

BASIC ELEMENTS OF AERATED LAGOON DESIGN

The following comments are intended to indicate and explain the basic design concepts and methodology used by Welles Products Corporation in the design of aerated lagoons for wastewater stabilization. The approach described herein has been found to be a satisfactory means of accurately determining the amount of aeration equipment (in terms of total motor nameplate horsepower required) which is necessary to achieve satisfactory aerated lagoon performance.

We define an aerated lagoon as a basin wherein active biological solids are in equilibrium with an applied waste. An aerated lagoon can be considered to be a variation of the activated sludge process, with the desired biological oxidation being accomplished without the return of settled sludge. Therefore, the basic biological relationships relative to activated sludge can be expected to apply. Actually, a number of simplifications can be made.

Defining the aerated lagoon further, we can say it is:

A basin of significant depth (6' to 12') in which oxygen is furnished by mechanical aeration, and in which the turbulence level is sufficient to provide complete liquid mixing (note that this is liquid mixing; it is not meant to imply that all solids are maintained in suspension). As a result of complete liquid mixing, uniform distribution of the waste and good dispersion of oxygen are achieved and rapid and efficient waste stabilization results.

Proper design of an aerated lagoon requires consideration of the following items:

1. BOD removal characteristics
2. Biological oxygen requirements
3. Oxygen transfer relationships
4. Liquid mixing and dissolved oxygen dispersion requirements
5. Sludge production
6. Settling

As for any waste treatment process design, certain basic data such as daily flow, amount of applied BOD, desired degree of treatment, etc., must be known. Since the rate of BOD removal in an aerated lagoon is affected by the liquid temperature, selection or determination of the lagoon operating temperatures must not be overlooked.

1. BOD REMOVAL ("K" FACTOR)

The rate of BOD removal for an aerated lagoon can normally be expressed by the pseudo first-order equation,

$$\frac{L_o - L_e}{L_o} = \frac{KT}{KT + 1} \quad (\text{Eqn. A})$$

where

L_o = the initial BOD concentration

L_e = the effluent BOD concentration

T = lagoon detention time in days

K = the lagoon BOD removal rate factor

Noting that $(L_o - L_e)/L_o$ is the BOD removal efficiency (E), Equation A can be rearranged to give the following useful equations,

$$T = \frac{E}{(1 - E) K} \quad (\text{Eqn. A-1})$$

$$K = \frac{E}{(1 - E) T} \quad (\text{Eqn. A-2})$$

While "K" is known as the "BOD removal rate", it is really only a number which characterizes the rate of BOD removal in an aerated lagoon. It might therefore more properly be termed the "lagoon BOD removal factor". There can be considerable variation of "K factor" values, even when the wastewaters involved are quite similar. For mixtures of domestic and industrial wastes K has often been found to be somewhat greater than for domestic sewage alone. It is often desirable to determine the applicable K factor value through laboratory and/or pilot studies. For certain types of industrial wastes K factor values of up to 3.0 have been reported.

The K factor is normally understood to be the K factor at a temperature of 20°C. Since the rate of BOD removal in an aerated lagoon is related to the water temperature, it may be advisable to consider the lagoon efficiency at liquid temperature other than 20°C. Where this is considered necessary or desirable the K factor can be adjusted to the appropriate liquid temperature according to the relationship

$$K_t = K_{20} \times \theta^{(t - 20)} \quad (\text{Eqn. B})$$

where

t = the temperature of the lagoon liquid in °C.

K_t = the aerated lagoon BOD removal rate at temperature, t

θ = the temperature correction factor

A temperature correction factor value of 1.075 was originally suggested, based upon batch (i.e., fill and draw) studies. More recently, a value of 1.035 has been found to apply under continuous-flow conditions.

2. BIOLOGICAL OXYGEN REQUIREMENTS

Since the level of solids in an aerated lagoon is low, the normal biological oxygen requirement (NOR) can be related to BOD removal according to the relationship:

$$\begin{array}{l} \text{NOR in lbs.} \\ \text{of oxygen} \\ \text{per hour} \end{array} = L \times \text{BOD}_5 \text{ removed per hour}$$

where L is the ratio of ultimate BOD to 5-day BOD

$$L = \text{BOD}_L / \text{BOD}_5$$

Experience has shown that for domestic sewage the L value normally ranges from 1.1 to 1.5. An L value of 1.4, for instance, would mean that the BOD_5 is approximately 68% of the BOD_L . To determine the design NOR

- a-) Determine the applied 5-day BOD in pounds per hour
- b-) Determine comparative value (i.e., the L value) of total BOD to 5-day BOD

Let: D = Applied 5-day BOD in pounds per hour

L = Ratio of total BOD to 5-day BOD

P = % BOD reduction, expressed as a decimal

NOR = Normal (biological) Oxygen Requirement in
lbs. of oxygen/hour

then: $D \times P = \text{BOD}_5 \text{ removed per hour}$

and $\text{NOR} = L \times D \times P$

3. OXYGEN TRANSFER RATE

The actual rate of oxygen transfer to the lagoon is dependent upon temperature, the lagoon dissolved oxygen concentration (i.e., relative liquid saturation), and the oxygen transfer ratio. The oxygen transfer ratio is known as the alpha (α) factor, and is the ratio of the rate of oxygen transfer in tap water to the corresponding rate of oxygen transfer in the wastewater. Values of alpha in the range of 0.8 to 0.95 are normally applicable to domestic sewage. For industrial wastes it is good practice to determine the approximate alpha (α) value by laboratory testing.

In order to insure satisfactory biological activity, the D.O. level should be 1.5 ppm or greater. The solubility of oxygen in lagoon contents will often be slightly less than the solubility in tap water due to the presence of dissolved solids.

Determination of the actual oxygen transfer rate to be expected in the lagoon under normal operating conditions (that is, at the actual lagoon liquid temperature and dissolved oxygen concentration, as opposed to the transfer rate measured under "standard" conditions of 20°C and zero D.O.) is calculated according to the relationship

$$R_s = R_a \frac{(C_{sw} - C_l)}{(9.17)} (\alpha) 1.024^{(t - 20)} \quad (\text{Eqn. C})$$

where

R_s = Actual rate of transfer of oxygen in the lagoon under normal operating conditions. This is also known as the "lagoon oxygen transfer rate".

R_a = Rate of oxygen transfer by Aqua-Lator under standard test conditions (water at 20°C, devoid of oxygen, under one atmosphere of pressure).

C_{sw} = Dissolved oxygen saturation value (in mg/l) at lagoon operating temperature.

C_1 = Concentration of D.O. in lagoon (in mg/l).

t = System operating temperature, (in °C).

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

4. MIXING AND OXYGEN DISPERSION

Optimum lagoon operation is dependent upon essentially complete mixing of the liquid and uniform dispersion of the D.O. throughout the lagoon. Indeed, the amount of aeration equipment required for proper mixing and dispersion can and often does exceed the amount required to supply the biological oxygen demands. Failure to recognize this often-neglected design parameter has resulted in unsatisfactory aerated lagoon performance in a number of cases. For Welles Aqua-Lator units operating in aerated lagoons of normal depth, a horsepower-to-volume (P/V) ratio of 8 HP/million gallons has been found to provide good liquid mixing and uniform dissolved oxygen dispersion. It should be noted that a considerably higher P/V ratio (75-100 HP/MG) is required to assure that all active bio-solids are maintained in suspension.

5. SLUDGE PRODUCTION

The activity of the bacteria in an aerated lagoon is sufficient to destroy most of the cells created each day, but some build-up of solids will occur. A non-oxidizable fraction is contained in the influent stream and some additional non-oxidizable solids will be produced in the system itself.

6. SETTLING

Some of the lagoon solids may settle to the lagoon bottom. The solids which settle will be partially hydrolyzed over a period of time, with the products of hydrolysis released back into solution. The remainder will compact on the lagoon bottom.* The actual amount of solids leaving the lagoon is therefore a function of both the P/V ratio and the detention time in the lagoon. Sludge settling and solids accumulation is not normally a significant factor in aerated lagoon design. For aerated lagoons receiving municipal wastes, it has been estimated that 25-50 years would be required before the lagoon volume was reduced by as much as 10%.

Aerated lagoons are generally designed according to the following sequence:

1. The appropriate basic data (i.e., daily flow, waste strength, etc.) and treatment requirements are collected and summarized.
2. The K factor is determined by pilot studies, or selected on the basis of past experience.

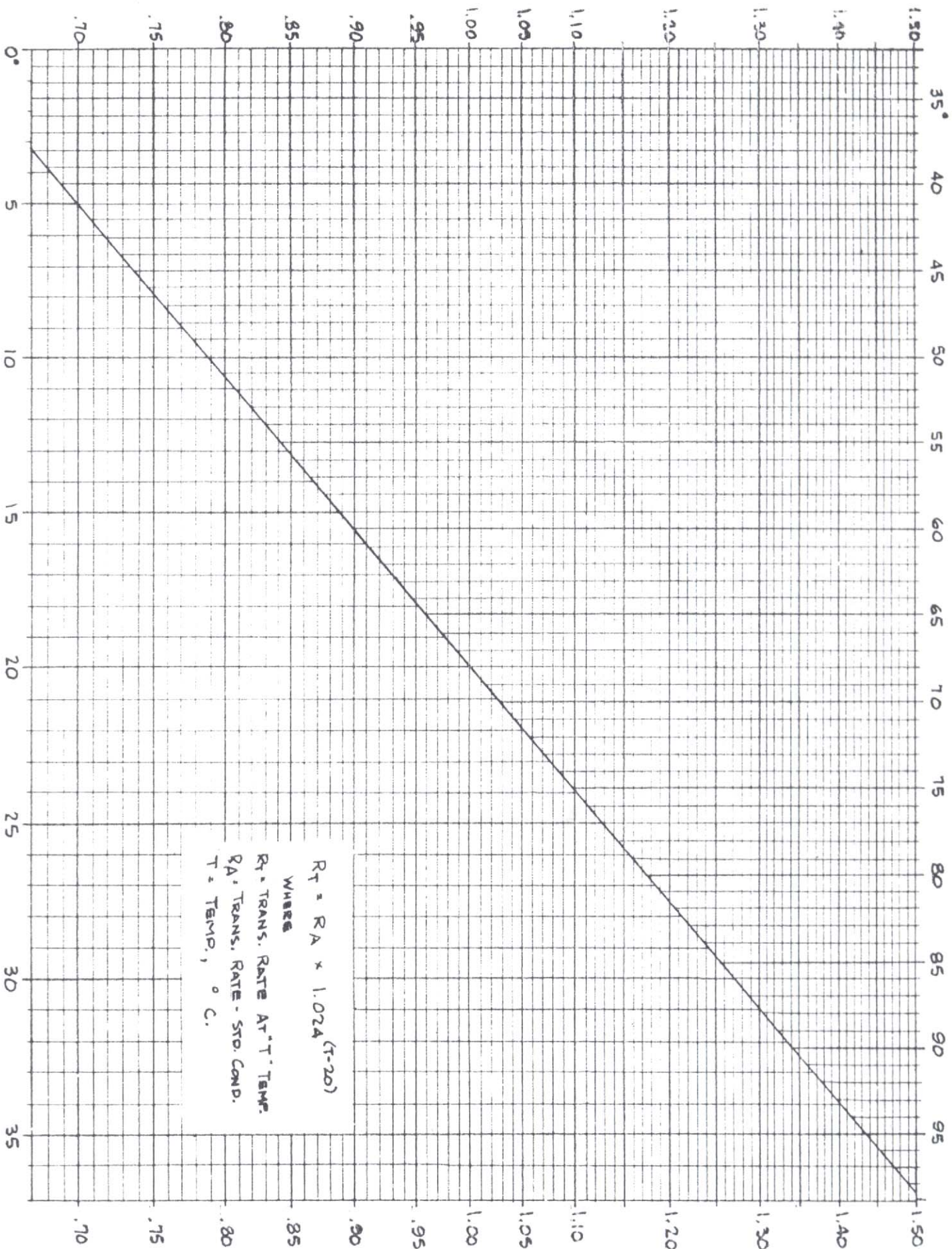
*Compaction of bottom solids to a specific density of 1.73 to 2.75, with a 6 - 11% volatile portion, have been reported.

3. The necessary lagoon detention time is determined using equations (A) and (B) in conjunction with the expected lagoon operating temperatures.
4. The amount of oxygen required to satisfy the biological oxygen requirement is determined. (This is, of course, the NOR.)
5. The lagoon oxygen transfer rate under operating conditions, R_s , is determined through the use of equation (C). (Note that the transfer rate should be expressed in terms of motor nameplate horsepower required per pound of oxygen transferred per hour. Expression of the transfer rate in terms of "gear reducer horsepower" or "shaft horsepower" result in a higher transfer rate number. Such numbers are misleading, however; they do not accurately indicate the operating power costs since the loss of efficiency through the motor and shaft drive system are neglected.)
6. The NOR and the lagoon oxygen transfer rate, R_s , are then used to determine the amount of aeration equipment (in terms of motor nameplate horsepower) required to satisfy the waste stabilization oxygen demand.
7. The lagoon volume and the P/V ratio (8 HP/MG for Welles Aqua-Lator units) are used to determine the amount of aeration equipment (in terms of horsepower) required for adequate mixing and oxygen dispersion.
8. The NOR horsepower requirement is compared to the mixing-and-dispersion (M.A.D.) horsepower requirement. The larger of the two is the amount of aeration equipment horsepower required for satisfactory lagoon operation.

There may be additional criteria to be met or other factors to be considered, depending upon the particular situation at hand. The above described approach and methodology, however, is applicable to aerated lagoon design in general and constitutes the basic items to be considered.

TEMPERATURE - DEGREES FAHRENHEIT

VALUES OF $1.024 (T-20)$



$$R_T = R_A \times 1.024 (T-20)$$

WHERE

R_T = TRANS. RATE AT T TEMP.

R_A = TRANS. RATE - STD COND.

T = TEMP., ° C.

1. OBJECTIVE:

It is desired to design an aerated lagoon system to serve a 400-house subdivision.

2. DATA:

The engineers have provided the following information and data.

- a-) The design population is 1480 persons; this is based upon a 3.7 person per dwelling estimate. (The development is located in an upper middle class suburb, with most children of high school or college age.)
- b-) The design flow is estimated at 105 gallons per capita, giving a total daily flow of 156,000 gallons per day (i.e., 0.156 MGD).
- c-) The 5-day BOD is estimated at 206 mg/l (or 206 ppm, since ppm is essentially the same as mg/l). Therefore the daily BOD loading in lbs. is

$$\begin{aligned}
 \text{BOD}_5 \text{ in lbs/day} &= \text{Flow in MGD} \times \text{BOD}_5 \text{ in ppm} \times 8.345 \\
 &= 0.156 \times 206 \times 8.345 \\
 &= 268 \text{ lbs/day of BOD}_5
 \end{aligned}$$

(Note that this is equivalent to 0.181 lbs. of BOD₅ per capita. The BOD₅ loading in the past was often estimated at 0.17 lbs/capita; however, there is a current trend toward the use of higher values; therefore the BOD loading in this case is reasonable.)

- d-) There are to be no non-domestic wastes in the system. Therefore a bottle BOD "k" rate of 0.10 is inferred, since this is the most commonly reported "k" value for domestic wastewater. At k = 0.10 approximately 68% of the total

- d-) oxygen demand (as determined by the BOD test) is exerted during the first 5 days; therefore $BOD_L = \frac{BOD_5}{.68}$

and

$$L = \frac{BOD_L}{BOD_5} = \frac{1}{.68} = 1.47$$

(Note: The significance and importance of determining the correct and applicable bottle BOD "k" value is often overlooked. When one considers that any rational design must involve the total oxygen demand rather than the five-day demand, the desirability of at least confirming the assumed "k" value is obvious. As an example, an organic material with an applicable "k" (bottle BOD) rate of 0.1 which has a BOD_5 value of 200 ppm will exert a total oxygen demand of 268 mg/l for complete biological stabilization; on the other hand, a waste which has a "k" value of 0.15 and BOD_5 of 200 ppm will exert a total oxygen demand of only 243 mg/l for complete bio-destruction. The "k" and "L" values can vary over a rather wide range, particularly when industrial wastes are involved. It is therefore extremely desirable and at times absolutely imperative to accurately determine the correct values.)

- e-) The desired BOD removal is 85%, as an average removal over the course of a year.

3. DESIGN PARAMETERS:

No additional information is available, since the consultant feels that the various factors and values generally associated with domestic-municipal sewage will apply to the wastewater in question. Therefore, the next step is to select the remaining factors and values on the basis of prior experience and the reported findings of research workers.

*The "bottle" BOD

Referring to Welles Products Bulletin 1204-1,

- a-) The first item to be determined is the applicable K_{20} rate. The " K_{20} rate" here refers to the rate of BOD removal in the lagoon. (It should be clearly recognized that the lagoon BOD reaction rate (K) is entirely different from the bottle BOD reaction rate (K), and that differences between the two occur as a result of the difference in the environment in which the BOD is exerted.)

Since no industrial or other unusual wastes are involved, a K value of 0.85 will be assumed. This is a realistic value, and generally representative of normal aerated lagoon performance. K_{20} values calculated on the basis of data taken from operating lagoons have turned out to be considerably higher than this, in some cases. However, a 0.55 value for K is sometimes chosen for the following reasons:

1. There is not sufficient valid and documented field operating data available to conclusively prove that the actual K value always exceeds 0.55 for domestic wastewater.
2. Even if the true average K value exceeds 0.55, use of this value provides a conservative design; i.e., incorporates a "safety factor" into the design.

The best means of resolving the dilemma regarding the "proper" K value is, of course, to conduct a pilot study to determine and document the specific K value which applies to the specific wastewater at hand.

- b-) Determination or selection of the critical lagoon liquid temperatures is the next item to be considered. Where it is in agreement with the requirements laid down by the regulatory agency involved, the lagoon detention time should be determined on the basis of the average BOD removal required during the year. (85%, in this case.) A conservative design will result if it is

- b-) assumed that the average yearly lagoon temperature will equal the average ambient air temperature for the particular geographic area involved. Therefore, we shall assume that the average lagoon temperature will be 15°C . (Since this is the average ambient air temperature for the area.) The lagoon size (i.e., the detention time, T) will therefore be selected on the basis of the K_{15} value.
- c-) An alpha factor of 0.9 will be assumed. This is conservative, since α values of 0.95 or even higher are not unusual for domestic wastewater. However, use of a slightly lower-than-actual α value will provide a margin of safety in the design.

The summarized design data is therefore:

Q = daily flow = 0.156 MGD

BOD_5 applied = 268 lbs/day

$L = 1.47$

$K_{20} = 0.85$

$\alpha = 0.90$

Average lagoon design temperature = 15°C

Summer lagoon design temperature = 24°C

4. DESIGN CALCULATIONS:

The initial step is the adjustment of the K_{20} value to the proper K values at the significant temperatures. The size of the lagoon is based upon the average yearly removal, so the K_{15} value is used. On the other hand, increased efficiency with increasing temperature means that the maximum oxygen demand will occur during warm weather. Weather bureau records for the area in question show that the average ambient summertime air temperature is 25°C . A maximum lagoon liquid temperature of 24°C is therefore reasonable, and the K_{24} value will be the controlling parameter for oxygen transfer considerations.

Since this will be a normal flow-through lagoon, $\theta = 1.035$ will be used for K factor temperature adjustment.

At 15°C , $\theta^{(t - 20)} = 1.035^{(15 - 20)} = 0.842$

and

at 24°C , $\theta^{(t - 20)} = 1.035^4 = 1.148$

therefore

$$K_{15} = K_{20} \times 0.842 = 0.85 \times 0.842 = 0.72$$

and similarly,

$$K_{24} = K_{20} \times 1.148 = 0.98$$

The required lagoon detention time is

$$T = \frac{.85}{.15 \times K_{15}} = 7.9 \text{ days}$$

The maximum removal efficiency at $T = 7.9$ days will be

$$E = \frac{K_{24} T}{1 + K_{24} T} = \frac{0.98 \times 7.9}{0.98 \times 7.9 + 1} \approx 88.6\%$$

The lagoon volume required is

$$7.9 \text{ days} \times 0.156 \text{ MGD} = 1.23 \text{ million gallons}$$

The maximum NOR value will occur at the time of maximum removal, so that

$$P = 0.886$$

and

$$D = \frac{268}{24}$$

so that

$$\text{NOR} = 1.47 \times \frac{268}{24} \times 0.886 \approx 14.54 \text{ lbs. of oxygen per hr.}$$

It is intended that the lagoon D.O. concentration (C_L) be at least 1.5 mg/l. The temperature correction factor value is 1.102 (from Welles graph WP 1168). For a 7.5 H.P. Aqua-Lator unit with a standard oxygen transfer rate (R_a) of 2.9 #/HP-hr., the actual transfer under the critical (i.e., summer) conditions will be

$$R = 2.9 \frac{(8.5 - 1.5)}{(9.17)} \times 0.9 \times 1.102$$

$$= 2.2 \text{ lbs. of oxygen per HP/hr.}$$

Therefore one 7.5 H.P. Aqua-Lator unit will provide sufficient oxygen ($7.5 \times 2.2 = 16.5$ lbs. of O_2 per hour).

For mixing and oxygen dispersion, using the recommended aerated lagoon power-to-volume (P/V) ratio of 8 HP/MG,

$$P = 1.23 \times 8 = 9.84 \text{ HP is required}$$

Therefore the M.A.D. requirement is the controlling parameter, and one 10 H.P. Aqua-Lator unit should be used in the 1.23 MG lagoon volume.

Assuming a 10 ft. lagoon depth, a 3:1 side slope, and the formula

$$\text{Volume} = 2.5d (A_T + A_B + \sqrt{A_T \times A_B})$$

where Volume is in gallons, and

d = water depth

A_T = water surface area in ft^2

A_B = lagoon bottom area in ft^2

The dimensions of the lagoon can be calculated. For a relatively small lagoon such as this, an approximately square configuration is desirable.

Use of the formula indicates that a lagoon with a water surface area of approximately 157' x 157' will give a liquid volume of 1.23 MG.

Therefore, the treatment lagoon should be square and have a volume of 1.23 MG, with one 10 H.P. Floating Aqua-Lator located in the center.



AERATED LAGOON DESIGN DATA

WELLES PRODUCTS CORPORATION

ROSCOE, ILLINOIS 61073

Telephone 815/623-2111

K Factor Adjustment 1.075 (t - 20) Batch System	Temperature		K Factor Adjustment 1.035 (t - 20) Continuous Flow System	Solubility of Oxygen in Water—mg/l			
	°F	°C		TDS of 400 mg/l	TDS of 800 mg/l	TDS of 1500 mg/l	TDS of 2500 mg/l
.253	32.0	0					
.272	33.8	1	.520	14.14	14.07	13.96	13.80
.292	35.6	2	.538	13.74	13.68	13.58	13.42
.314	37.4	3	.557	13.44	13.38	13.28	13.12
.338	39.2	4	.577	13.04	12.98	12.89	12.75
.363	41.0	5	.597	12.74	12.68	12.59	12.45
.391	42.8	6	.618	12.44	12.38	12.29	12.15
.420	44.6	7	.639	12.15	12.10	12.00	11.88
.451	46.4	8	.662	11.85	11.80	11.70	11.58
.483	48.2	9	.685	11.55	11.50	11.42	11.30
.522	50.0	10	.709	11.25	11.20	11.12	11.00
.561	51.8	11	.734	11.06	11.01	10.94	10.82
.603	53.6	12	.759	10.76	10.71	10.64	10.52
.648	55.4	13	.786	10.56	10.51	10.44	10.32
.697	57.2	14	.813	10.36	10.32	10.25	10.15
.749	59.0	15	.842	10.16	10.12	10.05	9.95
.805	60.8	16	.871	9.96	9.92	9.85	9.75
.865	62.7	17	.902	9.66	9.62	9.55	9.45
.930	64.4	18	.934	9.46	9.43	9.36	9.27
1.000	66.2	19	.966	9.36	9.33	9.26	9.17
1.075	68.0	20	1.000	9.16	9.13	9.06	8.97
1.156	69.8	21	1.035	8.96	8.93	8.86	8.77
1.242	71.6	22	1.071	8.77	8.73	8.68	8.60
1.335	73.4	23	1.109	8.67	8.63	8.58	8.50
1.436	75.2	24	1.148	8.47	8.43	8.38	8.30
1.543	77.0	25	1.188	8.37	8.33	8.28	8.20
1.659	78.8	26	1.229	8.17	8.13	8.08	8.00
1.783	80.6	27	1.272	8.07	8.03	7.98	7.90
1.917	82.4	28	1.317	7.87	7.83	7.78	7.70
2.061	84.2	29	1.363	7.77	7.73	7.68	7.60
2.382	86.0	30	1.411	7.57	7.53	7.48	7.40
2.783	88.6	32	1.511	7.4*			
3.181	93.2	34	1.619	7.2*			
3.676	96.8	36	1.734	7.0*			
Limit	100.4	38	1.858	6.8*			
	104.0	40	Limit	6.6*			

* At TDS = Zero

TDS means Total Dissolved Solids.