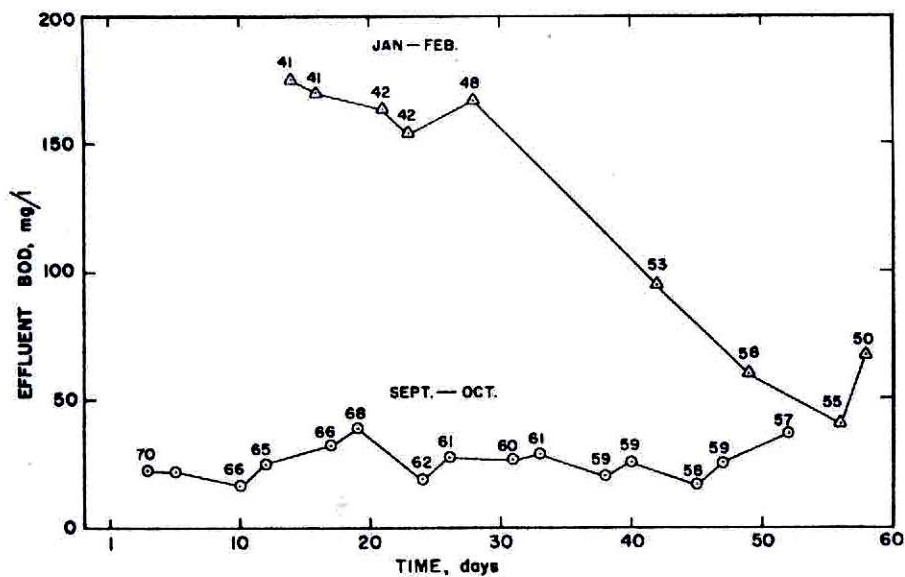


FIGURE 2.—Comparison of effluent BOD's.

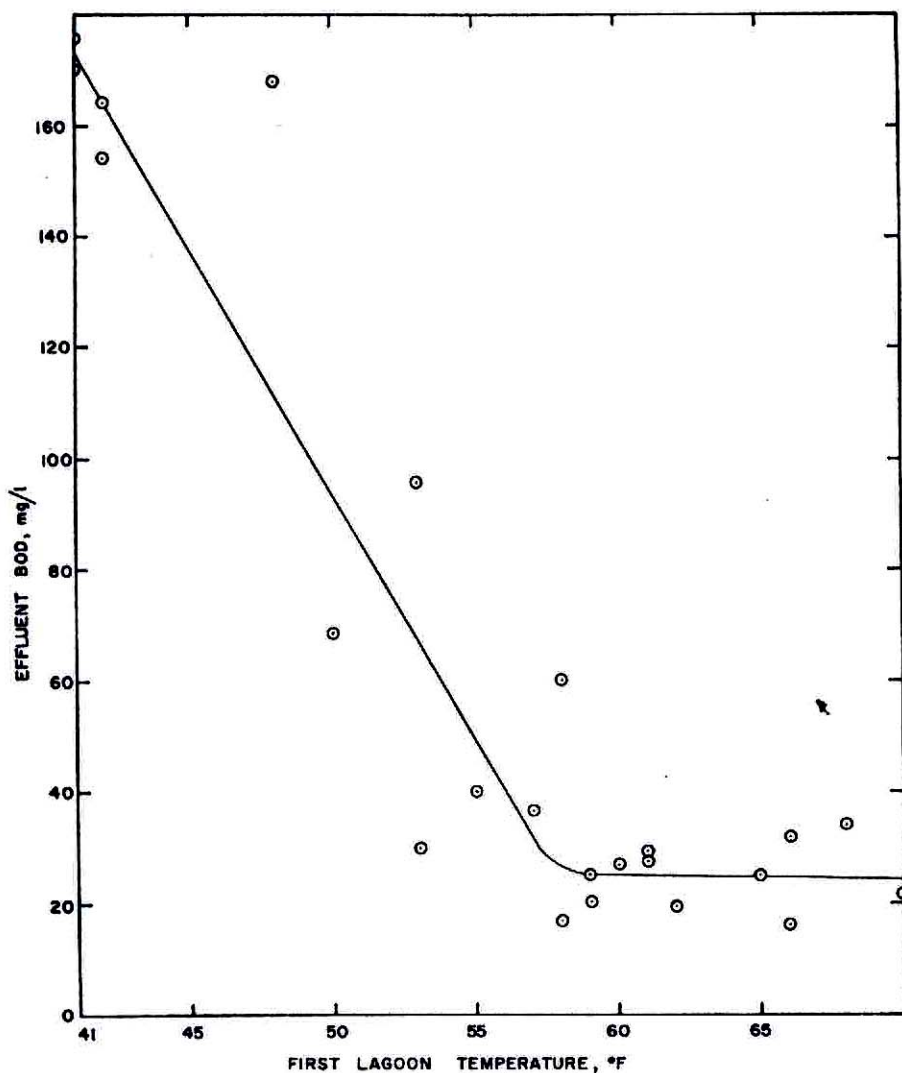


FIGURE 3.—Efficiency break point. $[0.555(^{\circ}\text{F} - 32) = ^{\circ}\text{C}.]$

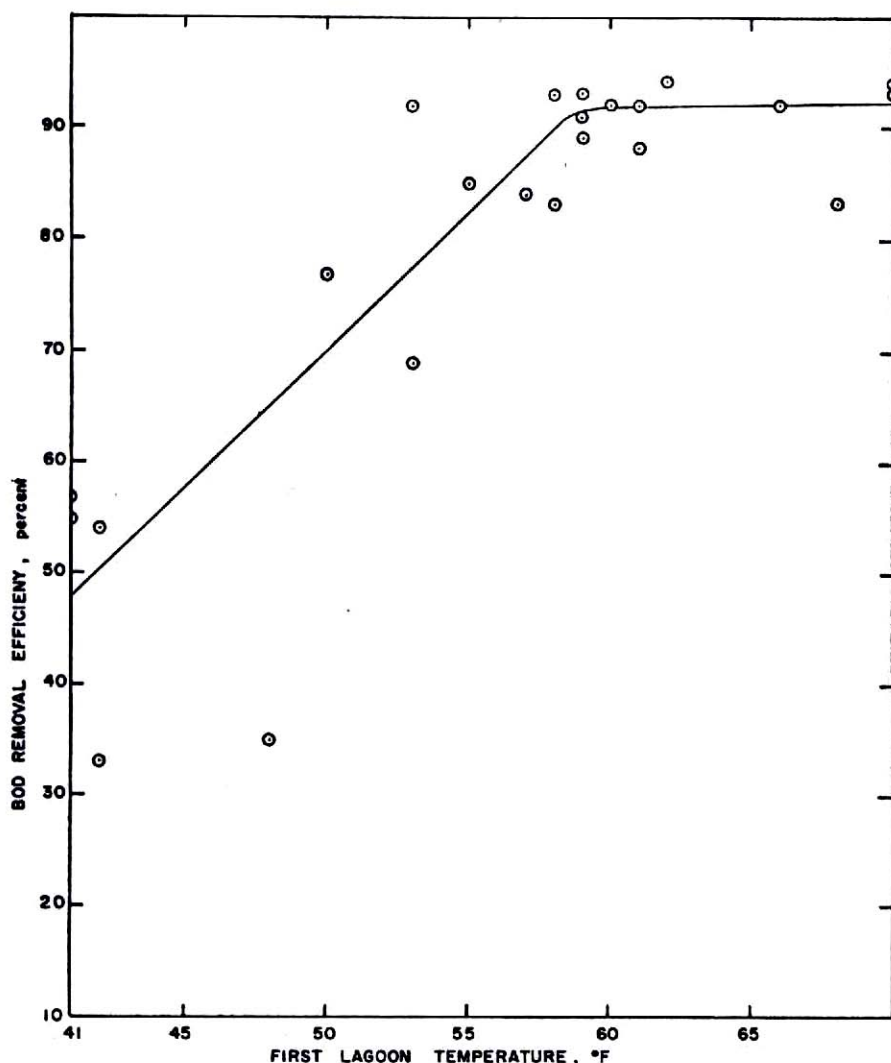


FIGURE 4.—Temperature effect of efficiency on BOD removal.
 $[0.555(^{\circ}\text{F} - 32) = ^{\circ}\text{C}.]$

average BOD removal of 90 percent and had a K rate of 2.5 days^{-1} at a temperature of 20°C . However, as temperature decreased below 60°F (15.5°C), the efficiency of the process dropped sharply. The effluent BOD concentrations for the months of September and October are compared to effluent BOD's of January and February in Figure 2. The number beside each point designates the temperature of the first lagoon at the time of observation in $^{\circ}\text{F}$.

Figure 2 shows that the effluent BOD was strongly affected by temperature change. The effluent BOD changed from an average value of 25 mg/l during the fall months to an average value

in excess of 160 mg/l during the winter months. The graph also indicates that there was a sharp breakpoint in efficiency between the temperatures of 55° and 60°F (12.8° and 15.5°C). This breakpoint is more clearly defined by Figure 3. This figure shows that for first lagoon temperatures of 58°F (14.4°C) and above, the effluent BOD of the system never exceeded 35 mg/l . It is also significant that temperature increases above 58°F (14.4°C) apparently had no effect at all on the effluent BOD. This seemingly indicates that 58°F (14.4°C) is a threshold temperature for the system. On the other hand, when the temperature fell below 58°F (14.4°C) in the lagoon,

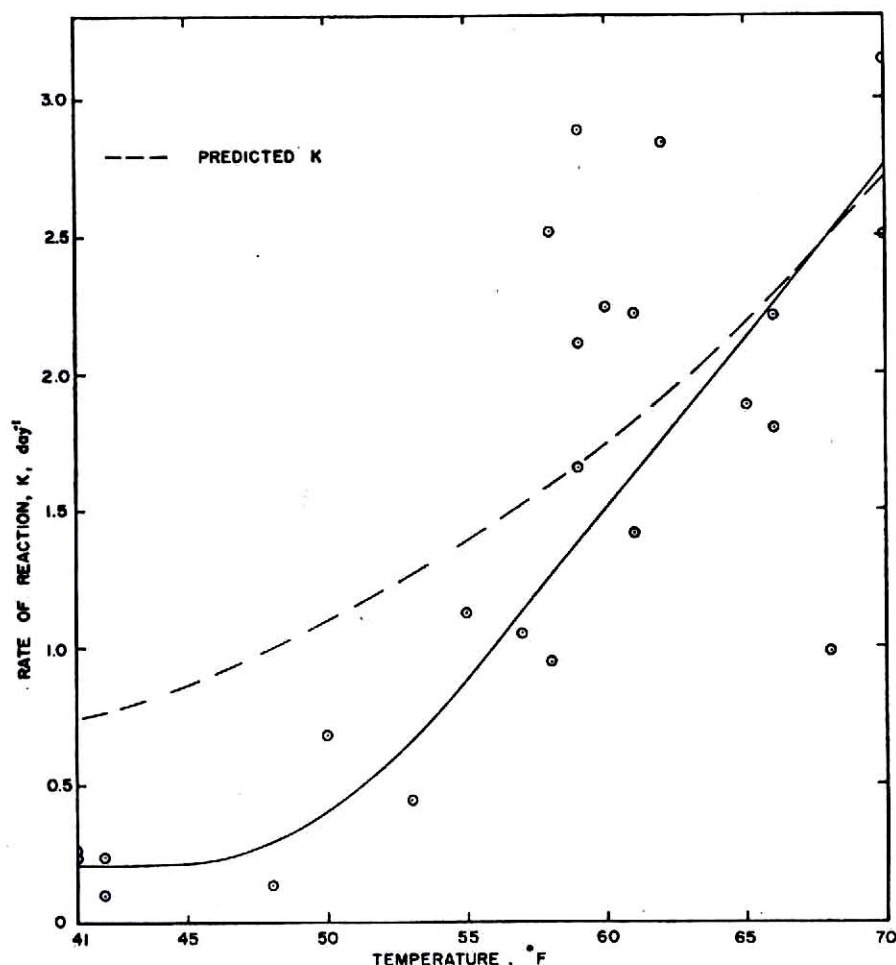


FIGURE 5.—Calculation of K for observed temperatures.
 $[0.555(^{\circ}\text{F} - 32) = ^{\circ}\text{C}.]$

the effluent BOD increased sharply. The effect of temperature on the BOD removal efficiency of the lagoon system is further illustrated by Figure 4.

The reaction rate K for the system was calculated for each temperature observed. These data are shown in Figure 5. A smooth curve fitted to the data illustrates the rapid decline in reaction rate that occurred with temperature decrease. As previously stated, the system was extremely efficient during the fall months, and this resulted in a cluster of data points considerably above the fitted curve. However, the bulk of the data indicates a rapid decrease in the rate of reaction with temperature decline to less than 50°F (10°C). Below that temperature the curve flattened out at a value of approximately 0.2 day⁻¹.

The dashed line in Figure 5 shows how the reaction rate K would decrease from a 20°C value of 2.5 day⁻¹ if it followed the formula $K_T = K_{20}^{\circ}\text{C}\theta^{T-20}$ when θ equaled 1.085, the most commonly stated value. As the graph shows, the predicted values are considerably in error at the low temperatures, and no breakpoint in the curve is predicted. The reliability of the 1.085 value was further checked by calculating the actual value of θ for all observations.

Figure 6 shows that there was a wide variation in the actual value of θ but, interestingly, the average of the calculated values was 1.097, a difference of only 0.012 from the most commonly quoted value. However, it should be pointed out that all θ values for temperatures of less than 50°F (10°C) were

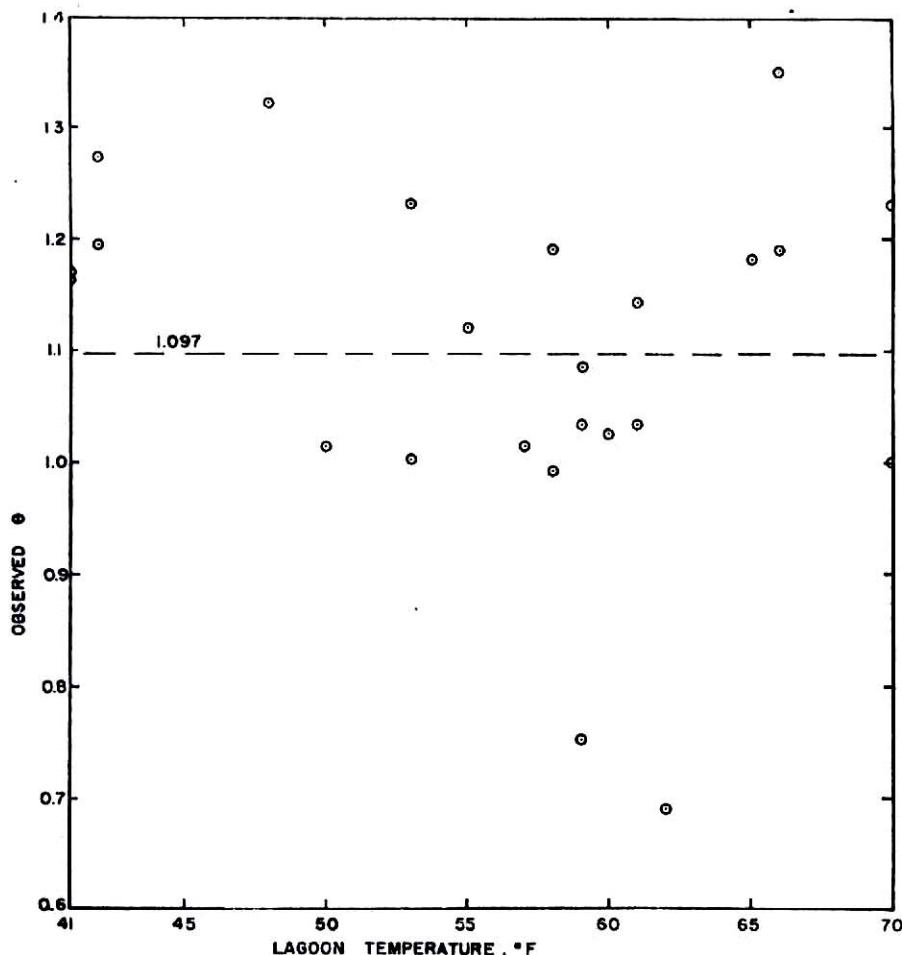


FIGURE 6.—Variations in θ because of temperature.
 $[0.555(^{\circ}\text{F} - 32) = ^{\circ}\text{C}.]$

in excess of 1.110 and ranged as high as 1.330.

In order to predict reaction rates for controlling winter temperatures, it is first necessary to predict the controlling lagoon temperature that will occur. An equation for calculating the lagoon temperature from air and wastewater temperatures has been proposed by Eckenfelder (Equation 6). The accuracy of this equation was checked against the observed values, and the results are shown in Table I. In most instances, the equation was remarkably accurate. On two occasions the predicted and actual temperatures did vary considerably $[+ 6^{\circ}$ and $- 7^{\circ}\text{F}$ ($+ 3.3^{\circ}$ and $- 3.8^{\circ}\text{C}$)], but in both instances a sudden change in air temperature had occurred shortly before the actual lagoon temperature was measured. Therefore, the lagoon had not had

sufficient time to reach thermal equilibrium with the atmosphere.

Conclusions from Operational Data

Based on the observed data, the following conclusions were reached:

1. The efficiency of the aerated lagoon system was strongly affected by temperature changes when the temperature was below 58°F (14.4°C). At temperatures of 58°F (14.4°C) and above, no significant change in efficiency occurred with a change in temperature. Apparently the system had a temperature threshold value of 58°F (14.4°C).

2. Present theory does not predict aerated lagoon reaction rates accurately. This is particularly true for low temperatures (less than 12°C).

TABLE I.—Prediction of Lagoon Temperature*

Date	Temperatures (°F)				
	Waste-water	Air	Lagoon		
			Actual Value	Predicted Value	Difference
February					
18	61	52	58	58.3	+0.3
19	60	37	55	53.2	-1.8
24	57	40	50	52.1	+2.1
25	60	38	55	54.0	-1.0
27	56	36	50	50.3	+0.3
March					
3	66	59	58	64.0	+6.0
4	63	48	60	59.0	-1.0
5	64	47	59	59.0	0
6	60	42	56	56.0	0
9	60	52	57	57.8	+0.8
11	65	45	59	59.2	+0.2
12	66	39	60	58.2	-1.8
13	60	29	58	51.0	-7.0
16	50	28	46	44.0	-2.0
17	58	38	52	52.3	+0.3
18	62	48	58	58.0	0

* D = 8 ft and t = 2 days.

Note: $0.555(^{\circ}\text{F}-32) = ^{\circ}\text{C}$.

3. If thermal equilibrium between the lagoon and the atmosphere has been reached, the lagoon temperature can be predicted accurately from air and waste temperatures using the formula suggested by Eckenfelder.

General Conclusions

Although facultative aerated lagoons have demonstrated their ability to produce relatively good quality effluents with a low power input and a savings in land area, it is doubtful, especially from the information presented in the literature concerning temperature dependence, that they can be depended on to produce high-quality effluents during the winter months. In instances such as municipal systems where the influent temperatures often approach ground temperature during winter months, the temperature of the lagoon will approach ambient temperature. If, as suggested in this paper, the detention time is based on winter conditions,

the detention time becomes exceedingly long when a high degree of BOD removal is specified. Because of the long detention times required for winter operation, the total power input required for mixing becomes excessive. Therefore, aerated lagoons may not be a practical year-round treatment method without provisions for process modification during winter months.

It is apparent from the literature that additional information is needed to:

1. Determine the applicability of Equation 1 to waste containing a significant portion of suspended BOD.
2. Determine the effect of basin geometry, aerator spacing, and power input on the BOD removal rate coefficient K .
3. Determine the temperature coefficient θ below 10°C since most facultative aerated lagoons will fall below 10°C during winter operation.
4. Determine the effect power input has on the temperature coefficient θ .

References

1. Eckenfelder, W. W., Jr., "Industrial Water Pollution Control." McGraw-Hill Book Co., Inc., New York, N. Y., 206 (1966).
2. "Yeomans Sigma Aerators." Clow-Yeomans Corp., Melrose Park, Ill., Section 13.3 (1966).
3. "Design Specification Guide." Wells Products Corp., Roscoe, Ill., Section D (1968).
4. Eckenfelder, W. W., Jr., "Water Quality Management." Virginia Water Resources Res. Center, Blacksburg, Va. (1968).
5. Wuhrmann, K., "Advances in Biological Waste Treatment." Pergamon Press, Oxford, Eng. (1963).
6. Howland, W., "Flow over Porous Media as in a Trickling Filter." *Proc. 12th Ind. Waste Conf.*, Purdue Univ., Ext. Ser. 94, 435 (1958).
7. Sawyer, C. N., "New Concepts in Aerated Lagoon Design and Operation." In "Advances in Water Quality Improvement." E. F. Gloyna and W. W. Eckenfelder, Jr., [Eds.] Univ. of Texas Press, Austin, 325 (1968).