PRR© Process
Progressive Reaeration and Recirculation© and Design Guide (draft).

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A THEORETICAL APPROACH: PROGRESSIVE REAERATION AND RECIRCULATION

The attached "white paper" entitled: Progressive Reaeration and Recirculation Process (PRR) was developed by Warren Enyart, under Wayne Ruzicka's direction, in an attempt to describe, quantify, and formulate the various observed phenomenon believed to be attributable to the Sunflo2 technology. The research was primarily based upon literature reviews of relevant principles researched by other renowned scientists that are known to be influenced by the Sunflo2 technology, and believed to be probable causes for observed pond-based wastewater and fresh water treatment. The object of the paper is to provide a rational background for developing a few "short cut" formulae that will enable engineers and/or trained wastewater treatment personnel to predict the BOD removal rate that one could expect from the application of the Sunflo2 units in a given pond environment.

The observed variables have been discussed in order of their theoretical importance to the outcome; measured in "BOD removal rate" (RR%). Ideally, the ultimate formula should be of the following order: RR% = f1 x f2 x f3x fn…, where, f1, f2, f3, etc are the variables discussed in the paper; the first of which has the most significant influence on the outcome, the next variable having less impact, and so on. Of course, at best this is only a theoretical framework to attempt to give relative weight to the variables as each might affect to treatment process, when the Sunflo2 technology is properly applied.

The observed target is dictated by frequently observed performance of Sunflo^2 technology operating in typical wastewater ponds. In many such cases, the measured RR% after the application of the Sunflo^2 technology, was found to be five times that achieved by the unassisted facultative pond. Most of these ponds, while now overloaded, were originally designed under the USEPA standards for areal loading in a given climate. This is a strategic targeted metric, as many of the 8,000 pond-based treatment facilities in the United States were originally designed under the EPA criteria. In any case, the primary metric for any treatment process, is the reduction of BOD. And because the Sunflo^2 unit's operating principles depend a great deal on the surface area, in addition to the mixed portion of the pond (hence, "PRR"), these two parameters should be inherent in the ultimate formula to be derived.

A mathematician might review the tested formulae included in the paper and draft an empirical relationship among them that incorporates the observed phenomena attributable to the Sunflo^2 units. The empirical formula could serve as the hypothesis for controlled experimentation; with the ultimate goal to deduce a reliable, but simplified, design formula that will predict the RR% of the Sunflo^2 units application in a given pond.

Although it is an over simplification, if our theory is correct, the empirical formula for RR% should be equal to five times the basic formal used to predict the performance of an unassisted facultative pond designed in accordance with EPA guidelines.

Research Sources

In addition to the sources listed behind each "white paper" material was also sourced from some of the documents shown below.

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2. Design manual: Municipal wastewater stabilization ponds **E. J Middlebrooks, 1983**
   https://scholar.google.com/scholar?q=Design+Manual,+Municipal+wastewater+

3. Environmental Systems Engineering, **Linvil G. Rich**
   https://books.google.com/books/about/Environmental_Systems_Engineering

4. Waste stabilization lagoons : a review of research and experience in design, construction, operation and maintenance: proceedings of a symposium at Kansas City, Mo., Aug. 1-5, 1960
   https://search.library.wisc.edu/catalog/999617268502121

5. Operations Manual, Stabilization Ponds, **Chuck Zickefoose**
   https://nepis.epa.gov/Exe/ZyNET.exe/9100

6. Sewage Stabilization Ponds in the Dakotas, **W. Van Heuvelen, ND Department of Health**
   https://nepis.epa.gov/Exe/ZyNET.exe/2000QW93.TXT?

7. Industrial Waste Treatment Practice, **E.F. Eldridge**

8. Sewage Treatment, **Karl Imhoff and Gordon Fair**
   https://www.amazon.com/Sewage-Treatment-Karl-Imhoff

9. Nitrogen Removal in Wastewater Stabilization Lagoons, **Joe Middlebrooks**
   http://www.bvsde.paho.org/bvsacd/leeds/removal.pdf

SUMMARY

Progressive Reaeration and Recirculation Process

Data gathered over five years from hundreds of applications have demonstrated that the Sunflo² technology generally improves the rate at which properly designed, otherwise unassisted, facultative wastewater and fresh water treatment ponds satisfy the daily influent of Biochemical Oxygen Demand (BOD). Provided the pond has adequate surface area, operating depth, and detention time, one or more Sunflo² units can effectively treat up to five times the recommended US Environmental Protection Agency (EPA) areal loading (lbs BOD/acre/day) for natural pond-based treatment for a given climatological region. The principles discussed in this approach to treatment are based on those inherent in a facultative pond regimen; typical to the unassisted pond-based treatment designs upon which the EPA's areal loading guidelines were formulated.

For the purposes of this discussion, "treatment" is generally taken to mean the decomposition of organic material. In a pond environment, decomposition is principally accomplished by the work of either aerobic (living in the presence of free oxygen) or anaerobic (living in absence of free oxygen) microorganisms. In a pond in which the pollution load is exceedingly high, or the pond is deep enough to be void of dissolved oxygen near the bottom, both types of microorganisms may be actively decomposing organic materials simultaneously. A third type of microorganism, known as the facultative anaerobic, is capable of metabolic activity under either aerobic or anaerobic conditions, assisting in decomposing the waste in the transition zone between aerobic and anaerobic conditions. Aerobic microorganisms, however, cause the most complete oxidation of organic matter and therefore are the most desirable agents in a wastewater or fresh water treatment pond.

As one might expect in a fluid environment, these creatures necessarily "go with the flow." Their respective stratum or habitat will vary in depth and may overlap. Besides the mixing of pond contents, the habitat for each will greatly depend upon the availability of dissolved oxygen in a given stratum. Inasmuch as oxygen dissolved at the surface will migrate downward until it has been taken up by the oxidation processes, its penetration, and therefore the depth of the aerobic zone, will be limited by the supply at the surface and the oxygen demand along its decent. While facultative and anaerobic conditions are helpful in the total wastewater treatment cycle, maximizing the aerobic treatment process has the greatest effect on the overall outcome from pond-based treatment designs.

Aerobic digestion will proceed at an optimum rate when there is proper balance among the key reactants including: dissolved oxygen, aerobic microorganisms, organic material, heat, and contact time. In an unassisted pond, oxygen is supplied principally from absorption from the atmosphere and photosynthesis; referred to as "reaeration." Reaeration occurs at or near the surface. This is the controlling factor underlying the EPA's areal loading model.

There are other factors however that are more difficult to quantify than simply dividing the daily load expressed in pounds of BOD by the surface area of the pond. These factors affect the performance of the Sunflo² technology in a given pond. Some have greater influence than others. Nevertheless, when understood and "weighted" in proportion to their relative affects, the treatment results, in terms of BOD removal, can be accurately predicted.

For example, when volatile sludge has previously accumulated in the pond, upon introducing the Sunflo² unit's functions of controlled mixing, surface renewal, reaeration and bio flocculation, there is often a dramatic acceleration in the digestion of sludge. Consequently, this additional demand upon oxygen resources will significantly reduce the amount of daily BOD removal that can be expected from nature or from the Sunflo² technology. Under these conditions, any appreciable dissolved oxygen (DO) residual is difficult to maintain until the sludge volatility has been substantially reduced, or otherwise allowed to digest via sustained anaerobic reactions.

When volatile sludge is present, the intake structure of the Sunflo² units must be raised well above the weight-bearing layer of sludge, and particularly above any slurry-sludge that might be present. By design, mixing by the Sunflo² units is confined to the zone between the surface and the depth of the intake structure. This mixed portion is subject to aerobic digestion. Therefore, the strength of the BOD in the mixed zone determines the demand upon dissolved oxygen resources. In order to maintain effective treatment, the supply of oxygen must be about 56% greater (see equation 17) than the desired BOD removal that is subject to aerobic digestion (demand).

As the above example may imply, pond-base treatment is very complex. There are dozens of factors that affect the outcome. Knowing what conditions will reliably produce predictable results requires a great deal of research and experience. This research and experience takes a large commitment of time and money, and as such, tends to cause those who have made the investment to hold onto the findings as proprietary intellectual property. However, there is a growing need to improve the performance of pond-based treatment facilities. Those who wish to modify (or enhance) pond-based treatment, but have not had the opportunity or the time to study all of the intricate biological, chemical, and physical reactions occurring in the pond, need to acquire at least a working understanding, or rely upon others who do.

Sunflo² technology is specialized in providing low-energy, low-maintenance solutions for wastewater and fresh water treatment in a pond environment. We have invested many years and millions of dollars in applied research related to enhancing natural treatment in pond-based environments. In the interest of advancing the state-of-the-art while growing our business, we believe it is prudent for us, and helpful to engineers and operators, to present the salient details of a ***process*** that takes into account the proprietary aspects of our research and experience, while providing a reliable "short cut" for evaluating alternatives and designing improvements for pond-based treatment facilities.

THE PROCESS

The process, which is referred to as **Progressive Reaeration and Recirculation (PRR™)**, is founded on the principle that the rate of stabilization in a pond environment can be influenced by mixing, and that optimum kinetics for specific conditions can be achieved through the selection of a specific portion of the pond volume to be mixed. The targeted amount of volume to be mixed is determined by the oxygen demand within a pond and the desired quality of effluent from that pond (or combination of ponds). The objective of the mixing regimen is to establish and maintain an aerobic stratum that maximizes the overall treatment outcome.

Controlling the mixed volume enables the operator to effectively control the amount of daily aerobic demand for given treatment conditions. This in turn affects the amount of oxygen to be supplied. In this case, the oxygen supply is achieved by substantially enhanced reaeration mechanisms. In short, the process optimizes the depth of the aerobic treatment zone within the given supply mechanism parameters as influenced by the Sunflo² technology. Experience has shown that the process also facilitates efficient sludge deposition and digestion.

However, **PRR™** is not simply another mixing machine. The Sunflo² mixing units are the "tools" of the **PRR™ Process,** which is tailored to each specific treatment facility. While these tools are designed to enhance the positive natural biological, chemical, and physical stabilization processes that occur in the pond environment and to minimize the negative bi-products and events, a clear understanding of the facility and its operation is necessary. A holistic approach is employed that encompasses the original treatment system design, operations, changes in conditions, performance, problems and their causes, and cost-effective solutions.

The holistic approach involves:

1) a careful analysis of the historical performance and operations of the treatment process, whether entirely natural or mechanically assisted;
2) an accurate description and quantification of the existing conditions;
3) a forecast of future needs and contemplated design and/or operation changes;
4) stated quantifiable objectives for the desired performance and effluent quality;
5) the prescription of mixing and aeration equipment including their strategic locations, controlled mixed volume settings and operating recommendations; and
6) stipulated monitoring protocols designed to measure the performance of the process.

When clearly understood, the desired effects of the **PRR™ Process** are predictable and are achieved through low-energy-low-velocity controlled mixing and reaeration; providing the calculated requirements for oxygen via stimulated absorption from the atmosphere, diffused air bubbles (in the case of the Sunflo² AS Model), and algae control. The number and type of Sunflo² units prescribed is determined by the specific requirements of the particular pond environment and treatment objectives. The units are carefully arrayed on the pond(s) and their depth settings are specified in order to provide the optimum mixed-zone influence.

A MATHEMATICAL EXPRESSION FOR PRR™

The purpose of this paper is to describe the mathematical relationships among the most important factors that influence the effectiveness of the Sunflo² units in facultative wastewater and fresh water treatment ponds and to provide rationale for various observed and measured effects. Because the industry relies heavily on the measurement of BOD removal, the mathematical relationships among the various factors are presented as functions affecting the removal rate. The following discussion will assist engineers and others who wish to enhance existing wastewater or fresh water pond-based treatment systems, or to design new systems in which the application of the Sunflo² technology and the **PRR™ Process** may be appropriate.

BOD REMOVAL DEFINED

For the purposes of this paper, the BOD removal rate is limited to the first-stage BOD (BOD_5) or carbonaceous BOD (CBOD). As used herein, the acronym "BOD" refers to the carbonaceous biochemical oxygen demand. By definition, the BOD removal rate (expressed as a percentage) is the amount of BOD satisfied in the pond (effluent BOD concentration x daily flow) compared with the amount of BOD incoming (influent BOD concentration x daily flow) with the wastewater stream, expressed as follows:

$$\text{BOD removal rate (RR\%)} = \frac{\text{BOD of influent (lbs. /day)} - \text{BOD of effluent (lbs. /day)} \times 100}{\text{BOD of influent (lbs. /day)}} \quad (1)$$

The removal rate of a thoroughly mixed concentration of reactants can be reasonably predicted by application of a "first-order" reaction rate. Mathematically speaking, the rate at which a reaction is observed to occur can be expressed in terms of a coefficient (constant for a given reactant and temperature) when such rate is dependent upon the initial concentration of the reactant. A first-order reaction is one in which the rate of completion is observed to be directly proportional to the first power of concentration of the reactant. In some reactions, the rate of change is proportional to the square of the concentration of the reactants. In the latter instance, the term "second-order" would apply.

Because this concept is based on the assumption that the reactants are in sufficiently close proximity to react continuously over a period of time (contact time), both mixing and adequate time for the reaction to take place are important factors. Even with aggressive mixing, the time required for optimum biological, physical, and chemical reactions to occur in a stabilization pond is critical. Often, hydraulic detention time $(D_h = V/Q)$, is relied upon as an approximation of "contact time." However, while detention time is an important factor in most design methods, short-circuiting, temperature stratification, sludge displacement, and other factors may effectively reduce the time for adequate reactions (BOD reduction) to occur.

PREDICTING THE BOD REMOVAL RATE

Metcalf and Eddy outlined a reliable basis for design that involves the selection of a mixing regimen employing a concept called the "Mean Cell Residence Time" (MCRT). When there is adequate mixing, MCRT is effectively "contact time" expressed in days. This concept will be discussed in detail later. For now, it suffices to say that optimum MCRT will ensure: 1) that the suspended microorganisms will bioflocculate for easy removal by sedimentation and fermentation, and 2) that an adequate factor of safety is provided when compared to the MCRT washout. This design concept demonstrates, empirically, that the MCRT of a compete-mix-no-recycle system, or a thoroughly mixed stabilization pond, approaches its designed detention time. As such, a first-order reaction calculation adequately predicts the expected BOD removal rate for these designs. The mathematical relationship is as follows:

$$RR\% = \frac{\text{BOD of influent (lbs. /day)} - \text{BOD of effluent (lbs. /day)}}{\text{BOD of influent (lbs. /day)}} \times 100 = 100 - \frac{100}{1 + K(V_{mix}/Q)} \qquad (2)$$

Where V_{mix} = the mixed volume of the pond (gals.),
Q = the daily flow (gals./day), and
K = overall first-order BOD removal rate constant (days^{-1}).

SELECTING THE "K" VALUE

As the formula demonstrates, the value of K greatly affects the removal rate. This removal rate constant is a function of temperature and the constituency of the wastewater. Reported overall K values vary from 0.25 to 1.0. The average value of K for domestic sewage is 0.39 at 20°C. Removal rates, and therefore the K factor, for soluble BOD are somewhat higher. For a given constituency of BOD, the BOD reduction will vary with time and with different K values. In general, the lower the K value, the longer it takes to achieve a given removal rate.

Since the rate of BOD reduction is affected by the temperature of the pond, it is therefore necessary to adjust the K factor for different temperatures, other than the standard "20°C." The following approximate equation may be used:

$$K_T = K_{20} C_T^{(T-20)} \qquad (3)$$

Where K_T = the BOD removal rate constant, adjusted for temperature,
K_{20} = standard BOD removal rate at 20°C for a given BOD constituency,
C_T = temperature coefficient, and
T = temperature of wastewater.

Research has found that the value of C_T varies from 1.056 in the temperature range between 20°C and 30°C to 1.135 in the temperature range between 4°C and 20°C.

The selection of an accurate removal rate constant (K value) is critically important in predicting the effectiveness of the Sunflo² units. A reduction in the K value requires a dramatic increase in the MCRT to affect the desired BOD removal. Table 1 shows the relationship between various K values and the corresponding required MCRT to achieve a 90% removal rate.

Table 1. Varying *K* values from 0.25-1.00 and their corresponding effect on MCRT (days) in order to achieve 90% BOD removal.

Varying Temperature

Different Wastewater Constituencies	20°C (std.)		4°C		8°C		30°C	
	K_{20}	$MCRT_{20}$	K_4	$MCRT_4$	K_8	$MCRT_8$	K_{30}	$MCRT_{30}$
	0.25	36.00	0.033	273.04	0.055	165.14	0.431	20.88
	0.30	30.00	0.040	227.53	0.065	137.61	0.517	17.40
	0.35	25.71	0.046	195.03	0.076	117.96	0.604	14.91
Domestic	0.39	23.08	0.051	175.02	0.085	105.86	0.673	13.38
	0.40	22.50	0.053	170.65	0.087	103.21	0.690	13.05
	0.45	20.00	0.059	151.69	0.098	91.74	0.776	11.60
	0.50	18.00	0.066	136.52	0.109	82.57	0.862	10.44
	0.55	16.36	0.073	124.11	0.120	75.06	0.948	9.49
	0.60	15.00	0.079	113.77	0.131	68.81	1.035	8.70
	0.65	13.85	0.086	105.01	0.142	63.51	1.121	8.03
	0.70	12.86	0.092	97.51	0.153	58.98	1.207	7.46
	0.75	12.00	0.099	91.01	0.164	55.05	1.293	6.96
	0.80	11.25	0.105	85.32	0.174	51.61	1.380	6.52
	0.85	10.59	0.112	80.31	0.185	48.57	1.466	6.14
	0.90	10.00	0.119	75.84	0.196	45.87	1.552	5.80
	0.95	9.47	0.125	71.85	0.207	43.46	1.638	5.49
	1.00	9.00	0.132	68.26	0.218	41.28	1.724	5.22

CYCLE RATE

One of the main attributes of the Sunflo² technology is its high-volume mixing capacity, while using a relatively small amount of energy, compared to other aeration equipment currently available. This is accomplished by its design. With a very low head (0.75 inches or less), a unique discharge dish, and a low-rpm impeller, one Sunfl2 Unit, at optimum (lower latitudes, summertime operation) daily average rpm (80 rpm), can move 1,200,000 gallons per 24-hour day. This pumping capacity is direct displacement only. It should be noted that this is the volume of water moved from the depth at which the intake dish is set to the surface of the pond; an average distance of only three feet. The details of the principles behind the pumping capacity of the Sunflo² technology is included in a "white paper" published by Sunflo², entitled: *Oxygen Transfer Via Progressive Reaeration and Recirculation.*

While this is considered the pumping capacity, what is significant in the pond treatment environment, is the rate at which the mixed volume is cycled per day (Cycle Rate). Some of the most important drivers of pond-based stabilization are dependent upon the diurnal cycle. In the case of the Sunflo² technology, the Cycle Rate is a reliable indicator of the exposure of the mixed portion of the pond to the surface, where several major natural treatment processes take place.

By definition, the Cycle Rate is the number of times that portion of the pond that is subject to mixing, is cycled per day; expressed as follows:

$$\text{Cycle Rate (\#/day)} = \frac{\text{daily pumping capacity (gal/day)}}{\text{mixed portion of pond (gal)}} = P_{cpy} / V_{mix}, \quad (4)$$

Where P_{cpy} = total pumping capacity (gal/day), and
V_{mix} = mixed volume of the pond (gal).

Under ideal conditions, the Cycle Rate for any given pond should approach 1/day. This should not be taken to mean mixing the entire contents of the pond each day. To cycle the entire contents of the pond each day would require machinery with pumping capacities of several million gallons per day. Cycling the entire contents of the pond is not practical nor is it necessary. Experience has shown that selection of optimum mixing depth and control of the volume to be cycled will result in desirable treatment results.

The Cycle Rate influences a number of biological, chemical, and physical reactions in a pond environment. These are discussed in detail in a set of "white papers" researched and published by Sunflo². Of the several factors that affect BOD removal in a facultative pond, because it is focused on optimizing the volume of the aerobic zone while enhancing the reactions therein, the Cycle Rate has the greatest overall effect, whether influenced by nature (wind, waves, etc.) or by man-made mechanical means such as Sunflo² floating pumps. That is, within certain parameters, gentle and continuous mixing significantly increases the rate of BOD removal over that of a quiescent pond.

On the other hand, turbulent, aggressive mixing can reduce BOD removal rates by inhibiting the precipitation of solids occurring in the form of; settleable, flocculation or coagulation of colloids, and suspended particles. The limiting velocity at which deposition will occur is in the range of 0.5 ft/sec to 0.6 ft/sec. Higher velocities tend to retard precipitation and may re-suspend insoluble BOD and other solids that should be allowed to settle to the sludge bed where a better suited stabilization process (less demand on DO resources) will occur. However, lower velocities may not cycle enough volume to maximize the MCRT, as we will see in the discussion of the Mean Cell Residence Time to follow. In general, the greater the Cycle Rate (provided the velocity does not exceed "scouring speed"), the greater the BOD removal rate.

Mean Cell Residence Time

The Mean Cell Residence Time (MCRT) ranks next to Cycle Rate in terms of its influence on the BOD removal rate. As with Cycle Rates, the MCRT is also dependent upon mixing functions in the pond, whether natural or mechanically assisted. By definition, MCRT is defined as the average time (expressed in days) that the mass concentration of the microorganisms remain in the pond; expressed mathematically as:

$$\mathrm{MCRT} = \frac{VX_p}{QX_f}, \tag{5}$$

Where V = volume of pond (million gal),
Q = inflow rate of wastewater (mgd),
X_p = mass concentration of microorganisms in the pond (mg/L), and
X_f = mass concentration of microorganisms in the influent flow (mg/L).

Simplified, one can see that the MCRT is equal to hydraulic detention time *($D_h = V/Q$)*, when the mass concentration of the living organisms contained in the volume of the pond is equal to the mass concentration of the living organisms contained in the flow rate. Put another way, this means that the average detention time of the organisms in the system is the same as that of the liquid. This is a very important concept that requires thorough mixing of the pond, not possible through natural means.

Of course, even with conventional high-energy aeration and mixing equipment, this is difficult to achieve when ponds have several acres of surface area and are five or more feet in depth. Typically, this type of equipment is designed to force high volumes of air (of which only 21% is oxygen) against a pressure head of several feet, while at the same time providing a mixing force sufficient to influence a large surface area. When this work is attempted at high rates, the horsepower (work/time) required is substantial.

However, there are more efficient methods to supply dissolved oxygen while mixing the upper portion of the pond contents. These principles are incorporated in the Sunflo² technology. The Sunflo² technology includes a patented floating pump that lifts oxygen-deficient water from the depth at which the intake dish is set to an elevation of only ¾" to 1" above the surface. At this point, thin sheets water spread radially outward from the distribution dish, with the force of gravity doing most of the work. The sheets radiate outward at an initial velocity of about 1.2'/sec. In their progression across the surface, the sheets maintain near-laminar flow and tend to remain on the surface until each sheet reaches the embankment, or until they encounter a converging laminar sheet. At that point a shallow head is created and the surface water descends once again to the depth at which the intake dish is set.

Over the distance from the point of distribution to the shore (or until they encounter another laminar sheet), the surface sheets are exposed to the atmosphere and have time to absorb pure oxygen from the air while spreading the saturated layer across the pond, facilitating more efficient diffusion of dissolved oxygen.

This mechanism provides increased absorption of pure oxygen from the atmosphere, the effective distribution of dissolved oxygen, as well as the efficient, low-energy partial mixing of the pond contents, thereby increasing the MCRT over that of a quiescent or unassisted pond. As such, the accuracy of the BOD removal predictions is greatly improved when using the "first-order" method.

When mixing is confined to some volume less than that of the entire pond, the effective MCRT is reduced. In a low-energy, partially mixed pond, the MCRT becomes a function of the mixed volume and the daily flows expressed as follows:

$$MCRT = V_{mix}/Q\,, \tag{6}$$

Where V_{mix} = mixed volume (gals.), and
Q = daily inflow rate of wastewater (gals./day).

Although the effective MCRT is less than it might be if the entire pond contents were mixed, the gentle, broad mixing influence provided by the Sunflo² units can effectively increase the MCRT over that of a quiescent (unassisted) pond. Notice that when the mixed volume approaches the total operating volume of the pond, MCRT approaches the value of the hydraulic detention time.

Because of its unique intake design and flow characteristics, the mixed volume influenced by the Sunflo² units is defined by the depth setting of the intake. The lateral range of mixing influence is significantly reduced at distances greater than 200 feet from the unit (i.e., ponds greater than three acres). While still providing mixing influence and wave action to the berms in ponds greater than three acres, the mass transfer at greater distances is reduced as a function (inverse) of the square of the distance from the unit. This concept is further detailed in a "white paper" published by Sunflo² units, entitled: *Oxygen Transfer Via Enhanced Reaeration & Mixing.* The MCRT, as influenced by the Sunflo² units is calculated as follows:

$$MCRT_{pd} = \frac{A \text{ x } d \text{ x } 43{,}560 \text{ ft}^2\text{/acre x sf x } 7.48 \text{ gals./ft}^3}{Q}\,, \tag{7}$$

Where A = surface area of pond (acres),
d = depth of intake setting from surface (ft),
sf = adjustment for volume due to sloping berm walls (slope factor), and
Q = daily flows into the pond (gals./day).

One can see from equation (6) that increasing the dimensions of the mixed portion of the pond effectively **increases** the valuable MCRT for a given daily flow. Equation (7) shows how the Sunflo² technology influences MCRT. However, equation (4) shows that increasing the dimensions of the mixed volume **reduces** the Cycle Rate for any given pumping capacity. The mixed volume in a pond in which the Sunflo² units are operating is determined by the depth of the intake. Also, as was pointed out earlier, the increased depth of the intake can increase the demand on oxygen resources. Therefore, there are inherent tradeoffs in determining the best intake depth setting. The optimum balance between Oxygen Demand, Cycle Rate and MCRT needs to take other conditions in the pond into account.

AREAL LOADING

One such condition is the areal loading on the pond. Next to MCRT, the surface area of a pond is critically important in facultative stabilization. The surface area is the "gate" through which oxygen enters, sunlight is admitted, and gasses escape. The surface is where the wind applies its mixing forces, evaporation influence, and carries away exhaust gasses. The surface (exposure to sunlight) is where the valuable oxygen-producing photosynthetic plants thrive. All of these obvious natural treatment elements as well as other more subtle processes are proportionate to the surface area.

Less obvious, but nevertheless important, are the biological activities that are surface-dependent. For example, the depth of the aerobic zone in an unassisted facultative pond fluctuates daily and seasonally. This phenomenon is related to the surface area as the depth (and therefore the strength) of the aerobic activity is the result of such factors as atmospheric and photosynthetic reaeration, wind and waves, surface tension, etc., all of which are dependent upon the surface area.

Although difficult to individually quantify, these complex and interdependent considerations are inherent in a simplified wastewater treatment design approach referred to as "areal loading." Of the five most frequently used methods to design facultative lagoons, the areal loading method is the most conservative. Most of the pond-base wastewater treatment systems in which the Sunflo² technology has been applied have been designed or modified using areal loading as the primary criterion.

The areal loading rate method is used by many of the western states and requires the least amount of design data. It is based on operational experiences in different geographical areas of the United States. This empirical database takes into account overturns, rising sludge, and seasonal algae concentration variations that can affect treatment. The areal loading method is recommended over the other methods unless comparable systems are available upon which to base rate constants for the other models.

There are nearly 8,000 "lagoon" systems in operation across the United States. More lagoon systems are being planned and constructed every year. The major reasons for their popularity are the basic simplicity of the concept and the low costs and energy requirements. However, many are subject to overloading and/or are in need of upgrading. With the use of the **PRR™ Process**, most of these systems could be made to work even though they may be overloaded with respect to their original design criteria. In order to understand how this can be done, a review of the areal loading design method is in order.

The primary biological design consideration under this approach is the organic BOD loading in pounds per acre per day. Areal loading is related to a pond's dimensional and water constituent variables as follows:

$$L_o = c\,(O_d/D_h)(L_a), \qquad (8)$$

Where L_o = organic load applied to a pond (lbs.BOD/acre/day),
L_a = influent BOD concentration (ppm),
D_h = hydraulic detention time (days),
O_d = operating depth of pond (ft), and
c = conversion constant having a value of 2.71(when ppm are to be converted to lbs. per acre-ft per ppm and O_d is expressed in feet).

It must be noted that the equation (8) sets the maximum parameters for the demand for oxygen resources in a given pond. If the design calls for something less than 100% removal rate in a particular pond, the actual BOD to be satisfied in that pond is related to the concentration differences between the influent BOD and the effluent BOD expressed as follows:

$$L_t = (L_a - L_e), \qquad (9)$$

Where L_t = actual BOD to be satisfied in that particular pond (ppm),
L_a = BOD concentration of influent wastewater (ppm), and
L_e = BOD concentration of effluent wastewater (ppm).

Recognizing that both overflow and percolation may carry soluble BOD, whereas evaporation contains no BOD (except for escaped gasses such as ammonia), the exact requirement of dissolved oxygen which must be satisfied through all pond resources is:

$$L_o' = c\, O_d(L_a/D_h - L_e/D_s), \qquad (10)$$

Where L_o' = the total oxygen demand in the pond (lbs.O_2/acre/day), and
D_s = hydraulic detention time when percolation and overflow rates are taken into account (days).

An abbreviated approach is often used which provides the designer with a calculated requirement for surface area for a given influent concentration but does not directly account for detention time. The simplified equation is:

$$A = \frac{(BOD)(q)(8.34\text{lb/gal})}{(LR)}, \qquad (11)$$

Where A = area for facultative lagoon (acres),
BOD = concentration of BOD in wastewater (mg/L),
q = wastewater flow (millions of gallons/day), and
LR = BOD loading rate selected from Table 2 for appropriate average winter air temperature.

$$Lo' = Kd(La/D - Le/Ds), \qquad (17)$$

The above calculations are intended to aid in sizing a new facultative pond system. Using it to explain why the system isn't working will require adjustments, especially if there has been an accumulation of sludge in the pond under consideration. The operating depth, O_d, in equation (10) is effectively reduced by displacement caused by sludge accumulations.

This operating depth also shows up in the calculation of hydraulic detention time, D_h, as follows:

$$D_h = V/Q, \quad (12)$$

Where $V = O_d$ x surface area x *sf* (ft³ x 7.48 gal/ft³), and
Q = daily flow rate (gal/day).

In order to be accurate, one needs to account for sludge displacement as well as percolation and overflow rates when calculating the actual performance of a pond when using the aeral loading method.

Temperature and detention time are important factors that are inherent in the calculations. It should be noted that when ice cover forms for extended periods of time, facultative lagoons perform essentially as cold anaerobic ponds that remove particulate BOD by settling, but with little biological activity.

The expected performance of a facultative pond has been rationalized by EPA over years of experience in regulating many ponds in various climatological regions. EPA has established areal BOD loading rates based on average air temperatures for the coldest month of the year. The recommended BOD loading rates for various ranges of temperatures are given in Table 2. Individual states have maximum BOD loading rates for lagoons, and the designer will need to verify this factor with the appropriate regulating authority.

Table 2. Areal loading rate values for different temperatures (U.S. EPA, 1983).

Average winter air temperature (°C)	BOD loading rate (lbs./acre/day)
>15	40-80
0 -15	20-40
<0	10-20

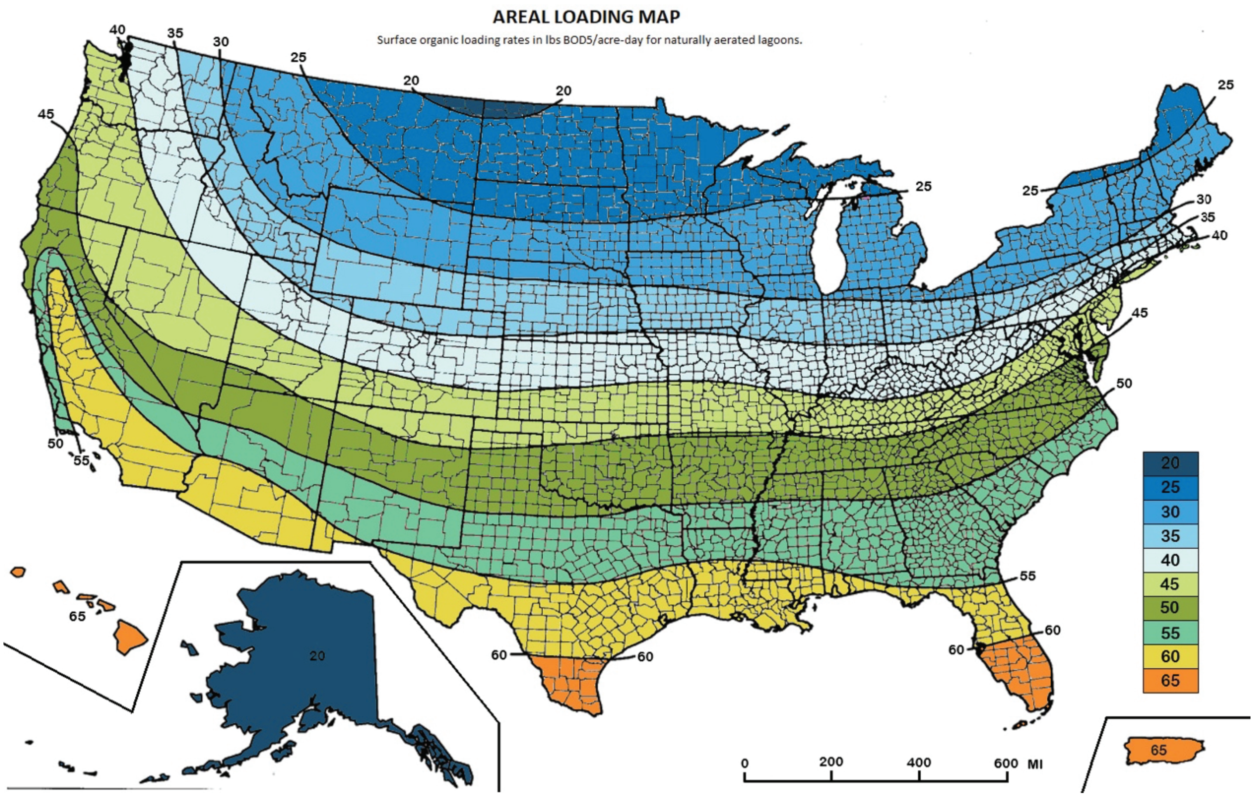

Figure 1 shows the areal loading rates associated with climatic conditions across the United States as determined by the U.S. Department of Agriculture, Natural Resources Conservation Service. This map seems to be based mainly upon climatic conditions, with temperature being dominant.

Figure 1. Aerobic lagoon loading rate, lbs. BOD_5/acre/day, (USDA, National Resources and Conservation Service, 1995).

As one can see, the application and reliability of the areal loading method is site specific. For example, the original North Dakota recommendations for complete treatment were based on an equivalent loading of 100 persons per acre of pond surface area or about 20 lbs. BOD/acre/day. With more experience, loadings of 200 persons per acre have been approved, and up to 68 lbs. BOD/acre/day have been employed successfully. The current Minnesota loading guide is 22 lbs. BOD/acre/day, while Texas recommends a maximum loading of 50 lbs. BOD/acre/day. Provided the more precise dimensions are used, the areal loading equation (10) taken together with the recommended "zones" shown in Figure 2, provide a reliable "short cut" to predicting what nature can do (without mechanical assistance) in facultative pond in terms of BOD removal.

REAERATION

Since areal loading designs are based on observations and experience on what nature will do in a given sized pond in a given climate, it is not necessary to calculate the actual supply of oxygen. For the purposes of demonstrating the "power" of nature acting on the surface area, however, it is worthwhile tracking the sources of oxygen that are behind the areal loading method. Oxygen supply in an unassisted pond is commonly referred to as "reaeration." This includes the absorption of pure oxygen from the atmosphere and the production of oxygen by photosynthetic plants.

When sewage enters the stabilization pond it is usually devoid of oxygen. Only two sources of molecular oxygen are available for aerobic oxidation: atmospheric absorption and photosynthesis. In the absence of algae, under conditions that inhibit algae activity, or when the hydraulic detention period is only 3-5 days, continuous oxidation of organic matter depletes any dissolved oxygen originally present in the pond. An oxygen deficit (O_2 saturation @ temperature, ppm - O_2 dissolved, ppm) will develop in continuously and heavily loaded ponds. Depending upon the magnitude of the oxygen deficit, oxygen will be absorbed directly from the atmosphere (atmospheric reaeration) at the surface and will diffuse toward the depths of the pond tending to restore the concentration of dissolved oxygen to its saturation value. The greater the deficit, the greater the mass transfer, as shown in Table 3. Such transfer moves in the direction of the deficit, and slows dramatically as the state of equilibrium is approached.

Table 3. Rate at which oxygen dissolves in water, after Eldridge.

Percentage saturation	Oxygen dissolved, g. per sq. ft. per day	Percentage saturation	Oxygen dissolved, g. per sq. ft. per day
0	1.00	45	0.15
5	0.83	50	0.12
10	0.58	55	0.10
15	0.47	60	0.08
20	0.38	65	0.06
25	0.31	70	0.05
30	0.27	80	0.03
35	0.23	90	0.01
40	0.18	100	0.00

Obviously, the rate of atmospheric reaeration is a function of the surface area. Less obvious is its dependence upon the nature of the interface between the water and the atmosphere. Theory suggests there are two films, one liquid and one gas, which provide resistance to the passage of gas molecules between the bulk-gaseous and bulk-liquid phases. For transfer of gas molecules from the gas phase to the liquid phase, slightly soluble gases, such as O_2, encounter the primary resistance to transfer from the liquid film, while very soluble gases encounter the primary resistance from the gaseous film. Gases of intermediate solubility encounter significant resistance from both films.

A sketch of the "two film" transfer theory is shown in Figure 2.

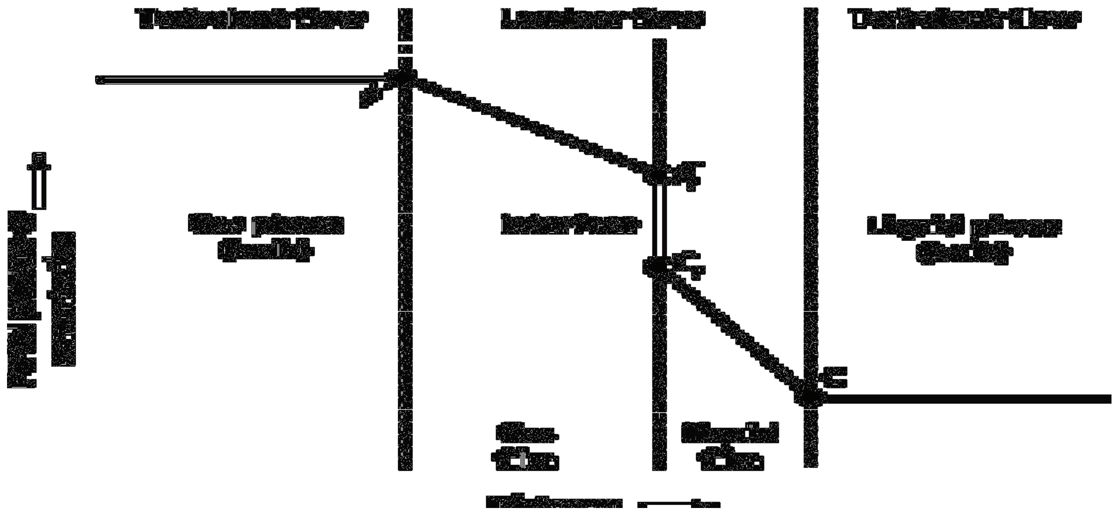

Figure 2. Definition sketch for two-film gas transfer theory.

The rate of gas transfer, in general, is proportional to the difference between the existing concentration and the equilibrium concentration of the gas in solution. The proportionality constant is a function of the resistance of either or both of the films and is also a function of the area of liquid-gas interface that exists per unit volume of the fluid.

The equilibrium concentration of gas dissolved in a liquid is a function of the partial pressure at the gas adjacent to the liquid, as expressed in Henry's Law. This law also contains a constant of proportionately which factors in the type, temperature, and constituents of the liquid.

When taken together these concepts, operating at the surface interface, act to either facilitate or inhibit oxygen transfer via atmospheric reaeration. It should be pointed out that the liquid surface tension (varies with constituents in wastewater) and surface chop (increases the surface area) are inherent in the transfer calculations.

Atmospheric reaeration and subsequent molecular diffusion, per se, plays a negligible role in quiescent water bodies. It has been recognized that since the work of Adeney and Becker in 1920, that disturbance of the surface and the creation of new air-water surfaces is the key to accelerated atmospheric reaeration. However, a constant pattern of surface agitation and surface renewal is difficult to maintain in unassisted stabilization ponds.

The work of Imhoff and Fair in their study of atmospheric reaeration in streams provides evidence that motion, surface agitation, and surface renewal substantially increases the rate of absorption over that of quiescent bodies of water. For example, these investigators found that a “large stream” of “low velocity," with an average depth of 6 feet absorbed 48 pounds of atmospheric oxygen per acre, per day, while maintaining constant oxygen deficiency of 7.4 ppm (1.8 ppm residual DO or 20% saturation)

It is interesting to note that if one assumes that a “large stream” is 100 feet across, such a stream will expose one acre of its surface to the atmosphere in about 436 feet of its length. Further, if one assumes that its “low velocity” is 1.0 feet per second and that the stream’s motion thoroughly and gently mixes its contents vertically, it will effectively expose a new acre of surface area at the rate of one acre in 43.6 seconds, or about 8.26 acres per hour. On a daily basis, such a stream would absorb over 7,227 pounds of oxygen from the atmosphere while traveling about 16 miles per day, provided that there is some mechanism to maintain a constant oxygen deficiency of 20% saturation in the surface stratum.

This theoretical rate of oxygen transfer was born out in studies of actual BOD reduction in streams by Imhoff and Fair. Even before their work, English scientists observed that no matter what the magnitude of BOD loading, 5 days were more than adequate for a “stream” to stabilize organic pollutants from the City of London before they reached the ocean.

Although there are several variations of formulations for atmospheric reaeration which will estimate its magnitude, none are applicable to unassisted ponds which show an oxygen deficit at night and are supersaturated during the day. However, for purposes of computations of oxygen balances referred to earlier in this discussion, the quantity of oxygen which will enter an unassisted stabilization pond by atmospheric reaeration can be calculated with the approximate empirical equation of Imhoff and Fair as follows:

$$R = 0.027(a)\,(O_d\,)(DO_{24}), \qquad (13)$$

Where R = atmospheric reaeration (lbs./acre/day),
O_d = operating depth of pond,
DO_{24} = the 24-hour average dissolved oxygen deficit (mg/l), and
a = assigned the value of about 40 (daily reaeration as a % of constant O_2 deficiency).

Assuming a quiescent, unassisted pond of two acres and a depth of 6 feet, and a constant O_2 deficit of 7.4 ppm (saturation of 9.2 - residual DO of 1.8 ppm), this formula suggests that such a pond will absorb 96 pounds of oxygen per day from the atmosphere.

In addition to atmospheric reaeration, the supply of oxygen by photosynthesis is very significant in a wastewater treatment pond. Oswald suggests that under satisfactory conditions of illumination, temperature and nutrition, photosynthesis may give rise to 200 pounds of oxygen per acre per day. In a quiescent stabilization pond, Oswald pointed out that photosynthetic production of oxygen is the major potential source. The classic reaction, $CO_2 + 2H_2O \rightarrow CH_2O + O_2 + H_2O$, when modified to account for the usual composition of algae may be written as follows:

$$NH_4^+ + 7.6CO_2 + 17.7H_2O + 886\text{ kcal.} \rightarrow C_7H_{8.1}\,O_{2.5}N_{1.0} + 7.6O_2 + 15.2H_2O + H^+ \qquad (14)$$

About 3.68 calories are fixed for each mg of oxygen liberated, and about 1.67 mg of oxygen are liberated for each mg of algae synthesized. The source of the energy for this type of reaeration is, of course, the sun.

If it is assumed that conditions in the pond are such that all of the oxygen demand is to be met by photosynthetic reaeration, and if the areal loading, Lo, is expressed in pounds per acre per day, the areal loading can be expressed as follows:

$$L_o = 0.226\ \underline{0.66FS}\ L_a, \qquad (15)$$

C_c

Where L_o = organic load applied to a pond (lbs. BOD/acre/day),
F = the fraction of available sunlight converted to fixed energy (energy fixed in algae/total visible light energy penetrating the pond surface expressed as a %),
S = sunlight energy (cal/cm^2/day),
L_a = influent BOD concentration (mg/L), and
C_c = algal concentration (mg/L).

Inasmuch as the ratio of oxygen to organic matter in photosynthesis (equation 13) is about 1.67, equation (14) may be expressed as:

$$L_o = 0.25FS \qquad (16)$$

Whether supplied by atmospheric or photosynthetic reaeration, in order for reactions involving oxygen to take place, dissolved oxygen must be distributed to those regions where it is required. The rate at which oxygen is absorbed by the pond volume depends not only on the initial concentration, but on the gradient of vertical concentration. Oxygen absorbed through, or produced at, the surface will diffuse downward, and laterally, and in time, a condition is established in which the concentration varies from almost saturation on the surface to the initial dissolve oxygen concentrations at some point below. The rate of diffusion is therefore dependent upon the depth of the water beneath a given surface area and the vertical gradient of dissolved oxygen concentrations.

Also, the quieter the water, the slower is the rate of diffusion. Diffusion proceeds until an equilibrium is established, even at low oxygen concentrations. At this point the diffusion almost ceases. Mixing of the water, or redistribution by advection, and convection, after this period of quiescence causes an even distribution of the oxygen and allows reaeration and diffusion to proceed to a new equilibrium.

One can readily see that atmospheric and photosynthetic reaeration holds great potential for supplying molecular oxygen, if suitable mixing can be established in a pond that maintains a constant deficit. Without such mixing, the reaeration processes become self-limiting. The surface becomes supersaturated with dissolved oxygen (from the atmosphere and from algal growth), effectively insulating it from further oxygen transfer from the atmosphere. Also, in a quiescent pond, algal blooms may blanket the surface. Until stripped off, these dying plants prevent sunlight penetration and inhibit oxygen production by other kinds of algae that provide valuable oxygen beneath the surface. Unless the saturated water is redistributed and/or the BOD oxygen uptake is such that there is a sustained deficit at or near the surface, the mass transfer will slow or stall; even though the depths of the pond may be devoid of dissolved oxygen.

Without mixing, the magnitude of the oxygen deficit required to draw significant quantities of oxygen into a quiescent pond is that at which odors may arise. For example, according to equation (13), a two-acre, pond 6 feet deep and having an oxygen deficit of 9.2 ppm (no DO residual), will consistently gain 119 pounds of oxygen per day. Unfortunately, a pond with a sustained oxygen deficit of 9.2 ppm throughout its depth will give rise to intolerable odors. A deficit of about 6 ppm (residual DO of about 3.2 ppm) is the maximum in order to avoid odors 24 hours per day. However, experience has shown that an "aerobic cap" of about 2 ppm sustained in the upper 18'' – 24" stratum of the pond will generally eliminate any foul odors.

In summary, oxygen provided by atmospheric reaeration alone in a quiescent pond is highly dependent upon the surface area. Photosynthetic reaeration is also surface dependent but depth is an important factor as well. When the areal loading ratio is exceeded, the oxygen supply mechanisms become insufficient to meet the requirements of sustained aerobic waste treatment. This is because of the low solubility of oxygen and the consequent low rate of oxygen transfer. To transfer large quantities of oxygen into water, additional interfaces must be formed, a maximum oxygen deficit must be maintained, resistance in the interface must be reduced, algal growth must be controlled, the surface must be rippled, and the volume beneath the surface must be well mixed, or other sources of oxygen must be supplied.

Oxygen Supply vs Demand

In general terms, for an unassisted pond, reaeration is considered the "supply" while the actual BOD removal in that particular pond is considered the "demand." Pond scientists have observed that the supply must exceed the demand for any given amount of BOD removal. This useful relationship is rationalized as follows.

Disregarding phosphorus, sulfur, and trace elements, the use of oxygen by organic matter in sewage in a thoroughly mixed pond has been found experimentally by Oswald, Hee, and Gottaas to follow the reaction:

$$C_{11}H_{29}O_7N + 14O_2 + H^+ \rightarrow 11CO_2 + 13H_2O + NH_4^+ \quad (17)$$

This is considered a "first stage" reaction since the first demand that must be satisfied is made by the carbonaceous components, sometimes referred to as the *ultimate carbonaceous* BOD (UBOD).

The second stage begins when the carbonaceous BOD ($CBOD_5$) is mostly satisfied and the demand by nitrogen compounds begins. This nitrification demand requires a "habitat" for nitrofying organisms, such as the fixed biofilm that may develop on surfaces in the aerobic zones of a pond. Since the sides and bottom of a typical facultative lagoon are normally anaerobic, there is little chance that these nitrofiers can become established.

In addition to a biofilm habitat, the nitrofiers' growth and sustenance are dependant upon dissolved oxygen and soluble BOD concentrations, wastewater temperature, pH and alkalinity, flows, and loading variability. Field data obtained from rotating biological contactor nitrification designs (a device that provides an artificial habitat), indicate that nitrification is typically observed when the soluble BOD declines to 15 mg/l, and maximum nitrification occurs when soluble BOD concentrations drop to 10 mg/l or less. Oswald found that the oxidation of ammonium ion (NH_4^+) to nitrate rarely occurs in unassisted stabilization ponds, as it is either lost to the air, assimilated by algae, or precipitated during high periods of pH, before nitrification can be established.

Without consideration for oxygen uptake in nitrification, from equation (13), one can calculate the weight of molecular oxygen required to completely oxidize organic matter. Using molecular weights and a stoichiometric (electron-balanced) equation, the amount of oxygen required is found to be 1.56 times the weight of the organic matter oxidized. This finding implies that the free oxygen supply (from all sources) must be about 56% greater than the desired BOD reduction, assuming no nitrification will take place.

Applying this supply-to-demand ratio to the two-acre pond used in the example under equation (13), wherein the supply of oxygen by reaeration amounted to 96 pounds, one could expect to remove a maximum of 62 pounds of BOD per day in that particular pond. If the desired removal rate in this pond was 90%, one could confidently plan an effective areal loading of up to 30 lbs. BOD/acre/day. This would allow some margin for residual DO.

Using this supply-to-demand ratio, one can formulate an expression that combines the areal loading method from equation (10) and the reaeration rate from equation (13) as follows:

$$L_o' \times 1.56 = R \quad (18)$$

This relationship confirms the "power" of reaeration. As an example, a facultative pond in North Dakota that is designed under the areal loading method at 20 lbs. BOD/acre/day must be supplied at least 31 lbs. O_2/acre/day via reaeration sources. The fact that a properly designed (and properly operated) facultative wastewater treatment pond consistently handles the recommended areal loading limits is evidence of the "power" of reaeration in a quiescent (unassisted) pond.

As one can see, the respective sources and mechanisms for the supply of oxygen are complex and difficult to quantify. It is far easier to observe the results and assume the supply. Nevertheless, engineers and regulators continue to use these relatively simple biological design considerations and equations to estimate, with reasonable accuracy, the amount of oxygen necessary (lbs./ac-day) to achieve the desired (ultimate) BOD reduction (stabilization) for a given influent consistency, flow, pond size, and temperature.

SLUDGE FACTORS

After areal loading, experience with the Sunflo^2 units and other circulation equipment has shown that sludge characteristics can have a significant influence on the effectiveness of mechanical assistance in the removal of BOD. The following characteristics are listed in descending order from most burden on BOD removal rate to least burden.

1. Slurry volume and its volatility.

Potential (volatile) BOD suspended in slurry form cannot be oxidized aerobically (stabilized) unless it has been dissolved. Solid particles carrying volatile BOD and that are soluble are more likely to dissolve when they are in suspension as the physical mixing action enhances dissolution. When the volatile solids dissolve, they will exert a demand on the molecular oxygen (O_2) supplies in the pond. If the availability of dissolved oxygen (DO) is sufficient to support aerobic bacteria, the BOD stabilization will occur at a relatively higher rate than it would if stabilization were to take place anaerobically. Volatile slurry, when mixed, will therefore exert an additional dissolved oxygen demand in an otherwise loaded pond, beyond that which would be required to satisfy the more quickly dissolved BOD in the influent. In other words, the exposure of volatile slurry to dissolved oxygen supplies will increase the oxygen uptake rate, thereby diminishing the oxygen supplies to other users. This affect is also operative when dissolvable solids that have settled out are subsequently re-suspended before stabilization has been completed anaerobically.

The low density and movement of particles in slurry are not conducive to efficient anaerobic stabilization. This is due primarily to three factors: 1) Non-dissolved particles in the slurry are not in sufficiently close proximity to sustain chemical and biological reactions which typically require continuous (uninterrupted) physical contact of all the critical ingredients, including heat. 2) Heat generated from the exothermic reactions that might occur, is quickly dissipated to the expanses of the pond (depending upon the mixing rates), preventing its recapture and stimulation of further anaerobic reactions. 3) Depending upon the supply of DO at the depths that slurry is found (settling near the bottom), the dominant bacteria will vacillate among aerobic, facultative, and anaerobic forms. Frequent changes in the dominance of a particular bacteria regimen result in a much slower stabilization rate than if the material were subjected to continuous aerobic, facultative, or anaerobic processes.

From the above facts, it can be concluded that the volatility and volume of the slurry are important factors. Unless the total resources of DO for a pond environment is sufficient to satisfy the additional burden introduced by continually mixing (and dissolving) a zone of volatile slurry, it is better to let it settle to the bottom where sustained anaerobic stabilization can take place. On the other hand, if the volatility of the slurry is minimal, the only consequence of keeping solids in suspension is turbidity. Apart from the advantages of precipitation to the sludge blanket, turbidity may adversely affect the Total Suspended Solids (TSS).

Turbidity may also affect algal growth. Turbid waters will restrict the sunlight penetration and prevent the growth of the algal species that flourish beneath the surface, thereby restricting the benefits of photosynthetic oxygen production.

Experience with the Sunflo^2 units has shown that when sludge in the form of slurry is present, the oxygen uptake is dramatically increased. In some cases, this additional demand on oxygen resources has in fact diminished the residual DO concentration to below that of the unassisted pond. When the intake depth setting was raised, the DO concentration increased somewhat, even though the BOD loading remained constant. This anecdotal evidence strongly supports the belief that, of the various sludge-related factors affecting Sunflo^2 unit's performance, the volume and volatility of the slurry ranks highest. That is, the more volatile slurry there is in a pond, the more work will need to be done per unit. This workload may be reduced somewhat by setting the intake above the slurry zone, however this action will reduce the MCRT, a parameter that is even more important than volatile slurry volume.

In terms of the Sunflo^2 unit's operations, this means that if the slurry is found to be volatile, the intake structure should be set such that is does not cause circulation in the slurry zone. Even when the intake is well above the slurry zone, the gentle localized mixing motion due to the waves generated by the Sunflo^2 units, will normally stimulate bioflocculation, and subsequent settling of particles in the slurry. This action has benefits that will be discussed later.

2. Weight-bearing volume and its volatility.

Volatile solids that settle to the bottom of the pond, where there is typically little or no molecular oxygen available in an unassisted pond, will begin to decompose via several chemical and biological reactions. These reactions require very little DO. Although these stabilization reactions do require oxygen, it is obtained from another chemical compound as opposed to relying on "free" oxygen molecules that may be in solution. Research has shown that stabilization in the sludge zone provides a significant reduction on demands for free oxygen resources; about 25% that of the aerobic stabilization of 1 lb of BOD. Anaerobic reactions however produce hydrogen sulfide and other odors that cause complaints if they escape into the atmosphere. Also, anaerobic reactions produce ammonia.

Even though anaerobic sludge digestion normally does not compete for the DO, research indicates that the rate, quantity and quality of sludge deposition and the temperature can have a significant impact on oxygen resources. For example, rapidly deposited sludge, under high loading conditions and/or low temperatures, can exert a secondary BOD load when temperatures rise and/or influent loading is reduced. Studies have shown that under natural mixing conditions by wind and wave action, about 90% of the suspended solids in raw sewage is removed in about three days and 80% of the dissolved solids in about ten days. However, in ponds where algae and bacterial growth has been established, and where incoming wastewater is mixed with pond contents, 85% of both the suspended and dissolved solids are deposited on the bottom within four hours.

The studies conclude that bioflocculation brings about a ten-fold increase in the speed of formation and deposition of suspended solids and more than a hundred-fold increase in the speed of deposition of dissolved solids. Bioflocculation is accelerated as temperature increases from 4^{o} to 25^{o}C, by the gentle action of waves, or by mechanical re-circulation, and probably by the movements of invertebrates. The presence of oxygen also greatly increases bioflocculation.

Although aeration and mixing by mechanical means can accelerate the formation of floc and thereby increase the rate of sludge deposition, if the velocity of the mixing action provided by the aeration equipment is sufficiently high (1.5 – 2.0 ft/sec.) to keep solids and colloidal material in suspension, the sludge deposit may be thinly disbursed throughout the zone of influence of the aeration equipment. Thin layers of sludge are more vulnerable to fluctuations in pH and temperature than sludge deposited at slower velocities. These fluctuations disrupt the biological and chemical processes that may have become established.

Once accumulated at the bottom the chemical and biological reactions will eventually become established and decomposition and stabilization will take place. Of these transformations, methane fermentation is probably the most important process. All materials that settle to the bottom of a stabilization pond through the various methods of sludge deposition are subject to methane fermentation, provided suitable conditions exist or become established. These conditions include:

- abundance of organic matter being continually converted to fermentable organic acids
- adequate population of methane bacteria
- pH level within the range of 6.5-7.5 (preferably, 7.0)
- alkalinity in quantities sufficient to buffer the organic acids
- temperature from 5^{o}C-60^{o}C
- lack of toxic substances
- sustained absence of oxygen

Another important reaction taking place in the sludge zone is acid forming decomposition. However, the uncontrolled occurrence of acid formation in heavy sludge deposits built up over a period of time is the primary cause of objectionable odors. The reaction produces carbon dioxide, hydrogen, ammonia, organic acids and many odorous compounds such as indole, skatol, cadaverin and hydrogen sulfide. Some of these compounds, particularly gases, escape into the atmosphere, and may constitute a severe odor nuisance. Also, partial decomposition of a sludge bed may decrease the pH to a point where the material “pickles” itself. In this case, the pond is said to be “stuck.” Recovery from this state requires an effective increase in the pH throughout the sludge be and rehabilitation of the bacteria colonies.

In order for wastewater treatment ponds to take the best advantage of sludge processing, several primary factors must be optimized:

1) The particles must be volatile. That is, there needs to be something left to be oxidized and transformed to a lower state.
2) The precipitation of volatile solids should be facilitated (volatile solids are more efficiently treated anaerobically in the sludge zone).
3) The particles must be in close proximity (fairly dense), such that the interactions among the critical ingredients can take place.
4) Heat is needed to stimulate the reactions. The warmer the mass, the faster the reactions. The denser the mass, the more likely heat generated in the exothermic reactions will be recaptured, raising the overall temperature of the reactants.
5) The particles should remain undisturbed by motion in order to facilitate complete stabilization.
6) The conditions supporting methane fermentation should be promoted and sustained.
7) The pH of the pond must be such that the chemical and biological reactions are not stifled.

It can be concluded from the above discussion that while not as important as slurry, the volume and volatility of sludge is important to consider when applying any device that is capable of mixing and/or stimulating bioflocculation. It should be noted that observations of the Sunflo^2 units in ponds with volatile sludge has resulted in a significant reduction in the weight-bearing zone. It is not known whether the proximity of the intake to the surface of the weight-bearing sludge had any affect on the rate of its depth reduction.

In terms of the Sunflo^2 unit's functions, it is again noted that the local mixing action of waves stimulates bioflocculation, resulting in more efficient precipitation of small biomasses and subsequent anaerobic digestion. This action tends to reduce the demand upon DO resources in the pond. The small amplitude, local mixing action by the Sunflo^2 units is primarily the result of the shallow, but continuous, waves produced on the surface by its impeller.

Circulation characteristic (bottom to top) produced by the Sunflo^2 units may result in a better distribution of the pH. To the extent pH is locally influenced by reactions (acid forming decomposition and methane fermentation) in the weight-bearing zone, gentle circulation may dilute the effects of pH in the sludge zone. Both hydrogen sulfide and ammonia can be arrested in an aerobic zone above the sludge, provided there is sufficient DO and zone depth, both of which are somewhat influenced by increasing the depth of the Sunflo^2 unit's intake setting. On the other hand, the intake structure should be set such that the weight-bearing layer of sludge is not re-suspended or in any way, agitated.

Therefore, if there is sufficient depth in the aerobic zone to capture most of the evolving gasses, and if there is no volatile slurry, the intake structure could be set near the weight-bearing sludge zone. While this maximum depth setting might assist in pH distribution and other desirable mixing results, including total sludge reduction, it leaves no margin for surges in the aerobic zone. A shallower intake depth setting is preferred and should be determined more by the “mixed volume” depth dictated for adequate MCRT.

3. Ratio of volatile slurry to total sludge.
Based on known characteristics of sludge stabilization, and the discussions above, it is clear that the depth of the slurry, depending upon its volatility, can present a greater burden on the BOD stabilization process than does the weight-bearing zone. In other words, a Sunflo^2 unit operating in an environment with two feet of total sludge, 18 inches of which is volatile slurry, will have more work to do than if it were operating in a pond with only 6 inches of slurry and 18 inches of weight-bearing sludge, even when the weight-bearing zone is volatile. Therefore, the relative ratio of slurry to total sludge is an important factor in predicting the removal efficiency of the Sunflo^2 units.

4. Total sludge depth as a percent of operating depth.
The assumption made here is that sludge consistency will vary from site to site. Some sites will have more slurry, while others may have no detectible slurry with all sludge in the weight-bearing form. Whether the sludge is slurry or weight-bearing, the combined depth becomes more significant as it occupies more and more of the operating depth of the pond. Besides exerting rapid uptake on oxygen resources (the nearer the surface, the greater its access to dissolved oxygen), the slurry reduces the effectiveness of any circulation method. Also, the nearer the surface, the more adverse affect slurry has on algal growth in the depths below the surface, by blocking sunlight penetration.

On the other hand, in ponds where all the sludge is of weight-bearing consistency, the most significant affect is its displacement of the treatment volume of the pond. This factor is addressed in a following discussion. In addition to its displacement affect, however, accumulations of weight-bearing sludge, reduces the mixing effects through both a reduction in the mixed volume, and through increased potential for short-circuiting.

When taken together, the combined depth of the slurry and weight-bearing sludge, as it occupies an increasing percentage of the operating depth of the pond, correspondingly reduces the effectiveness of any treatment approach, whether man made or natural. In terms of the Sunflo^2 unit’s functions, the sludge depth as a percent of operating depth inhibits the ability to “grab” a suitable volume for the MCRT. In other words, when applying the other criteria for setting the depth of the intake, there may not be enough operating depth remaining to provide the minimum MCRT.

5. Displacement of treatment volume due to weight-bearing sludge accumulation.

Most facultative ponds with controlled discharges are designed with a certain detention time. That time, in days, is a function of the daily flows and the absolute volume of the pond. While this design is usually used to accommodate the reserve capacity required to store flows between discharges, it is also designed to provide sufficient time for BOD removal. Short-circuiting, increased flows, and volume displacement due to sludge can significantly reduce the effective detention time in a pond. In some situations, the effective detention time is reduced to the point that there may not be adequate time for the bio-chemical reactions to take place. When this happens, there is an increased burden on any treatment process, especially on oxygen resources.

Therefore, it is important to consider what portion of the original designed volume of the pond has been displaced. The degree to which the actual treatment volume has been diminished, will adversely affect ultimate BOD removal, either by the reduced time for reactions, or by the reduced volume of water to be circulated and distributed (dilution). In terms of the Sunflo^2 unit's functions, it has the ability through its circulating and sludge reducing characteristics to increase the effective detention times. However, any improvement will be limited by the volume of the weight bearing sludge. In other words, initially the maximum volume that can be included in the calculation of the MCRT will be the designed operating volume of the pond, less the volume that has been displaced by the weight-bearing sludge. Over time, to the extent the weight bearing sludge was volatile and reduced by the Sunflo^2 units, the effective detention time may be increased somewhat. This will consequently provide a little improvement in the potential MCRT.

DEFINITION AND QUANTIFICATION OF SLUDGE FACTORS

SS_d = Depth of the sludge as slurry, expressed in feet above the weight-bearing layer of sludge. The observed measurement of suspended material in the column of water above the sold mass in "sludge judge" samples. Requires training and practiced technique.

BS_d = Depth of the sludge that is weight-bearing, expressed in feet above the actual bottom of the pond. The observed measurement of dense and settled material in the column from the actual bottom of the pond to the top of the settled material in "sludge judge" samples. Requires training and practiced technique.

TS_d = Total sludge depth (SS_d + BS_d) in the pond expressed in feet as observed in the column in "sludge judge" samples.

SS_v = Volatility of the slurry sludge sample, expressed in lbs. of BOD as a percent of the total weight of the sample as reported from laboratory analyses.

BS_v = Volatility of the weight-bearing sludge sample, expressed in lbs. of BOD as a percent of the total weight of the sample as reported from laboratory analyses.

V_d = Volume displaced by the weight-bearing sludge, expressed in gallons and computed from pond dimensions and BS_d .